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Editor

Jon Ogborn

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NOTE: COMMISSIONS NOT INCLUDED
Commission 1 is an administrative Commission, responsible for finances
Commission 7 Acoustics has become Affiliated Commission 3 Acoustics
Commission 13 Physics for Development is being re-organised.

Introduction

Jon Ogborn

This collection of reviews of the state of the art in physics is an updated version of a collection edited by Paul Black, Gordon Drake and Leonard Jossem, to mark the beginning of the new millennium. Several years on, physics has moved forward and it is time once again to take stock and to look a little into the future.

The first collection arose out of discussions at a meeting of the Council of the International Union of Pure and Applied Physics in 1998. The Commission on Physics Education, C14, had raised the question of whether IUPAP would arrange any special activity to celebrate the millennium. It was decided to ask the chair of each IUPAP commission to contribute a short article to explain recent major advances in their field, and suggest how it might develop in the next few years.

The authors were asked to write for physicists who are not specialists in their commission's field, aiming at physicists – including high school teachers – who might use the material to enliven their classes. Many of the contributions rise nobly to this difficult challenge. Browse amongst them to see which appeal to you and your students. However, the special strength of the collection is that each piece is authoritative — written by recognised international experts in the field with a passion for their particular part of it. Thanks are due to the original authors for their willingness to contribute to the collection, and to those in the new commissions who undertook the revisions.

The pieces are presented in the order in which the IUPAP commissions happen to be numbered. There are many links between these fields, and sometimes some overlap. As editor, it has been my privilege to read each contribution several times, and this has led me to note a number of trends across the various commission, which give a hint of how physics as a whole is changing and developing.

One such trend is towards increasing interdisciplinarity. More and more, physicists are working with others to develop ideas at the boundaries of different fields, including chemistry and biology. In the work described by several commissions there is also a trend to tackle more complex and realistic systems, evidenced for example by the interest in 'soft matter'. Going along with this is a widespread theoretical interest in non-linearity, in complexity, critical phenomena, and the renormalisation group.

Several commissions report the growing importance of miniaturisation, of manipulation of matter at the nano-scale, together with recognition of the importance of phenomena at the meso-scale. Instruments and sensors are rapidly getting smaller, as well as more accurate.

It is notable, in many reports, how optics has regained its importance and value for a range of new applications in many areas of physics.

Finally, the computer now plays a central role in the work of most physicists. It has become an indispensable tool of research, both experimental and theoretical. Computational modelling of physical systems, allied to the rapid growth in computer power and speed, thrives in very many areas. Sophisticated image processing is vital in many areas of both fundamental and applied physics. It seems safe to predict that uses of computing in physics will grow in the future, notably in those areas such as astrophysics, statistical physics and particle physics that already make heavy demands on computing.

Such changes in character of physics deserve to be brought to the attention of students, amongst whom is the next generation of physicists. In particular, it is important that high school physics courses reflect these changes, so that students can make better informed choices of the subjects they will study.

Reading and editing these pieces has been a pleasure. Taken together, they expand ones vision of physics and show that the subject is very much alive, still full of intriguing surprises, worthwhile problems and fascinating promise.

Symbols, Units, Nomenclature and Fundamental Physical Constants

Commission 2

Brian W Petley

Introduction

New developments in the field of units, measurement and fundamental constants can arise unpredictably from developments in almost any branch of physics, which make new levels of precision available. So likely future developments in the field will emerge from future developments in the whole of physics.

The subject is a very pragmatic one: use is always made of the best measure available. This both builds on and helps provide the most stringent tests of our understanding of physics and it is therefore very difficult to predict these in advance. We will therefore concentrate on those aspects that will not be highlighted in the other chapters of this book.

It should be emphasised that, although a wide range of talents can be deployed in the field, the physics in this general area is just as intellectually demanding as is any other part of physics. Although often frustrating, physics in the last decimal place has a beauty of its own, as those who practice it will confirm. We are taught to do our physics by isolating the variables. In the last decimal place, however, one never knows what other physics will intrude on this sound principle. Physicists come into the field, some stay, others move on - some collecting their Nobel Prize as they do so. It is not necessary to be obsessive about accuracy. The interest is stimulated by the observation by eminent physicists that "God is in the detail" (as also is the Devil). The metrologist must have a general interest in physics as well as in measuring things accurately - and that is part of the interest in the subject.

In order to communicate the discoveries of physics and in order to compare theory with experiment, it is necessary to have an internationally agreed vocabulary, a system of quantities, a method of conveying how well the measurement has been made, and a correspondingly well defined system of units. This enables others to relate our work to their own.

Vocabulary, quantities, units, and uncertainties are therefore even more an essential part of modern physics than they were in the past. It is, of course, salutary but rather irksome to have a colleague point out that we have not paid sufficient attention to this aspect of our work

In physics we tend to match our terminology to fit the particular purpose, for we would obviously expect to pay more care when working to a large number of decimal places than if we were performing a yes/no type of measurement. The terminology of physics, the units of measurement and the associated uncertainty statements must all be capable of use to the highest accuracy and to whatever degree of sophistication the circumstances demand. Since the accuracy of scientific measurements is being improved all the time so too must the measurement system in which they are discussed.

Vocabulary and Code of Accuracy

Physicists do not work in isolation, so even greater problems have to be surmounted for successful two-way communication of ideas and data between physics and other branches of science and technology. We also have to be able to communicate (i) with the man and woman in the street who, one way or another, ultimately play a major part in paying for our work, and (ii) with the next generation of physicists who are still in the classroom. All of these aspects, although again sometimes irksome, are essential to modern physics. As physics moves to ever higher accuracy, so too the requirements for a stable and agreed platform for our work become ever more important.

Many aspects of our system of units (for example its dimensionality, and the vocabulary of measurement) are made for science, technology and every-day purposes, and our ideas evolve in response to fresh discoveries. Despite our strong instincts that it should do so, Nature has not so far provided us with any unique *natural* units of length, mass, and time, and there are many possibilities based on combinations of the fundamental physical constants: the electron and proton masses, the Planck constant, the elementary charge, the speed of light, the Newtonian constant of gravitation, and so on.

The SI Units

Physicists will always need their own *local* units in order to discuss particular problems. There is often a group vocabulary which is used for abbreviated communication of ideas within the group but which can leave the outsider baffled.

There is therefore a requirement for a universal system comprehensible to all. The International System of units (SI) provides a common system of units for science and technology. Although they may like their local units, it is recommended that physicists give their results in terms of the SI units the first time that they are used, so that everyone knows exactly what is being said or written. During its nearly forty years of use, the SI has been modified as science and technology have advanced. To the great satisfaction of most physicists, the artefact standards are being replaced by units and standards that are based on atomic and quantum phenomena. The process seems likely to continue for the next few decades, reflecting the fact that nature does not provide a unique set of natural units.

The second and time measurement

Once the accuracy of measurement of time surpassed the one part per million level, the Earth proved an increasingly poor timekeeper. The second was thus re-defined by the Conférence Générale des Poids et Mesures (CGPM 1968) in terms of the frequency associated with a specified microwave hyperfine energy transition in the ground state of the caesium-l33 atom. Today the accuracy is such that a general relativistic correction must be made to the measured caesium frequency in order to allow for the frequency shift associated with the black-body radiation associated with room temperature apparatus, and for the effects of altitude. Such gravitational and other corrections will be of even greater importance in the future.

Precision timing techniques have been used to measure the distance of the moon with centimetre accuracy and satellite navigation systems should soon tell us our position in space, in the air, sea, or on the surface of the earth with comparable 0.1 nanosecond timing accuracy, or better.

The developments in our ability to laser-cool atoms has led to caesium fountain atomic clocks, in which caesium atoms move a few tens of centimetres vertically before falling back through the same microwave cavity - thereby permitting the observation of very narrow optical (Ramsey) fringes. These have increased our ability to realise and measure time with very high accuracy. There are other systems which are ideal secondary standards, including mercury and rubidium ions, room temperature and cryogenic hydrogen masers, and very high Q microwave cavities.

Extremely narrow resonances have been observed in the visible region of the spectrum and beyond, and one or more of these may well prove to provide more accurate frequency standards or clocks in the future. The definition of the second in terms of the hyperfine transition in caesium may well be replaced in the next thirty years or so.

The metre

Laser technology has enabled the metre to be defined in terms of time and an agreed value for the speed of light. The consequence of this is that in principle the metre is realisable with the same accuracy as the second. The development of the necessary enabling technology makes this possibility an increasing reality. However, the accuracy of length measurement has not yet quite caught up with the accuracy of time measurement.

Ion and atom traps enable very narrow transitions to be studied in the visible region and even higher frequencies. As above, the measurement accuracy is advancing very rapidly and one day may lead to an optical transition being used to define the second. The ls-2s transition in atomic hydrogen is already part of the *mise en pratique* for the definition of the metre.

The volt and ohm

Low temperature solid-state physics has led to the use of the Josephson superconducting junction effects, and the quantised Hall resistance of Klaus von Klitzing to maintain very stable units of potential and resistance respectively. The Josephson effects particularly may be capable of refinement to even greater accuracies in the future. There is rather less accuracy in hand with the present generation of measurements of the quantised Hall resistance. There may well be other solid state measurements in the future which permit other combinations of the fine structure constant and the impedance of space, rather than with the quantised Hall resistance.

In the past our knowledge of physics has so often been shown to be but an approximation to the truth. The future will provide increasingly stringent tests of the underlying theory of both of these effects as part of this process.

The kilogram

The accuracy achieved by the prototype kilogram is well within the sights of metrologists. They have an alternative method which is based on the realisation of the electrical watt, and as soon as the accuracy reaches the next decimal place they should be able to see drifts in the realised mass unit. We have been accustomed to a measurement system derived from units of mass length and time, and one can already speculate on how we might replace our definition of the kilogram by some type of *atomic* mass definition. There are several related possibilities, including an agreed value for the Avogadro constant. It is conceivable, but unlikely, that the watt might even become a base unit, and the kilogram a derived unit. However it seems much more likely at present that this will happen in an equivalent way, much as the ohm was once suggested as the base electrical unit but is now implicit in the definition of the ampere. The solution adopted will depend on the views of the scientific, technological, commercial, and other communities, and will only be arrived at after the widest possible consultation.

The kelvin

Our unit of temperature is currently based on the triple point of water. It is not very clear what is intended by the term *water*, for there are marked differences between the triple points of water containing deuterium and that containing hydrogen. The deuterium content of water varies according to the source. Consequently, although the isotopic composition of the water is not specified at present, this will gradually become more important as demands for higher accuracy temperature measurements develop in science and technology. In the longer term it is likely that a definition based in some way on the Boltzmann constant (or, equivalently, the molar gas constant, rather than the triple point of water, will be increasingly discussed and brought to fruition in the next twenty years or so.

The candela

The candela is very much a physiological unit, for it is strongly based on properties of the human eye. It is a unit that is essential to the very important cinema, illumination, photographic, television, and other allied industries. Our increasing ability to measure optical energies with high accuracy by substituting an equivalent electrical energy in a cryogenic radiometer suggests that the lumen might be a better long term choice as the base optical unit - but only if that is what the majority of people want. Certainly for many purposes the watt is more often used to express the power of lasers than the candela is used to express their luminous intensity. The unit is currently realised to better than 0.1%

The mole

This quantity is central in modern chemistry and in the parts of physics that overlap with it. The mole is often not properly understood by physicists. This spills over to the Avogadro constant and to other physics constants involving the mole, such as the

Faraday constant and the molar gas constant. Many of these problems reflect the continued use of the centimetre, gram, second unit system and the misconception that the SI is simply derived from it. In some respects it is, but in others there are important differences, particularly where the mole is involved.

The Avogadro constant is implicit in the definition of the mole but its value must be obtained experimentally. It is an important part of the relationship between units and measurements based on atomic mass and atomic energy quantities and measurements based on the corresponding SI units. Its measurement is therefore related to our knowledge of the atomic mass unit, the Planck constant, and so on, which are discussed below.

The Fundamental Physical Constants.

The experimental confirmation of the existence of a group of invariant quantities in nature – the fundamental physical constants – led to a variety of methods of measuring their values experimentally. There were soon more measurements than constants, so statistical methods had to be developed to find a set of values consistent with the bulk of the data. This process was pioneered by R. T. Birge and continues today under the Committee on Data for Science and Technology (CODATA) — Task Group on Fundamental Physical Constants. The extent to which values from different parts of physics agree, or disagree, provides a stringent test of our understanding of the phenomena concerned as well as the accuracy of the associated experiments. Such comparisons have sometimes led to new discoveries.

The accuracies of knowledge of the values of many of these constants have advanced tenfold every fifteen years or so and this process is likely to continue. This has been made possible in part by our ability to make accurate measurements at ever higher frequencies and our ability to reduce thermal noise and Doppler motion by working at ever lower temperatures.

We do not attempt to give here a detailed listing of the likely future accuracies of many of the fundamental constants as they are increasingly interdependent. This reflects our understanding of the physics of the last decimal place. There will, of course, be an ultimate accuracy for all measurement but in many areas of physics we are still some way from this frontier.

Atomic masses

These are a sub-set of the fundamental constants and the accuracies of the measurements of atomic masses have similarly been making spectacular advances.

This applies not only to the masses of the stable nuclides, but also to those far from stability, and to measurements of the masses of the new trans-fermium elements. The island of stability in the region of element 114 is a particular area of interest and effort is likely to be devoted to the production of elements in this region.

Ion traps have been used to make very accurate measurements of the atomic masses of the proton, and of silicon and caesium ions in terms of carbon-12. These masses are simply corrected to the corresponding atomic masses by correcting for the mass and binding energy of the electron removed in the ionisation process. Ion traps are likely to be used increasingly with other ions in order to build up our understanding of the properties of the elements, and the formidable progress in this field will lead to improved tables of atomic masses.

The Fine Structure Constant $\alpha \approx 1/137$

The quantity known as the fine structure constant, in effect the pure number representing the strength of the electromagnetic interaction, plays a deep role in physics and also in metrology, particularly in our choice of suitable units in which to express our measurements. In consequence we need to know this constant as accurately as possible. Because it is so universal, being particularly important in the field of quantum electrodynamics, it provides an opportunity to check the accuracy of our understanding of physics in markedly different areas.

The availability of laser-cooled atoms is already being used to improve our knowledge of the fine structure constant via improved measurements of the Compton wavelengths of heavy atoms such as caesium, a process that is likely to continue. However, other spectroscopic measurements provide important information, as exemplified by the accurate measurements of the anomalous magnetic moments of the leptons, and the von Klitzing resistance.

The Measurement of the Planck Constant

If we rely on the theory of the Josephson and von Klitzing effects, the accuracy of the Planck constant, and of many other constants, is limited by our knowledge of the SI watt. For much of the twentieth century this was realised using the ampere and ohm. However a new method was developed by Bryan Kibble and others which enables much greater accuracy to be obtained via an absolute realisation of the watt. This realisation may then be compared with the one that is maintained via the Josephson volt and von Klitzing ohm. In this way the accuracy with which we know many fundamental constants has already advanced by a factor of about five, depending on the constant. It seems that the accuracy of the method is capable of further refinement, possibly to the extent of allowing the replacement of the kilogram. One can therefore look forward to the day when the values of many of the constants are really constant when expressed in SI units - much as the speed of light is already fixed by its involvement in the definition of the metre. This method of deducing fundamental physical constants currently looks more promising than the alternative route involving deducing the Avogadro constant from a measurement of the lattice parameter and density of silicon. However, the future will decide, for physics is ever full of surprises.

Conclusion

The area covered by Commission C2 is an important part of the engine room of physics and it plays an essential role in helping physics to be applied to the benefit of mankind. This brief survey illustrates that the whole area of symbols, units, nomenclature and fundamental constants is making spectacular advances. These advances both build on those made elsewhere in physics and help to make them possible. Further advances can be expected for some time to come.

Statistical Physics

Commission 3

Kurt Binder and Pierre C. Hohenberg[1]

Introduction

Statistical mechanics is that branch of physics that tries to make a connection between the physics of atoms (0.1 nm or Angstrom scale), and the properties of matter on a macroscopic scale, and related mesoscopic and macroscopic phenomena. Given a knowledge of the forces between atoms, the problem consists in dealing with the large number of these to calculate all quantities of interest (note that one cm^3 of condensed matter contains on the order of 10^{22} atoms). If this task is accomplished one not only understands the principles of thermodynamics, but one also creates a basis for applications in many other fields, such as engineering, materials science, and physical chemistry.

This concept of statistical physics as sketched above is now about 100 years old. It dates back to Ludwig Boltzmann, J. Willard Gibbs and of their contemporaries at the turn of the 19th century. Thus it is interesting to ask where we stand now in this branch of physics after 100 years, and what are the milestones marking progress along the road that had been taken? Simultaneously we will attempt to identify the fundamental questions that remain unanswered, and to look ahead to the next few decades and speculate where the future emphasis will be.

Problems with the Basic Foundations

Perhaps surprisingly, even the most basic foundations of statistical mechanics are still areas of active research. Let us briefly sketch these problems. As is well known, on the scale of elementary particles and atoms the basic equations describe the evolution of the system in time. Also when we consider the limiting case where the equations of motion reduce to the simple Newtonian equations of classical mechanics, it is the time evolution of the entire state of the system that is described. Consequently it would be natural to describe any observable of a macroscopic system (which we assume to be at rest in thermal equilibrium) as a time average along the trajectory of the system in

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[1] Edited and updated by Mustansir Barma (chair of Commission 3)

phase space (in classical statistical mechanics, phase space for a system of N atoms is the 6N-dimensional space of all the co-ordinates and momenta of the particles).

A fundamental strategy of statistical mechanics is to replace this time average by an average over a suitable statistical ensemble, describing the probability distribution of these points in phase space. Justifying this replacement requires the ergodicity hypothesis of statistical mechanics. For example in a ‘closed’ system (i.e., one completely isolated from its environment) energy is conserved, so the trajectory of the system must lie on the constant-energy hypersurface in phase space. According to the microcanonical ensemble of statistical mechanics, all regions on this energy hypersurface are equally probable, and a corresponding average can then be deduced from the principle that the (statistically definable) entropy of the system is maximal. Of course, it is highly nontrivial that the time average along the trajectory and this ensemble average over the energy hypersurface are equivalent, for it is then implied that the trajectory on the hypersurface is sufficiently chaotic that it comes close enough to any point on the hypersurface in a short enough time. It has been a challenging problem to make these conditions (which we have only stated rather broadly here) as precise as possible, and to understand which properties of a system are responsible for ensuring that the ergodicity hypothesis will hold, as well as why it does not hold in the case of a few rather special counter-examples.

A related problem is irreversibility: Newton's equations of motion of classical mechanics are perfectly reversible in time - how can we then derive from them the second law of thermodynamics, stating that the entropy of a closed system, that is not yet in equilibrium, will always increase and never decrease with time (apart from statistical fluctuations which are absolutely negligible in the thermodynamic limit)?

Both problems, ergodicity and irreversibility, are rather subtle and the answers that can be given are fairly mathematical. So we do not attempt to describe them here, but we emphase that the understanding of both problems has profited a lot from a refined insight into non-linear problems in classical mechanics, in ‘non-linear dynamics’ and in the science of chaotic motions. The progress that has been achieved is documented by Boltzmann medals awarded to D. Ruelle (1986), Y. Sinai (1986) and J. L. Lebowitz (1992). Even so, the round table discussion on irreversibility held at the STATPHYS conference in Paris in 1998 is a vivid testimony that there continue to exist conflicting views, and this situation will no doubt persist for the next few decades. We should emphasise that these controversial issues mostly concern matters of fundamental principles, but do not make much difference to practical computations, including calculations of irreversible phenomena. In fact, small deviations from equilibrium are very conveniently handled with linear response theory (Boltzmann medal for R. Kubo 1977 and many further related developments), while phenomena far from thermal equilibrium still pose important problems to our fundamental understanding, as will be discussed below.

Theories of Critical Phenomena

In equilibrium statistical mechanics, the formulation of the various statistical ensembles (microcanonical, canonical, grand-canonical) provides in principle a precise connection between the Hamiltonian describing the atoms and their interactions with the macroscopic properties of matter in equilibrium. However, working out this connection in practice is simple only for rather trivial systems (ideal gases, dilute solutions, harmonic oscillators and systems that can be described by them, e.g. crystals at low temperatures, ideal paramagnets, etc.). These are the systems that are extensively described in the various standard textbooks of statistical mechanics, whilst everything else still is the subject of active research! A good example is a dense fluid undergoing gas-liquid condensation. Its qualitative description in terms of van der Waals' theory is about 100 years old, and we have known for more than 50 years from experiment that this theory fails to describe correctly the vicinity of the critical point. (It implies that near the critical point the gas-liquid coexistence curve has a simple parabolic shape, that is, with an order parameter critical exponent $b = 1/2$ instead of, as we now know, $b \approx 0.325$). Quantitatively accurate descriptions of liquid-gas coexistence have emerged only in the last few decades. Historically, an important role in elucidating these issues was played by exact solutions of lattice models, for instance the two-dimensional Ising model and, more recently, arrow-vertex models (Boltzmann medals for R.J. Baxter (1988) and E. Lieb (1998)).

A further very important step was the understanding of critical phenomena in general terms. Examples of important questions are:

- How can it happen that near a critical point the order parameter (the density difference between liquid and gas in the above example) can be arbitrarily small and nevertheless the free energy cannot be expanded in a Taylor series, as assumed in Landau's theory?
- How are the critical singularities of various physical quantities related i.e. what are the scaling laws between the critical exponents characterising them?

- How can we understand the physical basis for the universality of critical phenomena, why the critical exponents at the gas-liquid critical point are the same as those of binary liquid mixtures, anisotropic magnets, and certain order-disorder transitions in binary alloys such as beta-brass?

How do time-dependent properties, such as the approach to equilibrium or the response to a perturbation, slow down near the critical point?

It has been one of the greatest successes of the last four decades that these aspects of critical phenomena have been clarified. The Boltzmann medals for Fisher (1983), Kadanoff (1989) and Widom (1998) honour in particular the developments of scaling laws, universality etc., but the particularly outstanding achievement is the development of the renormalization group theory, pioneered by Wilson (Boltzmann medal 1977, Nobel Prize 1982). This theory allows one to understand which properties define a universality class, i.e. it clarifies the properties on which critical exponents and related universal quantities (such as scaling functions and universal amplitude ratios) depend, and on which properties they do not depend. These concepts can be extended also to time-dependent phenomena and allow us to characterize dynamic universality classes as well (Boltzmann medal for K. Kawasaki 2001).

Numerical Methods

It must be emphasised, however, that no model (apart from the rather simple ‘spherical model’ that can be solved in any space dimension) is known that can be solved exactly in three space dimensions and yields a critical point. For the study of critical phenomena and phase diagrams, in three dimensions, the development of numerical methods has been very valuable, such as the Monte Carlo method (Metropolis et al. 1953) and the method of Molecular Dynamics simulations (where one simply solves Newton's equations of motion on a high speed computer). These techniques have become a most important tool of statistical mechanics in the last few decades only, although some important discoveries were made quite early by means of computer simulation e.g. the solid-fluid transition of hard spheres (Boltzmann medal for B.J. Alder 2001). Note that while renormalization group techniques yield accurate estimates for universal quantities such as critical exponents, they do not predict non-universal quantities such as the critical temperature and critical density of a fluid, or the absolute magnitude of critical amplitudes. Such tasks can now be accomplished satisfactorily with the Monte Carlo method, using suitable analytic input from the theory of finite size scaling for the appropriate analysis of the computer simulation results (note that in practical simulations N is not 10^{22} but on the order 10^2 to 10^8 only, and using the variation of N as a control parameter is a most useful tool).

Since computer simulations can implement many concepts of statistical mechanics in a rather straightforward manner (linear response concepts such as switching on and off various perturbations, and the analysis of small subsystems of a larger system) and because computers are now easily accessible for every scientist on the desktop, unlike thirty years ago, this development of computer simulation as a standard tool to solve the tasks of statistical mechanics is a fairly recent development, and is as yet far from being fully exploited. It is clear that these methods will continue to find broad application, but it is also clear that the interplay with both analytical theory and experiment is indispensable if their full potential is to be achieved. We also note that there are important problems that are not fully solved - both molecular dynamics and Monte Carlo methods in their original forms deal with classical statistical mechanics, and though there exist some extensions to deal with quantum statistical mechanics, there are sometimes severe difficulties, such as the famous ‘minus sign problem’ encountered when one tries to extend the quantum Monte Carlo methods to fermionic degrees of freedom. This problem, whose solution would allow more widespread applications of computational statistical mechanics to various condensed matter systems at low temperature (e.g. magnetism, superconductors, semiconductors, metal-insulator transitions) is the subject of strong current interest.

New Types of Ordering and of Phase Transition

An area of phase transitions that is still not well understood is that concerned with the effects of quenched random disorder. While the replica method (Boltzmann medal for S. Edwards 1995) is a useful tool for some aspects, many problems remain. Famous examples are Ising models exposed to random fields, or Ising models with random bonds of competing sign, the so called ‘spin glasses’. Qualitatively new types of ordering and phase transitions have been discovered in such systems in the last three decades. Already the formulation of a mean-field theory, which is trivial for an Ising ferromagnet, is a tour de force for an Ising spin glass, and hence was honoured by a Boltzmann medal (Parisi 1992). However, the location of the ‘glass transition’ in a three-dimensional Ising spin glass, as well as the nature of the low temperature phase of this model, are controversial issues even today. One also does not understand how much this problem has in common with the ‘ordinary’ glass transition, from a supercooled fluid to an amorphous solid. The understanding of this glass transition clearly is one of the ‘grand challenges’ in condensed matter physics in our time.

Consequently, it finds much attention now, and will remain a primary theme of research in statistical mechanics in the next decades.

The same statement applies also to surface and interfacial phenomena. While the description of surfaces exposed to a saturated gas as ‘wet’ or ‘non-wet’ in terms of Young's equation for the contact angle of a droplet dates back almost two centuries, it was only in 1977 that the concept of a wetting phase transition between these two states was formulated. Meanwhile, the statistical mechanics of wetting phenomena and related issues (multilayer adsorption, interfacial roughening and capillary waves, critical adsorption and surface critical phenomena, faceting transitions of crystals, surface melting and other types of surface-induced order or disorder) are very active fields of research, and are far from being exhaustively exploited.

Soft Condensed Matter

The last topic of equilibrium statistical mechanics that we emphasise here, ‘soft condensed matter’, is concerned with many materials, notably liquid crystals, polymer solutions and melts, rubber, microemulsions, soap molecules at water-air interfaces and related Langmuir films formed by lipid molecules, biological membranes and supramolecular structures formed by them. While fifty years ago this was considered as a topic of chemistry, and early theories on such problems were honoured by Chemistry Nobel Prizes (Flory 1974), this is now a large area of statistical physics, particularly pioneered by de Gennes (Nobel prize 1991), who showed how useful the tools (scaling, renormalization group) developed for the study of critical phenomena were in this area, solving long-standing and disputed problems like understanding of the end-to-end distance of a long flexible macromolecule in a good solvent.

There are many connections between transitions in soft matter and other problems of statistical physics: for example, the sol-gel transition can be related to the percolation problem where the bonds of a lattice are randomly filled with conducting elements and one asks at what fraction of conducting bonds a conducting path appears across the whole lattice. Mesophases in microemulsions, in block-copolymer melts, for example, have surprising analogies to ordered structure, such as in simple solids, but are much more accessible to analytic treatment by statistical mechanics than the latter, because, due to the large length scales involved, ‘mean-field’-type descriptions are more accurate. This area clearly is one of the fastest growing fields of research in statistical mechanics, and is particularly rewarding because often very interesting connections with other important problems can be made (e.g. there exist links between the problem of ‘protein folding’ and the ‘glass transition’ with its complicated ‘energy landscape’ in phase space). Soft condensed matter is also most usefully studied by methods of non-equilibrium statistical mechanics, since processes are slower and occur on larger length scales and thus are better accessible to experiment. Thus, the process of ‘spinodal decomposition’, the un-mixing of a binary mixture in its unstable region via spontaneous growth of concentration fluctuations, can be studied most completely for polymer mixtures.

Non-equilibrium Problems

Non-equilibrium statistical mechanics is of course a very important sub-field as well, and is a particular area of growing activity. We have already mentioned ‘non-linear dynamics’ in the context of ergodicity, but this field has also given a boost to the study of problems like the onset of turbulence and hydrodynamic pattern formation. While some problems, like scaling aspects of fully developed turbulence, have been under consideration since the middle of the century, the physics of pattern formation in non-equilibrium condensed matter systems has become a particular focus area only in the last three decades. This includes classical problems of hydrodynamics such as Rayleigh-Benard convection, but also other topics such as dendritic solidification, viscous fingering, eutectic crystallisation, and growing interface fronts on surfaces, all of which obviously have important technological applications, such as for the understanding of metallurgical micro-structures.

Unlike equilibrium problems, which can be formulated in terms of a free energy function that needs to be minimised, no such unifying principle exists for phenomena far from equilibrium, where dynamical equations need to be solved. For the description of patterns in chemical reactions (such as spiral waves) there are reaction-diffusion equations, for hydrodynamical patterns (e.g. Rayleigh-Benard rolls) there are the Navier Stokes equations of hydrodynamics or simplified versions thereof, like the amplitude equations that resemble the Ginzburg-Landau equations, used for describing the dynamics of critical fluctuations, or for the dynamics of concentration fluctuations in phase-separating systems. For certain systems, like driven granular matter, the derivation of suitable phenomenological equations is still an unsolved problem, and much of our knowledge of patterns in granular media stems again from computer simulation. Of course, all these flow phenomena have important industrial applications.

Non-equilibrium processes lie at the heart of many biological phenomena, and links between statistical physics and biology have grown strongly over the past decade. The development of new experimental methods to probe and manipulate single molecules, like stretching proteins and DNA, unzipping DNA by external forces, and probing the dynamics of the folding process by fluorescence correlation spectroscopy and other techniques, have inspired extensive activity in statistical physics aimed at modelling these phenomena. Methods of statistical physics have helped in understanding several other problems in biology, such as the source of directional motion in molecular motors, and the extraction of information from genetic data.

While some applications of statistical mechanics are fairly obvious - for example developments concerning equations of state in equilibrium, used by engineers dealing with thermodynamic processes - there are also some applications which have developed as unexpected spin-offs. For example research on spin glasses has led to the concept of simulated annealing, which now is one of the established strategies for optimisation problems, and to neural networks, which also have diverse practical applications. The study of the statistical mechanics of complex networks, which operate in systems ranging from biological cells to computer networks, has shed light on their robustness and clustering properties. Stochastic processes (from random walks to Levy flights) seem to find applications in the analysis of the stock market; however, whether such analogies are just curiosities or are expressions of deep analogies between underlying principles remains to be seen.

Future Trends

In summary, it is quite obvious to most researchers in the field of statistical physics that it is an area of great potential, which is far from being fully developed, and finds more and more areas of science to which it may be applied. The area of 'soft condensed matter', previously a domain of chemists rather than physicists, is a good example. Often statistical physics also contributes to closing gaps between different fields of physics - e.g. lattice gauge theory as a method of regularising quantum chromodynamics, which established a formal analogy with the path integral formulation of the partition function of statistical mechanics (as in Monte Carlo simulations) has found applications in the theory of elementary particles and astrophysics , notably in theories of the early universe, and of phase transitions of the quark-gluon plasma.

We will not attempt here to make specific predictions about the subjects that researchers in statistical mechanics will consider in the next few decades. What is clear is that they will be very diverse, ranging from condensed matter physics, physical chemistry and biology to various problems with applications in technology (e.g. simulation of traffic flows) and economics. We also expect that the interplay between analytical tools and computer simulation methods is far from being fully exploited; indeed that it will remain one of the dominating methodological aspects in the future.

Cosmic Rays

Commission 4

Peter Wenzel[1]

Historical Introduction

The study of Cosmic Rays began early in the 20th century with attempts to understand the mysterious residual conductivity observed in the electroscopes then commonly used for measurements of radioactivity. As so often in physics, careful investigation of an unexplained background led directly to a startling discovery; in this case that the Earth is continuously being bombarded by energetic particles of extraterrestrial origin, the cosmic rays.

In the early years interest focused as much on what these particles did in the atmosphere as on where they might be coming from. The first of these scientific interests developed into experimental particle physics and high energy physics, but from about the middle of the century particle physics moved almost entirely to the new terrestrial accelerators with their precisely controlled beams and well-instrumented targets. Nevertheless, the positron, the muon, the pion and several other mesons, as well as the first strange particles, were all discovered by cosmic ray experiments before they were produced in accelerators. Just 30 years ago, the first evidence for charmed particles was also discovered in cosmic ray experiments.

A remarkable feature of the last decades of the 20th century was a reversal of this trend and a considerable movement of scientists from experimental particle physics back into cosmic ray physics, or astroparticle physics as it is now often called. This had several causes. One was certainly the search for proton decay which stimulated

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[1] This article is an update of the previous C4 report co-authored by Luke O'C Drury and Tom Gaisser. Contributions to this update were provided by Richard Mewaldt, Paolo Lipari, Simon Swordy, Heinz Voelk, and Enrico Zas.

investment in many large underground detectors. While none has recorded a decaying proton, two at least detected the burst of neutrinos from supernova 1987A .

Another factor was the possibility of seeing point sources of very high energy gamma-ray (or other neutral particle) emission. This renewed interest in cosmic rays as an astrophysical phenomenon is developing into what should perhaps now be called particle astronomy. This is not a precisely defined term, but it serves as a useful distinction from the classical astronomies (optical, radio, UV, infrared, X-ray) which all exploit the wave behaviour of the photon to focus, refract, reflect or otherwise concentrate the signal on a detector. By contrast, charged particle studies, high-energy gamma-ray astronomy and neutrino astronomy all operate with techniques derived from particle physics and typically register simply the direction of arrival and energy of the particle. However, the pioneers of X-ray astronomy came from the cosmic ray community, and this field has always retained strong links with cosmic ray physics.

A continuing theme has been the use of the Sun and heliosphere as a laboratory for investigating on a small scale the basic processes of cosmic-ray physics. Space experiments allow direct observation of the interaction between cosmic rays and dynamical structures in the solar wind, in particular the collisionless plasma shocks that form when the solar wind hits an obstacle. This provides the experimental basis for the theory of Fermi acceleration at shocks, a process now thought to operate in a wide range of astrophysical systems and to be the major process in the production of cosmic rays. Similarly, the long-term study of solar modulation provides observational data to constrain theories of cosmic ray transport.

Some Recent Highlights

Structure and dynamics of the heliosphere

The heliosphere is the volume of space around the Sun that the solar wind carves out of the interstellar medium. It is the local environment which cosmic rays of galactic origin have to penetrate if we are to observe them on or near the Earth. The so-called anomalous cosmic rays (ACRs), discovered by spacecraft thirty years ago, provide a direct sample of local interstellar material. They are nuclei of neutral atoms swept into the solar system, ionised in the inner heliosphere, and accelerated at the solar wind termination shock. Because all stages of this process can be observed in considerable detail, ACRs provide a "Rosetta stone" for understanding similar processes in more distant sources.

Space missions have provided *in situ* observations of new frontiers of the heliosphere. The Voyager mission launched in 1977, explored the outer heliosphere and recent observations suggest that Voyager 1 is in the vicinity of the solar wind termination shock. The Ulysses space probe, sent out of the ecliptic plane and over the solar poles, has been providing *in situ* observations of the three-dimensional structure and dynamics of the solar wind plasma over a full solar activity (11 years) cycle and of the latitudinal dependence of the solar modulation of cosmic rays.

The Advanced Composition Explorer (ACE), placed in 1997 into orbit 1.5 million km upstream of the Earth, observed the composition and energy spectra of more than 50 large solar energetic particle events, as well as many smaller events enriched in ^{3}He, neutron-rich isotopes such as ^{22}Ne, and ionic charge states indicative of coronal material with temperatures in the range from 106 to ~107 K. ACE has found that the seed particles that are accelerated by interplanetary shocks do not originate predominately in the bulk solar wind, as was expected, but instead come from a pool of suprathermal ions in the interplanetary medium. The rare isotope ^{3}He is enriched in almost all large SEP events, suggesting that some of the material accelerated by interplanetary shocks in these events originates in previous ^{3}He-rich solar flare events.

ACE has also measured the abundances of two radioactive isotopes (^{49}V and ^{51}Cr) in galactic cosmic rays and found a distinct energy dependence that changes from solar minimum to solar maximum. This change is directly explained by the increased amount of adiabatic energy loss that cosmic rays experience at solar maximum as they move from the interstellar medium through the heliosphere to 1 AU.

Neutrino mass

Probably the most important contribution of cosmic ray physics to particle physics since the discovery of the pion in the 1940's has been the discovery, using natural fluxes of neutrinos, of the phenomenon of neutrino flavour transitions, i.e. the transformation of one type (or flavour) of neutrinos into another. The neutrino flavour transitions have been observed for solar neutrinos, produced in nuclear reactions in the center of the Sun, and for atmospheric neutrinos, produced in cosmic ray showers in the Earth's atmosphere. The results obtained from both observations are compatible with each other and give important constraints on the neutrino masses and mixing. The average mass of the neutrinos is now known to be larger than a lower bound of approximately 15 milli-eV.

Neutrino oscillations occur if the neutrinos have non-vanishing (and non-identical) masses and if “mixing” exists, i.e. if the neutrino flavour eigenstates do not correspond exactly to the states that have well defined masses, as is the case for quarks. The study of neutrino oscillations makes it possible to determine the mass differences between neutrinos and the parameters of the mixing. These quantities may play a crucial role for an understanding of the origin of the masses of elementary particles and for the construction of a simpler and deeper theory of fundamental interactions, beyond the existing “standard model” of particle physics (in which neutrino masses are zero); hence the importance of these results.

The experimental study of solar neutrinos began more than thirty years ago with the Homestake detector, that measured the highest energy part of the solar neutrino flux, obtaining a flux approximately one third of that expected from models of nuclear fusion in the Sun. After this result several other experiments, the water Cherenkov detectors Kamiokande and Super-Kamiokande in Japan, the radiochemical (gallium) experiments Gallex and Sage in Europe and the heavy water SNO experiment in Canada, have also measured the flux of solar neutrinos with greater accuracy. These experiments have established that while all solar neutrinos are created in the core of the Sun with the electron flavour, only approximately one third of them reach the Earth in this original state, while the remaining fraction arrives transformed into muon and/or tau neutrinos.

The experimental study of atmospheric neutrinos started in the 1980’s with large underground detectors, originally built to search for the existence of proton decay. These studies demonstrated that approximately one half of the muon neutrinos that travel on trajectories that cross the Earth transform into tau neutrinos. A key role in these studies has been played by water Cherenkov detectors, and in particular by the Super-Kamiokande detector.

The results on both the flavour transitions of solar and of atmospheric neutrinos have now been confirmed in studies using man-made neutrinos: the solar neutrino results by studying the propagation of anti-electron neutrinos generated in nuclear reactors over a distance of more that 100 km with the Japanese KamLand experiment, and the atmospheric neutrino results by studying the propagation of accelerator neutrinos over a distance of approximately 250 km. Several other “long-baseline” neutrino experiments are under construction for future more detailed studies.

It is rewarding for this field that two pioneers of neutrino detection, Ray Davis and Masatoshi Koshiba, were amongst the 2002 Physics Nobel Laureates.

Opening the TeV astronomy window

TeV astronomy, using optical telescopes to register the Cherenkov light from air showers due to cosmic gamma rays, became a reality twenty-five years ago. Then the imaging technique was introduced by the Whipple group in Arizona (USA). This allowed the separation of hadronic showers due to charged particles from those due to gamma rays. As a result the Whipple telescope could detect with high statistical significance cosmic rays originating in the Crab Nebula.

The last decade has seen a remarkable technological breakthrough with the introduction of sophisticated imaging systems on Cherenkov telescopes, which have so improved the background rejection that real observational astronomy is now possible in the TeV region.

As so often, when a new observational window is opened, something unexpected was found. In this case the Whipple, and subsequently other groups, discovered strong and rapidly varying emission from two nearby Blazars. These are thought to be galaxies with active nuclei (powered by accretion onto a central, super-massive black hole) where we happen to be looking almost straight down the axis of the relativistic jet of material emitted by the nucleus. During outbursts the power registered in the TeV region from these objects exceeds that at all other wavelengths! By now these observations are placing important limits on the intergalactic optical/infrared background radiation field and on possible quantum gravity effects on the propagation of high-energy photons.

In addition to extragalactic sources, several galactic sources have been detected apart from the Crab Nebula. Most importantly, TeV emission has been detected from three shell-type supernova remnants (SN1006, RX J1713-3946, and Cassiopeia A). Both the Inverse Compton radiation from electrons of energies up to about 100 TeV and the neutral pion decay emission due to collisions of high energy protons with gas atoms inside supernova remnants could be responsible for this TeV emission. Their successful separation is expected from synchrotron measurements at radio and X-ray wavelengths, with the hope of finding out whether supernova remnants are indeed the sources of the bulk of the cosmic rays.

Particles with too much energy?

Soon after the discovery in 1965 of the 2.7K microwave background radiation from the Big Bang, Greisen in the U.S. and Zatsepin and Kuz'min in Russia independently pointed out that protons of energy more than 10^{20} eV would interact with this microwave background through photo-pion reactions and lose energy on a length scale of order 5 megaparsecs, which is a relatively short distance in cosmological terms. It was confidently expected that the ultra-high energy cosmic ray (UHECR) spectrum would show a cut-off at this energy limit. This is quite challenging to observe because the fluxes at these energies are of order one particle per square km per century. Tens of particles above this cut-off have now been detected by the two largest aperture air shower arrays HiRes (High Resolution Fly's Eye Experiment) and AGASA (Akeno Giant Air Shower Array). But there is considerable disagreement in the conclusions regarding the existence of this cut-off between the two experiments.

There are many difficulties in explaining the origin of these highest-energy cosmic rays because there are hardly any known astrophysical objects believed to be capable of accelerating particles to such energies. Most "bottom-up" scenarios, in which particles are accelerated by the Fermi mechanism, would show the cut-off feature. If the cut-off does not exist, the difficulty is even greater because "astrophysical accelerators" would have to be found within a distance characterized by the photo-pion interaction distance, and the particles, believed to be protons, would point back to their sources and it is not clear from the data that they do. These difficulties have stimulated a great deal of speculation about possible models involving new physics which range from the violation of special relativity to the annihilation of topological defects created from transitions in the Early Universe which mitigate the cut-off in the predicted spectrum. Establishing the cosmic ray spectrum in this energy regime is of great importance for understanding the origin of these particles. This requires a larger data set than acquired so far.

Prospects for the Future

Particle detectors in space

Two magnet spectrometers are scheduled to be flown as space experiments for cosmic ray detection in the near future. These experiments follow on from a continuing series of measurements with detectors on high altitude balloons.

The first of these, PAMELA, will be flown aboard the Russian Resurs DK-1 mission to be launched in 2004. This combines a permanent magnet with other detectors to provide measurements of cosmic antiparticles, electrons and light nuclei. The major scientific goals of PAMELA are to measure antiprotons and positrons in the range 10^8 to 10^{11} eV and a search for antihelium with sensitivity for antiHe/He $< 10^{-7}$.

A second, larger experiment, the Alpha Magnetic spectrometer (AMS), uses a superconducting magnet spectrometer which is scheduled for exposure on the International Space Station after 2005. The emphasis is on a search for antimatter and measurement of antiprotons and positrons. This instrument is also capable of measuring individual light isotopes into the region above 10^{10} eV, which can be used to study the diffusion region of galactic cosmic rays via radioactive "clock" nuclei such as Be-10. For the antimatter search AMS is designed to have sensitivity for antiHe/He ~ 10^{-9}.

While the accurate studies of cosmic ray abundances and their variations with energy are the key science motivations for these missions, the discovery of heavy antimatter would have a major impact on our understanding of the origin of matter in our universe.

The CALET mission being developed for the International Space Station is a large electromagnetic calorimeter primarily aimed at detecting electrons and gamma rays in the 10^{12} eV energy range. The spectrum of high energy cosmic ray electrons is expected to "cut-off" in this energy range because of radiative losses in the interstellar medium.

Another major experimental challenge is to study directly the composition of cosmic-ray nuclei at energies above 10^{14} eV, where the conventional acceleration models (based on shock acceleration in supernova remnants) fail. Space missions to achieve this goal are at present under study.

A new astronomy

Neutrinos have the potential of becoming in the near future the "messengers" of a new astronomy. Two astrophysical sources (the Sun and SN1987A) have already been "seen" with neutrinos, and new large area telescopes are being designed (or are already under construction) with the potential to observe many more sources.

Neutrino astronomy is intimately related with the acceleration of protons. In fact, in any astrophysical setting where relativistic proton interactions occur, pions are produced with approximately equal multiplicity for the three charge states. Each neutral pion decays to a pair of photons, while charged pion decays produce neutrinos. Any cosmic accelerator with gas nearby is therefore a potential source of both high-energy photons and high-energy neutrinos. Photons can also be produced in purely electromagnetic processes by electrons (e.g. bremsstrahlung). Therefore neutrino astronomy is complementary to gamma-ray astronomy, having the ability to distinguish hadronic sources from purely electromagnetic sources of photons. Moreover, and most important, because of their small interaction cross-section, neutrinos can emerge directly from the energetic cores of astrophysical sources carrying direct information on their structure and dynamics.

Overcoming the small interaction probability of neutrinos requires very large detectors. The biggest sensitive volume so far has been achieved by AMANDA (Antarctic Muon and Neutrino Detector Array) which looks for flashes of Cherenkov light from muons moving upward from their origin in neutrino interactions within and below the sensitive volume of the detector. AMANDA uses a large transparent volume of ice, instrumented with photodetectors, deep in the Antarctic ice sheet. A similar approach is being pursued in the deep ocean by several groups in Europe. Both projects aim eventually at sensitive volumes on the scale of a cubic km that is required to give a good chance of seeing multi-TeV neutrinos from distant astrophysical sources.

Alternative techniques for the detection of extremely high-energy neutrinos (energy $>10^{18}$ eV) are also under active investigation. A source for these neutrinos is the decay of pions produced in the interaction of UHECRs interacting on the microwave background radiation. Large fluxes of extremely high energy neutrinos are also predicted in the so-called “top-down” models, where the highest energy cosmic rays are produced in the decay of super massive relics of the Big Bang. Examples of these alternative techniques are the detection of quasi-horizontal showers in air shower arrays on the ground (such as the Pierre Auger Observatory), the detection of radio emission from neutrino showers in air, or the detection from space of the fluorescent light emitted by neutrino showers in the atmosphere.

Next generation of gamma-ray astronomy

The success of the imaging technique for TeV gamma-ray astronomy has led to the construction of two new arrays of 10 m and 12 m diameter Cherenkov telescopes with ten times higher sensitivity and a lower energy threshold (100 GeV) in Australia by CANGAROO (Collaboration between Australia and Nippon for a GAmma-Ray Observatory in the Outback) and in Namibia by the European-African collaboration H.E.S.S. (High Energy Stereoscopic System), respectively. The H.E.S.S. full arrays – from 2004 onwards – will use the stereoscopic technique of coincident observation with up to four telescopes, originally pioneered by the HEGRA collaboration on La Palma. A similar array will be built in Arizona (USA) by 2005, as the successor of the Whipple telescope, by the US-led VERITAS collaboration (Very Energetic Radiation Imaging Telescope Array System). A larger, single 17m diameter telescope, called MAGIC (Major Atmospheric Gamma Imaging Cherenkov) Telescope, is in the final construction phase on La Palma, starting operations in 2004. It aims at the very low threshold of 30 GeV. This suite of instruments is strategically distributed over geographic latitudes and longitudes. Thus complementarity is ensured both scientifically and in terms of sky coverage.

Ideally, the threshold energy of these TeV observatories should be sufficiently below 100 GeV, so that the future Gamma-ray Large Area Space Telescope (GLAST) could reach this energy comfortably from below the GeV region. This NASA project with international partners is being developed with this goal in mind for launch in 2006.

Another exciting possibility would be the discovery of gamma-ray lines of very high energy with these new facilities. Rotation curves of galaxies show that there must be a substantial amount of dark matter in halos of galaxies like our own. One possibility is that this matter is in the form of exotic, massive "neutralinos" not yet discovered in accelerator experiments (although there are indirect hints from accelerator data for the existence of such particles). Annihilation channels could involve high-energy gammas, or jets of particles which would produce excess antiprotons or energetic neutrinos. The latter would give an excess of neutrino events from concentrations of neutralinos captured in the core of the Earth or the Sun.

Quest for the highest energy

Two techniques have been used in the detection of the highest-energy particles (UHECRs) by the two largest aperture experiments. Both indirectly detect the chain of reactions, or air shower, which is initiated as these particles interact in the upper layers of the atmosphere. The HiRes observatory images the fluorescence light from atmospheric nitrogen as the shower develops in the atmosphere, while the AGASA experiment samples the particle front with an array of particle detectors at ground level. There is still exists a discrepancy between the results obtained so far.

A very important task is to increase our knowledge of the highest energy cosmic rays and obtain a statistically significant useful sample above 10^{20} eV with good sky coverage. The Pierre Auger observatories have been designed both to resolve the data controversy as well as to obtain a sufficiently large data sample with complete sky coverage. Two observatories are planned for this purpose, one in the southern hemisphere and another in the northern hemisphere. They combine the two detection techniques in a hybrid experiment which should serve to solve the exiting experimental controversy. This detector also has the potential to detect high-energy neutrinos by looking for inclined showers. The construction of the southern observatory is in progress in Mendoza (Argentina) where data are already being taken.

A more recent idea is to observe air showers by imaging the fluorescence flashes over a very large volume of the atmosphere from a vantage point in space. Several proposals to do this have been formulated. Their expected aperture would represent a significant enhancement of statistics over ground-based detectors. They also have the potential to search for fluxes of very high energy neutrinos. These proposals will benefit from continuing developments in adaptive optics, computing power, pattern recognition and signal processing. It is quite likely that these proposals will turn into the next generation of experiments to continue the study of the highest-energy parts of the cosmic-ray and neutrino spectra. The EUSO project aims to put such a detector in the International Space Station. It is however crucial that discrepancies between the fluorescence technique and the technique involving arrays of particle detectors become better understood.

Conclusion

Cosmic ray physics, in both its dual aspects of non-accelerator particle physics and particle astronomy, is making significant contributions to our understanding of the universe. The new facilities now planned or under construction will certainly continue this trend into the first few decades of the new millennium. In addition to their intended function, history teaches us that well-instrumented sensitive detectors often discover things other than those for which they were built. We may be in for more surprises.

Low Temperature Physics[1]

Commission 5

Tomasz Dietl, Hidetoshi Fukuyama, Mikko Paalanen, and Dieter Vollhardt

Ever Lower

The hallmarks of low temperature physics have been the quest for ever-lower temperatures, the remarkable discoveries along the way and the many studies of the workings of quantum mechanics at the macroscopic scale. Very roughly, over the past century or more the record low temperature has been reduced by a factor 10 every 10 years. The background temperature of the universe, 3 degrees above absolute zero (3 K), was overtaken in 1908, and 10^{-10} K was achieved in 2000 in a cascade nuclear cooling experiment with rhodium metal. To put this in perspective, particle physicists have achieved similar progress from keV electrons at the turn of the century to TeV protons and electrons at Fermilab and CERN, and over a shorter interval the semiconductor industry has miniaturised from the first mm-sized transistor to single electron and molecular devices, again about a factor 10 every 10 years. No other human achievement comes close!

The landmarks in this quest have been: the liquefaction of helium at 4 K in 1908 by Heike Kamerlingh-Onnes*[2]; magnetic cooling of solids proposed in 1926, independently, by Peter Debye* and William Giauque*; refrigeration to 0.002 K from the dilution of liquid ^{3}He with liquid ^{4}He, suggested by Heinz London, shown to work by P. Das in 1964, and perfected by many others over the following decade; magnetic cooling of nuclei proposed by C. J. Gorter in 1934, realised by Nicholas Kurti in 1956 and most famously by Olli Lounasmaa in 1970; and finally laser cooling of atoms,

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[1] Updated from the previous article by Marcel Ausloos, George V. Lecomte, John Harrison, and Matti Krusius

[2] Many Nobel prizes have been won in the field of low temperature physics. Nobel prizewinners cited here are indicated by an asterisk * after their names.

first proposed by T. Hansch and A. Schawlow in 1975, shown to cool into the μK region by Steven Chu*, even lower by William Philips* when combined with a magnetic trap, and sub-μK with refinements proposed by Claude Cohen-Tannoudji* in 1989. The laser cooling of atoms has thus been demonstrated to produce 2-3 nK temperatures.

Discoveries

Superconductivty

Low temperature physicists are proud of the string of fundamental discoveries in the field of condensed matter physics. Some were serendipitous and some resulted from dogged searches in response to a theoretical challenge. The first and still perhaps the greatest was superconductivity in a metal: at a low enough temperature well over half the metals in the periodic table, as well as many alloys and compounds, enter a state where their resistance to current flow disappears. If the superconductor is a wire loop and a current is generated in that loop, then it flows for years with no significant decay. The current flow is not deterred by impurities, atomic vibration or crystalline defects. Discovered by Kamerlingh-Onnes in 1911, a satisfactory understanding was not achieved until 1957, in the theory of John Bardeen*, Leon Cooper* and Robert Schrieffer*. They showed that the electrons form into pairs and that the motion of these pairs becomes very highly correlated. Together, the electrons can be described by one wave function or order parameter.

Rather than closing the story of superconductivity, the theory was innovative enough to be adopted in many other areas of physics. Implicit in the theory was the existence of an upper limit to the superconducting transition temperature of about 25-30 K, but to some people any such limit forms a challenge. New classes of superconductor were found but the upper limit still seemed to be 23 K. This was the background for the enormous excitement that accompanied the discovery of a high-temperature superconductor by Georg Bednorz* and Klaus Alex Mueller* in 1986 and the rapid discovery of many others soon after. The upper limit has been pushed up to 160 K in these exotic copper-oxide compounds, and many theorists are still trying to come to a full understanding of the underlying mechanism. At the same time the search for new superconducting materials is still going on and has led to many unexpected discoveries in recent years. For example, in strontium ruthenate (Sr_2RuO_4), whose structure resembles that of the high temperature cuprates, a type of superconductivity was discovered which is similar to superfluidity in Helium 3. Novel materials such as buckyball (C60) compounds and even ferromagnets were found to become superconducting. And most recently the simple intermetallic compound MgB_2 turned out to become superconducting at an astonishingly high 40 K. Clearly, the quest for superconductivity will continue to lead to many more surprises in the future.

The Josephson effect

In 1962, Brian Josephson*, a Cambridge graduate student, presented two equations describing how the electron pairs responsible for superconductivity can "tunnel" from one superconductor to another across a very narrow gap. The "tunnelling" current is driven not by a voltage, but instead by the difference in the coherence factors, $f_1 - f_2$, of the electron pairs in the two superconductors. Again, this is quantum mechanics operating at the macroscopic scale. If a voltage difference V is applied then the tunnelling current oscillates at a frequency given by $(2e/h)V$ where e is the electron charge and h is Planck's quantum of action. Both equations were soon verified and yet another major field of research was created. Josephson's equations showed that $f_1 - f_2$ is very sensitive to small magnetic fields and that so therefore is the tunnelling current. This paved the way for the invention of very sensitive magnetometers. There is no significant radiation from the oscillating current generated by a voltage because of the impedance mismatch between a tunnel junction and free space. However microwave radiation can be mixed in with the tunnel current and so-called Shapiro voltage steps measured, which correspond to $f = (2e/h)V$. One major application has been the present voltage standard defined by this equation and realised with a Josephson junction. Josephson junction circuits have been a test-bed for quantum mechanics and have led to a quantum theory of circuits which will have important implications for the future of electronics.

Superfluidity

The discovery that should have come first but which eluded experimentalists for 30 years was the superfluidity of liquid ^{4}He below 2 K (Piotr Kapitza* and Jack Allen in 1938). The superfluid shows persistent mass flow or zero viscosity and supports quantised vortices. A complete theory of superfluidity has been a much greater challenge, but through the work of Lev Landau* and Richard Feynman* in particular we have a very good phenomenological understanding. Once again, we view all of the helium atoms as moving coherently and described by a macroscopic quantum wave function.

For 50 years liquid ^{3}He, the light isotope of helium, has been acknowledged as an analogue of the electron gas in a metal; the ^{3}He atom and electrons both act as gases of spin-1/2 particles. There was excitement after the understanding of superconductivity that ^{3}He atoms might form pairs and condense into a macroscopic quantum state. After several frustrating searches, the quest was abandoned. However, while looking for something else, the transition was discovered by Doug Osheroff*, Dave Lee* and Bob Richardson* in 1972, at 0.003 K. This discovery opened a new field and rejuvenated very low temperature physics in a way that was seen later in high temperature superconductivity following its discovery by Bednorz and Mueller. The ^{3}He transition was again into a superfluid state but this new superfluid was far more complex with exotic texture and magnetic properties. A very remarkable aspect of the developments after 1972 was the way in which experiment and theory moved along together. Indeed, theory was able to point the way to new phenomena with great precision. The uniquely rich symmetry structure of superfluid ^{3}He later led to the discovery of deep connections with particle physics leading to prediction of the Higgs boson. The theory of superfluid ^{3}He even made it possible to quantitatively test, and confirm, a theory of defect formation in the early universe.

Bose-Einstein condensation

In this short history, the final remarkable discovery resulted from a systematic programme of research highlighted by brilliant experimental techniques. The goal arose from one of Einstein's predictions from 75 years ago. In 1924 Satyendra Bose sent to Albert Einstein* a paper in which he had created quantum statistical mechanics. Einstein appreciated this, arranged to have it published, and then developed the ideas. He found in the equations that if a gas of integer spin particles (e.g. the hydrogen atom) was cooled sufficiently all the atoms should condense into the same quantum state. While ^{4}He atoms in superfluid helium and the electron pairs in a superconductor bear a resemblance to this Bose-Einstein condensation, the strong interactions prevent them from mimicking Einstein's model system. For many years several groups searched for this holy grail with hydrogen gas and standard low temperature techniques. In fact Dan Kleppner and Tom Greytak did succeed in 1998. Before that though, a group of atomic physicists had taken a different approach. They started with a dilute gas of Rb atoms and slowed the atoms with a set of six lasers. The lasers are tuned to slow atoms that approach them. A set of magnetic field coils were then switched on and trapped the magnetic Rb atoms. Once trapped the outermost atoms are force-evaporated so that the gas becomes colder and smaller in extent. Remarkably, with this elaborate table-top experiment, the final 2000 atoms were cooled to 20 nK, with Bose-Einstein condensation setting in at 170 nK. This achievement by the group led by Carl Weiman* and Eric Cornell* at NIST in Colorado was soon repeated by Wolfgang Ketterle's* group at MIT with 5 million atoms and a transition temperature at 2 μK. Subsequent experiments have confirmed the quantum coherence of the condensate by allowing two condensates to overlap and observing quantum interference fringes. This is a new field with much interesting physics and the potential for the creation and application of atom lasers.

The quantum Hall effect

Klaus von Klitzing* made a remarkable discovery in 1980 when studying the Hall resistance of a two-dimensional semiconductor at low temperature. The Hall resistance is the ratio of the transverse voltage divided by the longitudinal current when a magnetic field is applied. This resistance should be proportional to the magnetic field and inversely proportional to the number of charge carriers. He found, instead, that as he changed the number of carriers the Hall resistance showed a series of very flat steps and that the resistance plateaux were equal to $(h/e^2)/N$, where N is an integer, to better than 10 parts in a million. The precision has since been put at 10 parts in a billion. This is remarkable in a solid with impurities, defects, and atomic vibrations.

The exactness of the Hall quantization has now been explained using a variety of theoretical approaches, but a key insight was provided by Robert Laughlin* in 1981. Using principles of gauge invariance in an annular geometry, Laughlin showed that the Hall conductance would be quantized, in the limit of low temperatures, whenever the electron Fermi level falls in an energy gap or in an energy range where the states are localized by disorder.

There is also a view based on electron transport along one dimensional edge states. In the presence of a crossed electric and magnetic fields, electrons skip along the sample edge without any backscattering, even in the presence of impurities and other defects. According to theory initiated by Rolf Landauer in the 1960s in another context, the corresponding conductance is quantized, provided that the bulk states are localized by disorder and that the voltage difference between the two edges is due to a difference of the chemical potentials, with no electric field inside the sample.

The unit of resistance is now defined in terms of this quantum Hall effect. The precision is such that the resistance of the former standard ohm can be seen to be changing linearly with time, at 50 parts per billion per year. While the quantum Hall effect could be understood in terms of a quantum model, this did not prepare us for what happened next. Horst Stormer* and Dan Tsui* worked with very pure semiconductors, very high magnetic fields and low temperature and found plateaux at *fractional* values of N. The implication was that the elementary charge was not e, but a fraction of e. It was Robert Laughlin who made sense of this, in terms of a composite quasi-particle arising from correlated interactions between the electrons.

Quantum coherence in mesoscopic and nanoscopic systems

The Quantum Hall effect is one of many other manifestations of quantum phenomena in electron transport. David Thouless realised in the 1970s that quantum interference of transmission amplitudes of quasiparticles in solids is destroyed by inelastic scattering processes. Since energy dissipation vanishes at absolute zero, searches for coherent phenomena in electron transport of normal metals have become an important field of low temperature physics. It has been found that interference accounts for localisation of electronic states by disorder, an issue pioneered by Phil Anderson* and Nevill Mott*. Furthermore, quantum interference and quantum repulsion between energy levels in small samples, the latter similar to that discussed by Eugene Wigner* in the context of nuclear states, leads to a universal character of conductance fluctuations and its distribution in an ensemble of nominally identical small conductors, as shown by Boris Altshuler, Patrick Lee, and others. These phenomena make the conductance very sensitive to the actual impurity distribution in a given sample, which among other things explains a large amplitude of resistance changes associated with defect migration in many devices, leading to the existence of $1/f$ noise.

The steady progress in nanostructure fabrication and material quality opened the possibility of addressing experimentally the question whether indeed the resistance vanishes in the absence of scattering centers. In contrast to the classical expectation but similarly to the quantum Hall effect, the wire resistance was found to be quantized, in units of $(h/e^2)/N$, where N corresponds again to the number of one dimensional sub-bands (propagating modes) below the Fermi energy of the channel.

The phenomenon of the Coulomb blockade, occurring when a sub-micrometre capacitor is charged at low temperature, is another example of new effects now in focus in low temperature research, which have led to the concept of the single electron transistor that will be discussed below. In essence, the studies of presently available nanostructures at low temperatures tell us about expected properties of room temperature devices, if progress in miniaturization continues as it has up to now. Investigations of mesoscopic objects, which lie on the border between macroscopic and microscopic worlds, have improved our understanding of the interface between classical and quantum physics. Recently acquired knowledge of mechanisms underlying decoherence, quantum measurement processes, and manipulations with quantum states is deployed in today's quest for quantum information hardware.

Applications

Much of our understanding of metals and semiconductors has come, and continues to come, from low temperature research but on the whole the applications of these materials are at room temperature in the everyday world. The most significant real application from low temperature physics is the superconducting magnet. This seems such a natural application, to run hundreds or thousands of amps through a resistance-less coil of wire and generate a large field with no Joule heating. However, the first superconductors were returned to normal metals by modest magnetic fields. A second type of superconductor that remained superconducting in large fields entered a mixed state at modest fields, with magnetic flux penetration and dissipation as this magnetic flux interacted with the current. Only in the 1960's did materials scientists learn to "pin" this flux and inhibit the dissipation. Then superconducting magnets really took off and are now a billion-dollar industry with most magnets used for magnetic resonance imaging (MRI) and for particle accelerators.

With improvements in high-temperature superconducting materials and in flux pinning methods, further applications of superconductivity can be expected within the next decade. The use of liquid nitrogen as coolant, instead of liquid He, may lead to the commercialization of levitating trains, superconducting motors and generators, as well as superconducting power lines. A possible important niche market for high-temperature superconductors could be the filters used for mobile-phone base stations. The quality and hence resolution of the filters appear to be a factor 10 better than for conventional filters.

Josephson junction magnetometers, called SQUIDs (Superconducting Quantum Interferometric Devices), are incredibly sensitive and have found many applications, particularly in scientific research. They are also used routinely in geophysical exploration and the emerging field of biomagnetism. Their sensitivity allows them to detect magnetic fields from electric currents in the heart and brain. Superconducting electronics, mainly based upon Josephson junctions, has long held great promise. The fundamental switching speed is governed by the Heisenberg uncertainty principle and can exceed terahertz (10^{12} Hz) in high temperature superconductors. This is several factors of ten faster than reasonable limits for semiconducting devices. Their implementation has been held back by the relative lack of investment, the need for refrigeration and the difficulty of achieving large-scale integration with superconducting materials. There is a parallel with alternatives to the gasoline engine: at some point the oil wells will run dry and at some point semiconductors will reach their limit. Recent achievements by Konstantin Likharev and Theodore Van Duzer with rapid single-flux quantum switching devices do look very good. These devices may find application as fast routers between the different parts of parallel computers.

The SQUID is not the only example of a cryogenic supersensor: others are the single electron transistor, low temperature scanning probe microscopes and various bolometers and calorimeters for radiation detection. In general, the noise properties of a sensor improve dramatically at lower temperatures. While not commercial in the usual sense, these low temperature sensors are being used more and more for detectors in fields far removed from traditional low temperature physics; examples include infra-red detectors for astronomy, x-ray detectors for materials science, and calorimeters for neutrino and dark matter searches. Recently, potential applications of single electron transistors are demonstrated in quantum computing and in ultrasensitive bolometers in detection of rare atmospheric gases and of concealed weapons.

The spread of low temperature applications has been slow due to the need for inconvenient cryoliquids. Pulse-tube and on-chip refrigerators, two recent innovations, may change this by providing a cryogen free alternative for low cooling power applications. The pulse-tube cooler, developed during the last 30 years, uses an oscillating gas, usually helium, to pump the heat away from a low temperature platform. It provides a simple, closed cooling system from room temperature down to liquid He temperatures, with no moving parts at the low temperature end. With recent improvements in cooling power and lowest attainable temperatures, use of pulse-tube coolers is increasing fast in applications where mechanical vibrations are not critical. In the tiny on-chip refrigerators the cooling is produced by evaporating hot electrons over a tunnel barrier. Thanks to the decoupling of electrons and phonons below 0.3 K, the temperature of the remaining electrons can be decreased well below the lattice temperature. The application of on-chip coolers looks most promising in increasing the sensitivity of miniaturized sensors and sensor arrays by cooling them from 0.3 K to well below 0.1 K temperatures.

The Future

It would be presumptuous to predict future discoveries, particularly given the complete surprise provided by several past discoveries. The areas where new phenomena and ideas are expected include dilute gas Bose condensates, theories for strongly correlated electrons, unconventional materials, and nanoscale structures and devices, which may have an important impact on nanoscience. In particular, a growing amount of effort will be devoted to the search for promising quantum information carriers as well as to develop concepts of quantum gates suitable for the fabrication of functional processors. One of the ultimate goals of the field referred to as spin electronics or spintronics will be mastering the manipulation of the spin of a single electron in a solid state environment.

Along with presently employed nanolithography methods, self-organization and related means will be developed for nanostructure and nanosystem fabrication, exhibiting complex, often three dimensional architectures. On the materials side, an increasing role will presumably be played by carbon-related materials, starting from carbon nanotubes and related structures, and from molecular solids to more complex organic systems. The rapid advances in micro-machining will lead to refrigeration on a chip and perhaps to widespread applications of superconducting electronics. Superconducting magnetometers will follow MRI out of the research laboratory into clinical use, particularly for imaging brain function. What can be said is that the excitement generated by past discoveries and achievements is contagious and it is a pleasure to see so many young scientists at the international conferences and gatherings on low temperature physics and technology. These people will leave their mark!

Biological Physics

Commission 6

Nobuhiro Go

The Relationship between Physics and Biology

The expansion of physics into chemistry took place after the birth of quantum mechanics. Physics and chemistry are now, in a sense, unified. Physics is also expanding rapidly into biology in many aspects, resulting in an increase of the number of contacts between the two fields. So, have physics and biology been unified? The relationship is not simple. It is clear that there are no biological phenomena that violate known physical laws. This situation is clearly different from that of a century ago, when the phenomenon of black body radiation was seen as violating the laws of physics known at that time. Study of this phenomenon led ultimately to the establishment of a new view of physical law: quantum mechanics. A similar event, finding a new law of physics which supersedes the currently established ones, is not expected from studies of biological systems, even although biological systems give us impressions very different from those given by objects of conventional physical studies. However, this does not mean that physics is enough to understand biology.

Biology and Information of Historical Origin

Any system of objects of biological study consists of a certain set of atomic nuclei and electrons. But such a description is absurdly far from being enough for any biological system. This absurdity comes from the large volume of information necessary to describe biological systems, such as how atoms are bonded to each other to form specific molecules and how molecules are assembled in space to assume specific morphological states. This extra amount of information has its origin in the history of molecular and biological evolution. Given such an amount of information, the behaviour of such a system obeys the laws of physics. What biological physics does is twofold:

(a) identify the information necessary to describe the system

(b) observe the system dynamics in accordance with the laws of physics.

To the extent that a history is a process of fixation of random events, biology cannot be contained within physics.

Biology in this century has passed through two important phases. Towards the middle of the present century, biology developed rapidly into the molecular level. Many molecules playing important roles in biological systems were identified. Often an identical or very similar set of molecules is found in different species. This finding gave birth to the concept of the chemical unity of biological systems as opposed to the enormous diversity of biological species. What was achieved during this period was identification of information accumulated during molecular and biological evolution.

The latter half of the 20th century witnessed an explosive development of molecular biology based on genetic information stored in nucleic acids. Information acquired by biological systems during the history of biological evolution has been stored as base sequences of deoxyribonucleic acid (DNA). Elucidation of this fact and subsequent development of technologies of reading and manipulating the sequences led to the explosion of molecular biology. Almost all branches of biology have been deeply affected by this development. The developed technologies are mainly chemical in nature, and the technical role that physics played during this period is relatively modest.

Proteins as Functional Molecular Machinery and the Era of Structural Biology

What is actually stored in base sequences of DNA are mainly amino acid sequences of proteins and information necessary to regulate the production of proteins in the cell. Proteins, the products of genetic information, are the molecular machinery that is responsible for elementary functions in the cell. There is a one-to-one correspondence between a gene and a protein and an elementary function. However, the biological function of a given protein is importantly dependent on the three-dimensional shape into which it folds. Biology is now entering into the era of structural biology, where various biological functions are studied not only at the level of genetic information but also at the level of three-dimensional atomic-resolution structures of molecular machinery. Behind this change of scene is the fact that the experimental determination of the three-dimensional structures of biopolymers is taking place at an accelerated rate due to the development of such technologies as sample preparation using genetic manipulation, X-ray crystallography and nuclear magnetic resonance (NMR). The importance of genetic information has been very persuasively demonstrated by the explosion of molecular biology based on it. However, its success is based on the logic of one-to-one correspondence between a gene and an elementary function, a logic that skips their intermediate, a protein. The era of structural biology means that we are now able to study how biological functions are performed by observing the behaviours of the actual protein machinery responsible for them.

In this new era, the relation between physics and biology has become tighter in two ways. Firstly, observation of three-dimensional structures and their dynamic behaviours requires technologies that are basically physical in nature. Here physics assists biology by providing important technologies. Secondly, studies of many biological phenomena, after the stage of identifying specific molecules responsible for them, are now raising questions that are physical in nature by performing observations of dynamic behaviour of real molecular machinery. The behaviours observed do not violate the known laws of physics. However, it is becoming clearer that we need new concepts to understand them well. This is natural, because biological systems are very different from the systems studied by conventional physics. The above two aspects will be discussed below.

New Physical Technologies for Biology.

Methods used for structure determination

In the physiological environment, protein molecules assume complex three-dimensional structures that are specific to their amino-acid sequence, and only when they assume their sequence-specific three-dimensional structure are they able to perform their biological functions. Therefore, the starting point of the study of structural biology is the elucidation of the three-dimensional structure at atomic level resolution. This is a much more difficult task than the determination of DNA base sequences. Base sequence information is essentially digital (only four letters A, T, G and C), while analogue information is needed to determine three-dimensional structures. Determination of analogue information to a high accuracy requires a large amount of information. In practice X-ray crystallography and NMR and, more recently, electron microscopy and neutron scattering, are used for the determination of three-dimensional structures of biopolymers and their complexes. In the field of X-ray crystallography, synchrotron radiation is becoming an increasingly important source of radiation, and is contributing to the opening up of new ways of structure determination. Similarly rapid technological developments are also taking place in NMR, electron microscopy and neutron scattering.

Observation and manipulation of one-molecule systems

The three-dimensional structures determined by the methods described above are averages for a certain state, such as in a crystalline state. In the physiological state the structures undergo fluctuations in shape or form due to thermal motions. When systems of biopolymers perform their functions, they generally go through a more-or-less specific series of dynamical steps. Identification of such steps is essential for elucidation of the molecular mechanism of biological functions. Usually each of the dynamical steps is a process characterised by a corresponding activated state. Going over to an activated state is inevitably a stochastic process.

This stochastic nature of the dynamical process presents a difficult problem for the experimental identification of intermediate steps. Usually a physical observation is made on an ensemble of molecules, which then yields an averaged picture. Even when a number of identical molecular systems are set to initiate a certain biological function consisting of a number of elementary molecular steps in a synchronised manner, the modes of action in the constituent systems become very rapidly de-synchronised. A picture obtained by averaging over such a de-synchronised ensemble of systems will be a very poor picture.

To escape from this difficulty, it is desirable to carry out a physical observation for a system consisting of as small a number of molecules as possible, ultimately just one molecule. This is precisely the direction of many studies in biological physics. There are by now many techniques by which observation and manipulation of a single molecular system has been successfully achieved. The physical principles used in such single molecule technologies are already quite diverse. This means that a wide variety of experimental methods will be employed in this important field in the near future. They in turn will contribute to the enrichment of the physical understanding of biological phenomena.

New Concepts from Biological Systems

Biological studies at the molecular level usually start by identifying the molecular species involved in a specific biological phenomenon. After this stage, observations are made of the system dynamics. The dynamics should follow the laws of physics. Therefore, we want to understand the observations, hopefully in terms of the language of physics. In the new era of structural biology, an increasing number of biological phenomena will be studied from a physical point of view. Will new concepts become necessary or useful in such studies? The answer appears to be “yes”. As an example of such a case, the problem of protein folding will be discussed below.

As mentioned earlier, protein molecules in the physiological environment assume complex three-dimensional structures that are specific to their amino-acid sequence. A protein molecule is then said to be in the native state. In the case of most small globular proteins (perhaps in the cases of any protein), the specific three-dimensional structure is determined solely by the amino acid sequence and by the environmental conditions. The history or hysteresis of the system has no influence on the molecule's three-dimensional structure.

Thus, after a polypeptide chain with a specific amino acid sequence is synthesised in a cell, no extra information is needed to fold it into the specific three-dimensional structure of the native state. This fact, expressed as Anfinsen's dogma in honour of the person who demonstrated it experimentally, is understood as a consequence of the fact that the native state is realised as an equilibrium state with global minimum free energy. When the environmental conditions are changed by more than a limited amount, proteins in the native state undergo transition into a so-called denatured state. This is a phenomenon similar to order-disorder transitions such as solid-liquid phase transitions. Therefore the native state needs to have a sufficiently low energy so as to cope with the large entropy gain if the structure were unfolded into random states.

Up to this point, basic experimental facts about protein folding are described together with their simple physical interpretations. Even although both facts and interpretations appear to be simple and innocent, they are in fact very peculiar. A protein molecule is a chain heteropolymer with a specific amino acid sequence. Its potential energy surface in a high dimensional conformational space should have a very large number of local minima reflecting the heterogeneity of the sequence of various amino acid side chains. It is highly unlikely that there is a unique state with a distinctively low free energy, which, if it were to exist, would become a native state.

However, if various energy components comprising the potential energy are mutually consistent in a particular conformational state, such a state would have a distinctively low free energy. In the native state of conformations of proteins, this consistency of various constituent energy terms is in fact found to be largely satisfied. This finding is summarised as a consistency principle (also referred to as a principle of minimum frustration) that is satisfied by the native states of proteins. It means that amino acid sequences that satisfy this principle have been selected during biological evolution for use as proteins. Therefore the consistency principle is a principle pertaining to the history of evolution, but at the same time it is the principle which explains the physico-chemical properties of proteins such as the uniqueness of the native state conformation and the character of folding-unfolding transitions that are similar to order-disorder phase transitions.

This field exemplifies the emergence of a concept that is unique to a biological system, and important in understanding it. Biological systems are generally enormously complex but yet well organised. This is a characteristic that physicists have not generally faced very seriously. But physicists have a tradition of creating new concepts to understand any new objects that they confront. In the new era of structural biology, when a wide range of biological phenomena will be studied from physical points of view, physicists will create many concepts useful for the understanding of these enormously complex biological systems.

Semiconductor Physics

Commission 8

Bo Monemar

Achievements in the Past.

Semiconductor physics has been alive for about half a century, starting essentially with the invention of the transistor, leading to the award of the Nobel Prize in 1956 to Bardeen, Brattain and Shockley. The bulk properties of silicon were carefully investigated already in the 1950s and 60s, and silicon is indeed the material upon which the giant microelectronics industry is still based, in turn producing the hardware basis of the present Information Technology revolution in our society. However, the developments now needed for silicon-based microelectronics mainly rely upon cross-disciplinary materials research related to processing steps involving a broad class of materials used in the manufacture of a chip.

Optoelectronics started to grow about three decades ago, with the demonstration of a semiconductor diode laser. This started an upsurge of interest in direct band gap III-V material structures, which are suitable for optical devices. Tunnelling phenomena in semiconductor structures also became understood, and the importance of this work was recognised with the Nobel Prize to Leo Esaki and Ivar Giaver in 1973. Novel growth procedures for growing thin layers of nanometre thickness were invented — in particular Molecular Beam Epitaxy (MBE) and Metal Organic Chemical Vapour Deposition (MOCVD) — and proved to be indispensable in the development of novel semiconductor structures. Quantum well (QW) structures were found to be advantageous for optical emitters, and the novel low-dimensional physics of semiconductor structures having less than 3 dimensions has since been extensively studied. About a decade ago there began an enormous growth of interest in the field of one- and zero-dimensional semiconductor nanostructures, which continues to bloom.

The increased perfection of the technology for Si-based (Metal Oxide Semiconductor) MOS transistor structures made possible detailed studies of the properties of a quasi-two dimensional electron gas (2DEG), confined in a few nanometre wide triangular potential at the interface between the Si and SiO_2. Similar structures were soon invented in the direct band gap systems, such as High Electron Mobility Transistor

(HEMT) structures, with a 2DEG confined at a heterojunction between two semiconductors. The AlGaAs/GaAs heterojunction became the model structure for a vast number of interesting investigations of the 2DEG. The basic discovery of the Quantum Hall Effect (QHE) occurred in the 1970s, and was recognised by a Nobel Prize to Klaus von Klitzing in 1985.

A sub-field of great fundamental interest that has developed mainly during the last decade is the behaviour of electrons confined to two dimensions in semiconductors in a high magnetic field. The idea of composite quasi-particles of boson or fermion character, involving fractional charge and attached magnetic flux quanta, provides an explanation of the fractional quantum numbers observed in experiments on transport in a 2DEG. This is a fascinating field of basic physics, which now attracts many physicists although the main ideas were presented more than 15 years ago. Experiments are also being refined to demonstrate directly the fractional charge. The classical developments in this field were honoured with the Nobel Prize in Physics to Robert Laughlin and Horst Stormer in 1998. At very high magnetic fields Wigner condensation of electrons in the 2DEG seems to occur.

Advanced Device Structures

In the history of semiconductor physics many advanced device structures have been explored. Recently the properties of excitons in a micro-cavity, with strong exciton-photon coupling and photon confinement, define an area that is intensively studied in many materials systems, revealing new physics related both to semiconductors and to optics. There has also been an upsurge in the interest of micro-cavity devices, i. e. devices which combine carrier control with photon control. Vertical micro-cavity lasers have been demonstrated in laboratories, and are expected to reduce the threshold for lasing as well as to increase the speed of such lasers dramatically, which is of considerable applied interest, not least for fast communication applications. For light emitting diode applications the advantage of micro-cavity structures is a much higher external quantum efficiency, due to the facilitated escape of photons from such structures. Such devices were in commercial production by 1999.

An interesting and related recent development in solid state optics has been photonic lattices. So far these have essentially been studied experimentally at longer wavelengths (microwaves) in metallic systems, but recently it has been possible to realise and study two-dimensional photonic lattices in semiconductor systems, with photonic band-gaps in the range of the electronic band-gaps. These systems are potentially very interesting for photon control in future optical semiconductor devices, such as micro-cavity light sources and integrated optoelectronic structures.

Dynamic Properties

Another area that has seen rapid development for semiconductors over more than a decade is that of dynamic properties on a very short time scale (femtoseconds and picoseconds). This is particularly important for quantum structures, where the distribution of electron energy states can be tailored at wish. Coherent oscillations related to interference between different electron states can be studied in real time, and infra-red optical THz emission is observed on the femtosecond time scale related to such oscillations. Quantum coherence can now be observed in real time in semiconductor systems. Nonlinear phenomena are very strong in this time domain, promising interesting future device applications. The development of spin dynamics in such systems has also been studied in real time. It has recently been demonstrated that spin transport can be directly monitored, possibly promising development of spin electronics. Other applications include the recent development of photoemission studies on the femtosecond time scale, allowing real time studies of electronic processes on surfaces, including for example relaxation phenomena in surface structures of semiconductors. Real time studies of ballistic transport in semiconductor structures have been demonstrated. For instance, very fast hot carrier transport has been monitored directly from optical transients measured in silicon integrated circuits.

Defect Studies

No other class of condensed matter is so sensitive to defects as semiconductors. Defects and impurities govern their electronic properties to a large extent, notably conductivity type, carrier recombination, and mobility of carriers. The shallow impurities were understood rather early, but the understanding of defects with electronic states deep in the band-gap turned out to be more difficult. These defects are important, because they govern the process of carrier recombination in many devices. Experimental methods were developed during the 1970s and 1980s to measure the most relevant properties of these defects, including their identity. The general picture of the electronic structure and excited states for different classes of defects is now rather well understood, but theoretical calculations of the electronic structure of defects are in general difficult, and accuracies for the position of relevant energy levels in the band-gap are usually not better than 0.5 eV. Calculations of formation energies of defects are probably good within 1 eV, and are very helpful in distinguishing what defects are expected to be dominant in a particular material. Defect vibrational energies can be predicted with very good accuracy, which is very important for defect identification via comparison with infra-red data for excitation of such local defect modes. The area of electron spin resonance has recently developed strongly towards the use of much higher microwave frequencies, providing very useful tools for identification of defects. The field of defect physics in semiconductors has therefore matured recently, but new materials still raise a challenge for defect studies.

Surface Properties

During the last decade the development of surface characterisation techniques has been strong, in particular after the very important inventions of the Scanning Tunnelling Microscope (STM) and Atomic Force Microscope (AFM) techniques which allow one to probe the geometrical structure of surface features, and simultaneously the surface potential, with atomic resolution (Nobel Prize to Gerd Binnig and Heinrich Rohrer in 1986). These techniques have been used to help to understand surface processes, among which epitaxial growth is very important. *In situ* reflectance measurements also allow the monitoring in real time of layer by layer growth with a resolution of one atomic layer. There is presently a strong development of instrumentation for *in situ* moderation and control of growth. Epitaxial growth can now be monitored precisely, and theoretical modelling has advanced to a degree that various growth modes can be simulated.

Nanometre-size Structures

Nanostructures involving semiconductor materials provide a fascinating area, which, as mentioned above, has now occupied a large fraction of semiconductor physicists for more than a decade. In particular, one dimensional (quantum wires) and zero-dimensional (quantum dot) structures can now be grown with improved techniques. The new techniques invented to produce such materials with nanometre scale features go hand in hand with the development and use of new techniques to characterise the individual features of such a structure with nanometre resolution microscopy and spectroscopy. An example is high resolution Transmission Electron Microscopy (TEM), where the precision in directly measuring the atomic distances in the lattice now approaches 0.01nm. High spatial resolution in optical measurements is achieved with near field spectroscopy.

Part of the development in this field is intimately connected with other areas of condensed matter physics, where nanometre size structures are intensively studied, for example in work on quantum transport in metals. Analogous effects are seen in semiconductors, and single electron transfer processes are detected and studied both electrically and optically (with near field spectroscopy). Recently, Coulomb blockade processes in semiconductor quantum dots have been studied. An active area is the study of noise in electrical transport data, related to fundamental fluctuations in the charge structure in ultra-small systems. Another interesting topic has been the demonstration of single electron processes at a single defect, both in optical measurements and in electrical transport. Single point defects have also been visualised directly via Scanning Tunnelling Microscopy in a semiconductor surface area. This parallels the studies of single molecule spectroscopy in molecular crystals.

Future Outlook.

Although there has been a decreasing trend in interest in bulk semiconductor properties over the last decade — this area being rather mature — a revival has occurred recently in the sub-field of wide band-gap semiconductors, notably SiC and III-V nitrides. The key to successful development in these materials systems lies in important recent advances in crystal growth techniques. Important applications in power devices and high temperature devices are strong driving forces for the current developments of SiC. Production of SiC power devices is foreseen within a decade, probably replacing silicon to a large extent in this application niche.

III-V nitrides and SiC represent an unusual class of direct band-gap semiconductors that are extremely tolerant to harsh environments and extreme operational conditions. Interesting physical properties occur in strongly strained III-nitride multilayer structures, but most of the physics remains to be explored. These materials are of interest in particular for optical devices covering the entire region between the ultra violet and the infra red. Violet lasers based on InGaN/GaN Quantum Wells are already on the market, and are needed in the expected revolution in home electronics and optical data storage. Digital DVD systems are a growing market, and have led to a tenfold increase in the storage density in both audio, video and data applications. Other important applications of light emitters are LED based general illumination, potentially replacing the incandescent lamps and the fluorescent tubes used today. The driving force for this development will be the improved reliability of these new light sources (100 year lifetimes), and low environmental impact in their handling or production.

Other interesting applications of these new semiconductors are for high frequency power devices, needed for example in future power amplifiers for satellite based communication at frequencies above 10 GHz. It is speculated that mobile telephone communication, today based on radio frequencies, will to a large extent be satellite based and at much higher frequencies within a decade from now.

For the III-nitrides the already successful realisation of light emitting devices has initiated a strong development of epitaxial techniques to prepare multilayer device structures of low defect density on a foreign substrate, e.g. using lateral epitaxial overgrowth on patterned hetero-substrates. This has proven to be a useful way to produce purple lasers with viable operating lifetimes (> 10000 hours). In a broader long-term perspective, the possible outcome of these efforts is the ability to grow a complicated device structure, using new semiconductor materials with a low defect density, on virtually any desired substrate. This is obviously of very large industrial interest, since the substrate cost is now often prohibitive for device development involving new semiconductor materials. A paramount example is diamond, a material with excellent semiconducting properties, but no viable growth procedure of diamond on a foreign substrate has yet been developed, in spite of extensive work over the last decade. A breakthrough in the general techniques for lateral epitaxial overgrowth may allow the technological use of many new semiconductor materials within the next two decades.

We expect the race towards higher and higher spatial resolution in many measurement techniques to continue in the near future. One example of present directions is the ambition to combine the high spatial resolution of optical and electrical measurements (single atom processes) with magnetic resonance techniques, which sense the spin quanta of single electrons or nuclei. A fascinating class of new sophisticated research tools, measuring different physical parameters of a semiconductor sample with atomic resolution, will probably be available to experimental physicists within a couple of decades. This will be important to many research fields, not least the study of surface reactions on semiconductors, relevant for various sensor applications as well as for the development of processing techniques for semiconductor devices. In general, the interest in the properties of surfaces and interfaces will grow as the physical sample dimension decreases.

As mentioned above, mesoscopic physics and nanostructures nowadays dominate the menu at basic semiconductor physics conferences. Indeed there will be more interesting discoveries to come in this field, as more materials systems are explored, and the perfection and homogeneity of nanostructure samples (such as quantum dot arrays) becomes much improved. We may safely predict that many new fascinating nanosize semiconductor devices will be demonstrated within the coming decade, of particular interest for basic physics. It should be mentioned that many properties of these nanostructures are similar for a wide range of materials (including metals, semiconductors, insulators), leading to a strongly interdisciplinary character of this research field. So far, the possibilities of a large scale use of nanostructured semiconductor materials (with features of a few nanometre size) in devices remain uncertain. It is not clear that the improvements which are predicted for some device properties warrant the advanced processing steps that are necessary to develop in order to move into industrial production. The paramount interest in this area from the basic physics point of view is obvious, however.

Magnetism

Commission 9

Roger Cowley, Michael Coey and Dominique Givord

Introduction

One hundred years ago there was no fundamental understanding of the properties of magnetic materials. Furthermore only a handful of materials had been discovered that were strongly magnetic: iron, cobalt, nickel and a few of their oxides. Although Ampère had shown in 1820 that circulating electric currents produced magnetic dipole moments, it was realised that the currents needed to produce the observed magnetisation in iron would, if they were conventional currents, easily melt the iron. This unsatisfactory state of the understanding of magnetism was summarised by the work of van Leeuwen in 1919 who showed that a system of charged particles described by classical mechanics and in thermal equilibrium can have no magnetic properties, in contradiction to all observations.

A Quantum Property

Magnetism is an intrinsically quantum property of matter and no fundamental progress in understanding was possible until the development of quantum mechanics. Firstly, quantum mechanics and the concept of electron spin provide an explanation of how there can be atomic or electronic dipolar moments without there simultaneously being dissipative currents. Secondly, the development of the Pauli exclusion principle and the need to have an antisymmetric electronic wave function led to the understanding of the electrostatic nature of exchange forces through which the electronic dipole moments interact to produce atomic moments and magnetic structures. The exchange forces are dependent upon the magnetic moments of the electrons and are much stronger than the classical magnetic dipolar interaction, which is quite unable to produce the alignment of the atomic moments in iron.

As a result of these developments there is now a good understanding of the microscopic properties of many magnetic materials. The variety and complexity of the different magnetic structures and properties has expanded enormously so that there are now thousands of known magnetic materials with an enormous range of properties. Examination of this progress shows many examples of where a better microscopic understanding has led directly to improved materials for applications. Maybe less obviously, this progress has also led to the development of new experimental techniques which are now routinely used far beyond their origins in magnetism and magnetic materials. The study of magnetic materials has also been crucial in the development of an understanding of systems showing co-operative behaviour. Experiments on phase transitions led to scaling theories that are now applied to the early universe, financial markets and the production of thin films, while work on disordered magnets has led to new models of the brain and artificial thinking machines. It is impossible to review all the important developments in a few pages and so only a few examples will be discussed and these very briefly.

We now understand that whether or not a material is strongly magnetic depends on the competition between different types of interactions. Firstly at the atomic level, atoms with magnetic moments are ones in which the magnetic moments of the individual electrons tend to be parallel. This occurs when the quantum mechanical exchange energy is larger than the atomic kinetic and potential energy difference between the atomic states. In practice this means that the electrons have to be in partially filled atomic shells where they are quite strongly correlated.

In a solid, the electrons are also needed for chemical bonding. For most magnetic atoms, all the aligned electrons from the last unfilled shell are used for chemical bonding and these bonding states are occupied by pairs of electrons with equal and opposite magnetic moments. The exceptions give rise to strong magnetic properties. These occur when the partially filled atomic shells are hidden within the atoms and there are other electrons outside them which participate in chemical bonding. This occurs predominantly for the 3d, 4f and 5f shells of the periodic table and most strongly magnetic materials have one or more types of atoms with these shells only partially filled.

Once there are magnetic atoms in a solid, there is a further competition between the exchange interactions coupling the electronic moments on the atoms and the interaction with the charges in neighbouring atoms, the crystal field effect. The latter arises because many magnetic atoms are not spherical but have an anisotropic electron cloud. When the atom is placed in a solid, the electrostatic energy of an atom in the crystal will depend on the relative orientation of the charge cloud and position of the neighbouring atoms. This reduces the number of degrees of freedom for the motion of the electron. Since there is a coupling between the shape of the atom and its magnetic moment, the magnetic properties of the atoms in the crystal may be very different from those of the free atom: they may even become nonmagnetic.

New Techniques

Continuous progress in the understanding of the magnetism during the 20th century largely resulted from the concomitant development of new experimental techniques, themselves exploiting the better understanding of the physical behaviour of matter. Throughout the last century, the ultimate sensitivity of magnetometry has been increased by order of magnitudes. In particular, SQUID magnetometry, which developed in the 1970's, exploits the properties of superconducting Josephson junctions; modern micro-SQUIDs may detect the magnetisation of a group of less than 1000 Fe atoms.

Much of the physics of solid-state magnetism was explored by optical spectrometry and in more detail by electron spin resonance (ESR). In an ESR experiment the magnetic ions are placed in a strong magnetic field so that different orientations of the magnetic moments have different energy levels. A microwave electromagnetic field then causes transitions between these levels, producing a resonance. The frequency of the resonance depends in detail on the atom and its neighbourhood, enabling the properties of many different atoms and their environments to be investigated.

Soon after the development of ESR, the technique was applied to study nuclear magnetic moments via nuclear magnetic resonance (NMR). This was experimentally easier because the necessary frequencies are in the megahertz region instead of gigahertz, but the main principles and concepts of NMR and ESR are very similar. There have been many developments of these techniques, and especially of NMR, which is now routinely used in chemistry and biology to determine the environment of particular atoms. With the development of imaging techniques, NMR is used to image the density of protons or other nuclei in biological tissue. Most hospitals now routinely use MRI (magnetic resonance imaging - the term “nuclear” having been omitted!) to locate tumours and other tissues. We can undoubtedly foresee future developments of these techniques to produce better spatial resolution in three dimensions and to enable routine measurements to be made with a wider variety of different atoms.

After the Second World War, the development of neutron scattering opened the possibility of directly examining the magnetic structures of ferromagnets and other magnetically-ordered materials. This is best exemplified by the discovery of the first antiferromagnetic structures, which was soon followed by that of complex magnetic arrangements. Neutron scattering constitutes an invaluable tool for investigating magnetic excitations such as spin waves and short-range magnetic correlations, such as are found in spin glasses.

Nanoscale magnetic point-probe techniques, which include magnetic force microscopy, near-field magneto-optic microscopy and spin-resolved scanning tunnelling microscopy, are still at an early stage of development. The intense X-ray sources provided by synchrotron sources has led to the spectacular development of X-ray Magnetic Circular dichroism and magnetic diffraction. By working in the vicinity of absorption edges, these techniques may offer the unique characteristics of being both element and electronic shell sensitive.

Magnetic Materials - Old and New

Despite much progress in the understanding of magnetic materials, there are two aspects of materials which are important for their practical application that have not improved at all over the past century. These are the magnetisation (magnetic moment/unit volume) and the Curie temperature for the onset of spontaneous magnetism. It is disappointing that the alloy $Fe_{65}Co_{35}$ has held the record for magnetisation and Co for the Curie temperature ever since the early years of the last century. Nevertheless, spectacular progress in the application of magnetic materials has followed from our ability to control the coercivity, anisotropy, magnetostriction, magneto-optics and magnetoresistance of materials. Permanent magnets have been improved by finding compounds of 3d and 4f atoms in which the 4f ions provide the anisotropy and the 3d ions provide the large interatomic exchange interactions. This progress was a direct result of the development of an atomic-scale understanding of magnetism. It led to Sm-Co magnets in the early 1970s and Nd-Fe-B magnets in the 1980s. As a result, the stored energy product (the figure of merit for the best permanent magnets) has doubled every 12 years throughout the 20th century, making possible many new applications of magnetism in sensors, electric motors and automobiles.

Soft magnetic materials, used for example as transformer cores, have been improved by reducing the crystal field anisotropies so that the electromagnetic losses have been roughly halved every five years. Magnetic recording has also been enormously improved by controlling the grain size and anisotropy of the magnetic media, and by improvements in the designs and magnetic constituents of the read and write heads. As a consequence recording densities have been doubling every three years since the 1950s, and every year since 1990.

Magnetism in reduced dimensions

The study of magnetism in reduced dimensions flourished during the last decades of the 20th century. This was as much concerned with magnetic model systems for phase transitions in one, two or three dimensions as the realisation of magnetic thin films and multilayer stacks. Original properties resulting from the reduced dimensions of the objects included surface anisotropy and oscillatory exchange. The discovery of giant magnetoresistance in 1988 was a development with spectacular consequences. Nowadays, much interest is focussed on understanding of the magnetic and transport properties of nanoscale objects: films, wires, fine particles and quantum dots; some topics of current research are magnetization reversal under an electric current and exchange-bias in small systems.

Future Prospects

It cannot be expected that all these technologies will progress at the same rate. In view of the difficulty in enhancing the maximum magnetisation and exchange interactions, the best possible permanent magnets are already within a factor of three of the maximum theoretical performance. Soft magnetic materials have already improved to such an extent that it is becoming pointless to make further improvements in the materials unless other aspects of their use can be improved.

In contrast, the density of bits stored on magnetic media can in principle be increased by several orders of magnitude before thermodynamic magnetic fluctuations lead to loss of information. The difficult part of achieving this is in the design of the read-heads so as to read the small magnetic fields created by the tiny magnetic particles. With the discovery of giant magnetoresistance, the electrical signals available from a given change in the magnetic field was considerably increased, and a novel trilayer spin valve read-head based on the giant magnetoresistance effect was implemented commercially within just eight years. These heads are now fabricated in quantities approaching one billion per year. Thin film magnetic tunnel junctions may feature in future-generation read-heads which will carry recording densities beyond 100 bits μm^{-2}. They seem set to form the basis of new non-volatile magnetic random-access memory arrays.

These technological developments have been made possible by methods such as sputtering for reproducibly preparing large-area thin film stacks with layer thicknesses of a few nanometers. Other methods of making magnetic thin films and superlattices, include chemical vapour deposition, or molecular beam epitaxy. Many 3d and 4f magnetic metals can be grown by these techniques, but there are plenty of thin film superlattices whose properties have yet to be explored. A related development is lateral patterning using electron-beam lithography of focused ion-beam techniques which permit nanoscale definition of magnetic objects. This is leading to advances in spin electronics. In conventional electronics, no use is made of the electron spin. Spin valves and tunnel junctions can be regarded as the simplest form of spin-electronic device, two-terminal magnetoresistors. In more complex devices, it will be possible to control the spin currents, and amplify the signal with one spin polarisation differently from that of the other. This opens up the possibility of directly integrating magnetic properties with conventional electronics or optoelectronics, thereby making possible a whole new generation of electronic devices.

On a more fundamental level, the study of the magnetic properties of materials can be expected to lead to new insights and unforeseen effects. One of the challenges of condensed matter is currently to understand the properties of strongly-correlated transition metal oxides, including high-temperature superconductors, and heavy fermion systems. New low-dimensional magnetic materials such as the quasi-one-dimensional spin ladders have fascinating properties, and in some cases exhibit quantum phase transitions.

All these materials show strong magnetic properties, and it is becoming clear that magnetism is a crucial aspect of them all. The challenge is to determine whether the well known weakly interacting electron model of conventional condensed matter physics can describe their properties, or whether new condensed matter physics is needed to describe the strongly interacting electrons and their electronic and magnetic properties.

Conclusion

In summary, the past century has seen enormous developments in our understanding of magnetic materials. A combination of quantum mechanics and conventional condensed matter physics now provides an explanation for the properties of many magnetic materials. This understanding has underpinned dramatic developments in technology and has facilitated explosive growth in the use of magnetic materials, hard and soft, in electrotechnology, communications, data storage, and sensors. Magnetism underpins many of our most advanced technologies, including magnetic resonance, which are now of great importance in biology and medicine. The study of magnetism has also led to enormous advances in our understanding of co-operative phenomena and competing interactions which have directly influenced our understanding of other fields within and beyond physics.

In the future this progress will continue and probably lead to a new understanding of the physics of condensed matter with strong electron-electron interactions. New artificially grown or self-assembled magnetic nanostructures will lead to progress in spin electronics and magnetic media. The ability to tailor magnetic materials on characteristic magnetic length scales in the nanometre range opens a new chapter in the long history of one of the most attractive branches of Physics.

The Structure and Dynamics of Condensed Matter

Commission 10

Rudolf Klein

A Source of New Ideas

Condensed matter physics is a broad area of physics in which about one half of all physicists currently work. This is partially reflected by the organisational structure of IUPAP, which has three Commissions in addition to C10 representing this part of physics (C5 Low Temperature Physics, C8 Semiconductors and C9 Magnetism) and two more which are closely related (C3 Statistical Physics and C6 Biological Physics). The physics of condensed matter comprises the study of properties of ordered and of amorphous solids, but also of fluids and gases and of complex systems such as polymeric liquids and solids and supramolecular aggregates.

New paradigms originating in condensed matter physics, notably those related to critical phenomena, have spread to other areas of physics and to neighbouring disciplines of science. Besides these contributions to basic science, condensed matter physics is of primary relevance to present-day technologies and to the manufacturing of products which influence and shape modern societies to a large extent.

The formation of condensed matter by bringing atoms and molecules together gives rise to complex systems which exhibit new phenomena and properties. To understand them it has often been necessary to develop fundamentally new concepts. One example is the study of critical phenomena, which is the behaviour of various physical properties as a critical point is approached. This study has led to the notions of scaling and universality; near the critical point the only relevant length is the correlation length, which serves as a scale for all distances. Moreover, the critical behaviour is the same for systems of a given dimensionality and identical symmetries of the order parameters. Wide variations of the values of the critical temperature or in the kind of microscopic interactions may give rise to identical critical exponents, which characterise the behaviour of physical properties as the critical point is approached. These concepts of scaling and universality are the content of the renormalization group. The notions of broken symmetry and order parameters are not only applicable to condensed matter systems but have also influenced other areas of physics. In similar fashion, the problem of understanding the electronic properties of metals and semiconductors, including high temperature superconductivity and the quantum Hall effect, has influenced the quantum theory of many-body systems. Yet the fundamental problem of treating the effects of strong Coulomb interaction in many-electron systems is only partially resolved. Recent awards of Nobel prizes underscore the relevance of condensed matter physics to the understanding of fundamental problems of basic physics (awards for the quantum Hall effect in 1985, for tunnelling microscopy in 1986, for high temperature superconductivity in 1987 and for polymers in 1991).

Interaction with Neighbouring Disciplines

The fertilisation of neighbouring disciplines by methods and results developed in condensed matter physics has a long tradition; there are smooth transitions to chemistry, materials science, electrical engineering, biophysics and chemical engineering. Important advances in the areas between established disciplines are often only made possible by close collaborations of scientists from more than one field. The application of methods and concepts developed in physics is often the basis for new understanding in neighbouring sciences. Parts of modern materials science and of electrical engineering are examples of cases where subfields have outgrown condensed matter physics to become independent disciplines. Important new results in biology such as the structure of DNA, of haemoglobin and of the photosynthetic centre became possible only by the use of methods developed for solid state research.

A good example of the importance of theoretical concepts and of the use of modern experimental methods for the description and understanding of systems that were not previously at the centre of interest for physicists, is the tremendous advance in the field of polymeric fluids, melts and solids. Concepts originating in the theory of critical phenomena have been of great help for the development of a quantitative description of the structure and dynamics of polymers. Scattering experiments with light and neutrons, which have been perfected for studies of more conventional condensed matter systems during several decades, have confirmed the theoretical models of these complex macromolecular systems. Similar advances for related materials, such as colloids and self-aggregating surfactants in solution, have been made and are still actively pursued. All these materials are of great technological importance and there is realistic hope of improving the understanding of their macroscopic functions on the basis of molecular properties in order to further advance the technology. Therefore, modern materials science includes polymers and the physics of complex fluids.

The Liquid State

The liquid state of matter is a very active field of research. Whereas simple liquids like the rare gases are rather well understood, more complex fluid states exist, such as liquid metals, electrolytes and many kinds of solutions. They are characterised by strong correlations and disorder, and to understand their macroscopic thermodynamic properties on the basis of the interactions between atoms or molecules is often a difficult task. Even the most important of all fluids, water in its liquid state, is only partially understood; the structure of water in the vicinity of a solute may have important effects on the properties of suspended particles. Significant advances in liquid state physics are coming from developments in statistical physics and from computer experiments. The study of liquids was among the first applications after the development of Monte Carlo and molecular dynamics simulation methods. These computational techniques are now rather common in all areas of condensed matter physics. Simulations are often crucial to investigate the validity of theoretical schemes. These numerical methods are now used for systems of increasing complexity, and the future development of faster computers will undoubtedly lead to improved understanding of more complex systems.

Properties of disordered and amorphous materials and of porous media are much more difficult to understand than those of crystals. The nature of the transition from the fluid phase to the glassy state, which is observed for glass-forming liquids ranging from low-molecular weight systems to polymers, and the properties of the glassy phase are only partially understood.

Surfaces and Interfaces

Properties of bulk materials of perfect crystalline order are largely understood. In the last few decades the emphasis has shifted towards non-crystalline materials and to systems whose properties are strongly determined by their finite size or by surfaces and interfaces. These modern developments are driven not only by a general interest from a basic point of view but also by demands of technology. The increased miniaturisation of components of electronic devices and the use of materials which are structured on a sub-micrometer scale demand the understanding of properties of systems, in which most atoms or molecules are at or not too far from a surface or interface. Adsorbates on smooth or laterally structured surfaces and thin films are important for many technological applications and the growth mechanisms of adsorbates and their structures are challenging problems. A related problem is the microscopic understanding of wetting. New microscopies, such as the scanning tunnelling microscope and related methods, have been developed to investigate surfaces. They can also be used to manipulate atoms and molecules on surfaces, and these methods will soon make it possible to tailor laterally structured surfaces.

Experimental Techniques

Although most research in condensed matter physics is "small" science, conducted by small groups of scientists, large scale facilities for scattering experiments with thermal neutrons and synchrotron radiation have been of extreme importance to obtain the atomic and electronic structure and the elementary excitations of solids and liquids. These microscopic properties of materials are necessary for the understanding of the macroscopic behaviour. The present state of knowledge about the structure and dynamics of solids and liquids is largely based on results of neutron and X-ray scattering and it can be expected that these methods will further enhance the understanding of condensed matter in the future. Besides the significance that these experimental methods have for basic research in physics, there is an increasing demand from neighbouring sciences such as physical chemistry, biology and materials science to use these techniques to solve problems relevant to their fields. Examples are the investigation of the microstructure of technologically relevant materials such as metallic nano-structures and polymeric solids. The structures of biologically interesting macromolecules like proteins can also be obtained.

Research in the Future

Future research in condensed matter physics will deal with increasingly complex materials. Work on semiconducting hetero-structures and on important metallic materials which are structured on the scale of nanometers will continue. Their interesting macroscopic properties are determined by the finite size of crystalline domains. The quantitative understanding of such technologically relevant materials needs to be further improved so that their properties can be designed in a systematic fashion.

Closely connected with the efforts to understand the physics of such mesoscopic systems is the question of how many atoms have to be arranged and in what kind of conformation in order to have the typical properties of a solid. This transition area between atomic, molecular and solid state physics is of considerable relevance for many systems of technological importance such as artificially structured semiconductors, metals and magnets, quantum wells and "artificial atoms" and thin films on substrates. The common theme of these systems is their lowered dimensionality and effects originating from their finite sizes. Although many physicists are currently working on such problems, research in this area will continue and expand.

There will also be an increasing trend to investigate amorphous, glassy and fluid systems consisting of small molecules as well as of complex macromolecules. Many of their properties are quite different from those of the ideal periodic structures and a detailed understanding of these differences is so far only partially available.

Besides providing results of technological importance, the study of such substances requires basically new methods for their theoretical description, thereby enriching general knowledge in physics.

Particle Physics

Commission 11

Peter I. P. Kalmus

From Simplicity to Diversity

The realisation that the great diversity of the world stems from a handful of elementary particles acting under the influence of a few fundamental forces was one of the triumphs of twentieth century physics. In the early 1930s we appeared to have only three elementary building blocks: the protons and the neutrons, which were the constituents of nuclei, and the electrons which complete the atoms. The electrons were bound into the atoms by electromagnetic interactions, since they were attracted by the opposite charge of the nuclear protons, but in order that the nuclei do not disintegrate by the mutual repulsion of their constituent protons, a new short range force, the strong interaction, was required.

This simple picture did not last long. Antiparticles – which had some properties (such as mass) equal and others (such as charge) opposite to normal particles – were predicted and later discovered. The apparent violation of momentum and energy conservation in nuclear beta decay led to the hypothesis that another new particle, named the neutrino, was emitted. The neutrino felt neither the electromagnetic nor the strong force, and hence escaped undetected in beta decay experiments. It would be created by another new short range force, the weak interaction, which was so feeble that neutrinos on average could penetrate light-years of material such as iron before having a significant chance of interaction. They were therefore thought to be undetectable. However, in the 1950s the huge flux of neutrinos coming from the decay of radioactive decay products in nuclear reactors led to their detection. Since then many experiments have observed neutrinos from various sources: accelerators, reactors, the Sun, supernova SN1987A, and from cosmic ray interactions.

Also in the 1950s and 1960s, experiments using cosmic rays, and later the new large accelerators, showed that if particles such as protons hit nuclei with sufficient energy, then additional new particles could be created by converting some of the collision energy into rest energy (that is to say, mass), according to the well known equation $E_{rest} = mc^2$. These particles were unstable and decayed rapidly into more stable forms, either in around 10^{-23}s by the strong interaction, or at a more leisurely pace, say around 10^{-8}s or 10^{-10}s by the weak interaction. By the 1970s the number of so-called “elementary particles” exceeded the number of chemical elements.

Back to Simplicity

Fortunately the present situation is again much simpler. There now appear to be only two classes of elementary building blocks, called quarks and leptons. Quarks feel the strong interaction, leptons do not. In our normal surroundings where energies per particle are low, we have only two of each. Electrons and neutrinos are leptons. However, the proton and neutron are no longer elementary, but are made up of two types or “flavours” of quark called up (u) and down (d). Each contains three quarks, the proton has constituents (u u d) and the neutron (u d d). The electric charges are +2/3 for u and -1/3 for d.

Leptons (do not feel strong force)	**Quarks** (feel strong force)	
electron e^- -1 electron-neutrino ν_e 0	up **u** +2/3 down **d** -1/3	Also **antiquarks** **antileptons**
muon μ^- -1 muon-neutrino ν_μ 0	charm **c** +2/3 strange **s** -1/3	**6 leptons** **6 antileptons**
tau t^- -1 tau-neutrino ν_τ 0	top **t** +2/3 bottom **b** -1/3	**6 quarks** **6 antiquarks**

Figure 1 Today's building blocks

At higher energies, this simple pattern of two leptons and two quarks is repeated, but only twice, leading to three generation of quarks and leptons, as shown in Figure 1. Also every quark and lepton has an antiparticle, so we are left with 6 each of quarks, antiquarks, leptons and antileptons.

The three types of neutrino have different weak interactions. According to the above classification, the particle emitted in beta decay is actually the electron-type antineutrino. Neutrinos were originally assumed to have zero mass. Experimentally the ν_e has a mass less than a few eV.

The evidence for only three generations of fundamental particles comes from the decay of the Z^0 particle. This has an extremely short lifetime ~ 10^{-25} s. Hence because of the uncertainty principle $\Delta E . \Delta t \sim h/2\pi$ there will be an uncertainty in its energy and hence in its mass. The Z^0 can decay into particle-antiparticle pairs of quarks, of charged leptons and of neutrinos. If there were more than three generations of "light" neutrinos (masses less than half the Z^0 mass) the Z^0 would decay more easily, have a shorter lifetime and hence a different quantum mechanical "width" or "line shape". From measurement of this line shape the number of generations of neutrinos has been found to be 2.984 ± 0.008.

Quarks and leptons all have an intrinsic angular momentum or spin of 1/2 measured in quantum mechanical units. Such particles are called fermions because they obey Fermi-Dirac statistics. In addition to the proton and the neutron, other combinations of quarks form strongly-interacting particles, collectively known as hadrons: these consist of three quarks, or three antiquarks, or one quark and one antiquark. Some hadrons consist of three similar fermions, such as (u u u) or (s s s). Because identical fermions cannot be in the same quantum state, quarks were given an additional attribute dubbed "colour", which can have three values, say red, green and blue. Of course, these are only names. However all hadrons are "colourless" so there is an analogy between a hadron containing one red, one green and one blue quark, and the white light that can be produced by mixing light of these three colours. Antiquarks have anticolours as well as antiflavours.

Forces

We expect all particles to feel the gravitational force, which however is fantastically weak in comparison with the others. For example, the electromagnetic force between a proton and an electron is 10^{40} times stronger than the gravitational force. All particles feel the weak force. Quarks and charged leptons also feel the electromagnetic force, and quarks feel the strong force.

The forces through which the building block particles interact are transmitted by the exchange of another type of object. The force-carriers are bosons, particles which have integer spin and obey Bose-Einstein statistics. The carrier of electromagnetism is the spin-1 photon. Gravity is believed to be transmitted by spin-2 gravitons, but these have not yet been detected.

The objects that carry the colour force between quarks and hence glue them together to form hadrons are called gluons. Unlike photons, gluons can couple to each other (via the colour force they carry). One result of this is that the strong force *increases* with distance. Quarks are therefore confined within hadrons, as it is energetically more favourable to produce a new quark-antiquark pair than to further separate two quarks. Gluons were first discovered in 1979 at the DESY laboratory in Germany. The theory of strong interactions, known as quantum chromodynamics (QCD), is well developed and consistent with experiments, although it is not easy to test it very precisely. The coupling "constant" (it actually varies with energy), which is a measure of the strength of an interaction has a value around 0.12 for the strong interaction, compared with 1/137 for the fine structure constant of quantum electrodynamics, and this makes calculations more difficult.

Initially it was thought that a charged carrier, called W for weak, was responsible for the weak force. Feynman diagrams allow one to visualise these interactions. Fig. 2 shows the weak interaction in beta decay where a neutron (free or within a nucleus) changes into a proton, and hence a down quark turns into an up quark by emitting a W^- boson which then decays into an electron and an antineutrino.

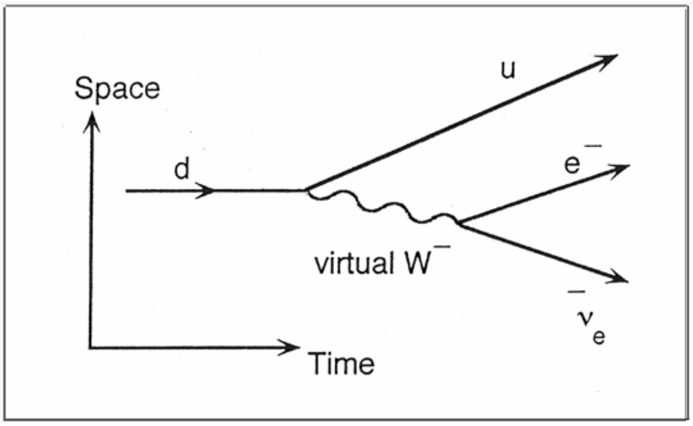

Figure 2 Feynman diagram for the weak interaction in beta-decay

In the 1960s, theorists achieved the surprising feat of unifying the apparently disparate phenomena of the electromagnetic and weak forces into a single framework. Electromagnetism has a classical inverse square law and infinite range. In contrast the weak interaction under normal circumstances is very feeble and is confined to sub-nuclear distances. Protons in the solar core collide many times a second, but on average a particular proton will only convert into a neutron after around five billion years of collisions. Hence it can be calculated that the Sun is only half way through its hydrogen burning and has provided both the environment and the time-scale for biological evolution on Earth. The weakness of the weak interaction has allowed time for life to evolve.

In electroweak theory, there are four mediating bosons. The massless photon transmits the electromagnetic force and the weak force is transmitted by three massive particles: the charged W^+ and W^- particles and the neutral Z^0 particle, which have masses about 100 times that of the proton. The intrinsic strengths of these carriers are identical, but the massive nature of the W and Z particles limits their range to very short distances, another consequence of the uncertainty principle. In collisions at relatively low energies, the particles do not approach each other sufficiently closely for W or Z exchange to occur. However at energies of around 100 GeV close encounters are common, showing electroweak unification. The most spectacular experimental verification of this theory was the discovery of the W and Z particles at CERN in 1983. Electroweak theory has now been tested to high accuracy.

Symmetries

Symmetries play a significant role in particle physics. In mechanics, in electromagnetism, and in strong interaction physics, there is no intrinsic difference between left and right. A process and its mirror image occur at the same rate. This is known as conservation of parity (P). Similarly, observable processes would occur with the same probabilities if all particles were changed into their corresponding antiparticles. This is charge conjugation (C). At the microscopic level, the laws for a process and its time-reversed process (T) should also be equivalent. For macroscopic systems, time reversal does not hold, but this is a consequence of its statistical improbability rather than of basic laws.

In the 1950s it was found that for weak interactions P and C were not conserved, and in fact they are violated maximally. The strict mirror image of beta decay is not observed unless at the same time particles and antiparticles are interchanged. Later it was found that the product CP was violated in some weak interactions involving neutral K-mesons. This CP violation was small. Its origin is not fully understood, but it is believed to be one of the ingredients required in the very early universe to produce the present tremendous preponderance of matter over antimatter. Two “B factories”, one in Japan and one in California, started operating in 1999, and are now working well at their design values. Experiments at these machines are investigating the origin of CP violation, as well as observing oscillations in the B^0 meson system, analogous to K^0 oscillations which have been observed since the 1960s. CP violation has now been observed also in the neutral B meson system. The first direct evidence for T violation was observed in the neutral K-meson system at CERN and at Fermilab. The product CPT is believed to remain conserved.

Electroweak theory and QCD have been incorporated into what is known as the standard model of particle physics. Although this model works very well it suffers from a number of defects. There are rather a lot of arbitrary numbers that are not intrinsic to the theory but have to be obtained from experiment. The theory predicts nonsensical results at energies slightly higher than now available - equivalent to processes having a probability greater than unity! In addition, the theory requires that the W and Z particles, like the photon, should be massless. A mechanism which gives mass to the particles by allowing them to interact with a field was first suggested by Peter Higgs. This would have a carrier object — the Higgs boson, which, so far, has not been detected.

Quark Mixing

The quarks participating in the weak interaction, such as the decays of hadrons, are quantum mechanical combinations of the “strong interaction quarks” listed in Fig.1. In the standard model with 3 generations, this mixing can be described by a 3 x 3 matrix, which can be expressed geometrically as a triangle whose sides and angles are related to various quark processes. A major objective of experiments at the B factories and elsewhere is to determine this triangle. An inconsistency, i.e. if the sides and angles do not form a closed triangle, would show a breakdown of the standard model.

Neutrino Physics

This has been one of the most exciting areas in particle physics in recent years. In the late 1960s, Raymond Davis discovered that the number of neutrinos reaching the Earth from the Sun was only about one third of the number expected from theoretical calculations of fusion reactions. The experiment was a very difficult one, but it was continued for many years and the calculations of reactions in the Sun were refined: the discrepancy continued. Later experiments using different detection techniques, and which were sensitive to different energies of solar neutrinos all showed similar deficits. One suggested solution to this solar neutrino problem, was that electron neutrinos ν_e generated in the Sun transformed into one or both of the other neutrino types, which would not be recorded in the experiments. Such neutrino mixing or oscillations requires neutrinos to have a non-zero mass.

In the 1990s, several very large underground detectors, most notably SuperKamiokande in Japan, investigated solar neutrinos and also neutrinos of much higher energies originating from decays of atmospheric cosmic rays. The Sudbury Neutrino Observatory (SNO) in Canada was recently able to measure the flux of ν_e and also the total flux of all neutrino species from the Sun. Another important experiment, Kamland, measured the flux of electron-type antineutrinos at a central location around 140 to 210 km from a large number of nuclear reactors in Japan. A consistent picture has now emerged. Neutrino mixing occurs. The weak interaction states ν_e ν_μ ν_τ are mixtures of 3 mass states ν_1 ν_2 ν_3 . Raymond Davis, and Masatoshi Koshiba the pioneer of Kamiokande, shared the 2002 Nobel Prize together with X-ray astronomer Riccardo Giacconi.

Particle Theory

In this short summary, very little has been written about the theoretical advances in particle physics. There are schemes that unite the strong interaction with electroweak theory. These are known as grand unified theories, GUTs. Another theory, supersymmetry, unites the building blocks, the quarks and the leptons, with the force carriers. This requires new partner particles for all these objects, none of which have so far been discovered. Superstring theories, and their recent extension, M-theories, which require supersymmetry, are exciting and fashionable. They treat particles as excitations of tiny strings. This avoids objectionable infinities that arise when particles are treated as point objects. Superstring theories do however require more than the usual three space and one time dimension. The unobserved dimensions are assumed to be compactified - curled up so that they are too small to be observable, just as a telegraph wire appears from a distance to be only one-dimensional. Superstring theories have the potential to provide a quantum theory of gravity and to unite it with the other forces, and there is much activity in this field.

Links with Cosmology

The hot big bang picture assumes that the early universe was a primordial soup of elementary particles, and today's high energy machines provide collision energies like those which existed when the universe was less than one nanosecond old. Accurate measurement of the fluctuations in the cosmic microwave background, observation of the acceleration of the expansion of the universe, and computer modelling of galaxy formation and clustering have recently provided a consistent view of the universe. The universe is geometrically flat: parallel light rays do not converge or diverge. The observable matter in the universe, i.e. that which can be detected in any part of the electromagnetic spectrum, only accounts for about 5% of the energy density of the universe. Another 25% is cold dark matter and the remaining 70% has been dubbed 'dark energy'. Neutrinos can only make up perhaps 0.5% of the total. Candidates for dark matter are WIMPs, weakly interacting massive particles, of which the favourite is the neutralino, the lowest mass supersymmetric particle. Searches for WIMPS are in progress in several undergound laboratories. Dark energy is even more mysterious, it appears like a negative pressure of space, reminiscent of the cosmological constant which Einstein put into his equations to prevent the gravitational collapse of a static universe, before Hubble's discovery that the universe was expanding.

Future Prospects

The large hadron collider, LHC, colliding proton beams at a centre of mass energy of 14 TeV, is being constructed at CERN in Geneva, and will start in around 2007. It seems highly probable that the Higgs boson will be discovered with that machine, indeed it might be discovered sooner at the Fermilab Tevatron which has been upgraded. If the Higgs is not found then some other new physics is certain to emerge, to avoid the excess of probability that would otherwise come from the standard model. Designs for a large linear electron-positron collider are in advanced stages, and there is hope that one such machine might be approved in a few years time, and built in Europe, America or Asia as a World collaboration. In the more distant future it may be possible to make intense and well-controlled high energy neutrino beams from decays of muons in a storage ring, although at present many technical problems remain unsolved.

The origin of CP violation, and hence the vast preponderance of matter over antimatter is likely to be discovered within the next few years. Supersymmetric particles, if they exist should be found at the LHC. If not found, supersymmetry will presumably be discarded and some alternative theory will take its place.

What else will emerge? We take for granted that the electron and proton charges are numerically equal, and indeed experimentally they are equal to better than 1 part in 10^{21}. This may not seem surprising. However, leptons and quarks are quite distinct. The numerical charge equality between 3 quarks and an electron cannot be a coincidence. Perhaps at high energies, such as existed in the early universe, leptons and quarks coupled with each other. At lower energies, this symmetry is broken in an analogous way to electroweak symmetry breaking. In 1997 there was excitement, when some collisions between positrons and protons at the HERA machine at DESY, gave some indication of the existence of such leptoquarks. With more data this interpretation turned out to be wrong, but it still seems likely that in the fairly near future some better understanding will arise of the connection between leptons and quarks. Superstring theory may come up with some predictions that can be tested. Although the graviton, the quantum transmitter of the gravitational force, fits well into the superstring picture, it seems unlikely that it will be found in the near future. However gravitational radiation is predicted from general relativity, and its existence can be inferred from the careful measurements over many years of the change in period of a binary pulsar. Several detectors for gravitational radiation are in final stages of construction. They are large optical interferometers, with arms 0.6 km to 2 km in length, looking for the distortion of space caused by violent astronomical events. So the wave properties of gravity will open a new window in astronomy.

There will no doubt be unexpected surprises, as there have been in the past. I predict that particle physics and its links with astrophysics and cosmology will continue to be exciting in the foreseeable future.

Nuclear Physics

Commission 12

Willem T.H. van Oers

Introduction

Atomic nuclei are the heart of all matter and comprise more than 99% of the mass of the directly observed matter in the universe. Yet nuclei, lying at the centre of atoms, occupy only about one million-millionth of the volume of normal matter, which tells us that they have a density beyond anything one may meet in daily life. The field of nuclear physics is therefore of great intrinsic importance in understanding the universe. However, it must be a very humbling observation that the directly observed matter constitutes only a small fraction of what the universe is composed of, dark matter and dark energy being in preponderance.

A discussion of where nuclear physics is now heading should be placed within the perspective of the past century of science, for much of which nuclear physics was the dominant field of science. The end-of-century complacency about science which characterised the final years of the nineteenth century was rudely shattered by the discovery of radioactivity and, shortly afterwards by the birth of nuclear physics and the emergence of quantum theory to describe the physics of the atom and its nucleus in which Einstein's special theory of relativity also plays a role. Both quantum theory and the theory of relativity were the major extensions to classical mechanics at the beginning of the last century.

It was Ernest Rutherford who introduced nuclear physics by creating the appealing picture of the atom as a miniature solar system: a tiny, massive nucleus, surrounded by orbiting electrons – or better said – by an electron cloud. The earliest work on radioactivity, to which Rutherford contributed, found that it consisted of three different kinds of radiation: alpha particles (helium nuclei), beta particles (electrons) and gamma rays (photons). In their classic work, over ninety years ago, Rutherford and Geiger used the deflections of alpha particles from a gold foil to show that most of the mass of the gold atoms had to reside in a tiny atomic centre (the nucleus) almost a million times smaller than the gold atom. Over the next few decades it was found, at the Cavendish Laboratory in Cambridge, which Rutherford headed, that the nucleus itself was made of neutrons and protons. The number of protons in the nucleus determined the element and for each element there were, potentially, many different isotopes differing in the number of neutrons in their nucleus.

Quantum theory, which emerged concurrently with nuclear physics, received its early important tests in describing the physics of the atom. In the first half of this century the atomic nucleus became the most important vehicle for the elaboration of the ideas of quantum mechanics. The binding of the neutrons and protons into stable nuclei – or, alternatively, into unstable radioactive nuclei – required a new short-range force which came to be called the strong interaction.

The Nuclear Landscape

The nuclear landscape, shown in Fig. 1, is a plot of all of the stable and radioactive nuclei versus their proton and neutron number. The stable nuclei form a diagonal ridge of stability across the figure, which terminates beyond lead. The thousands of unstable nuclei have, generally, shorter and shorter lifetimes as we proceed away from this ridge and eventually one reaches the driplines at which extra neutrons or protons are no longer bound and therefore simply "drip" off. It is a rich and varied landscape. All of the nuclei, stable and unstable, contribute to the understanding of nuclear systems and are involved in astrophysical processes.

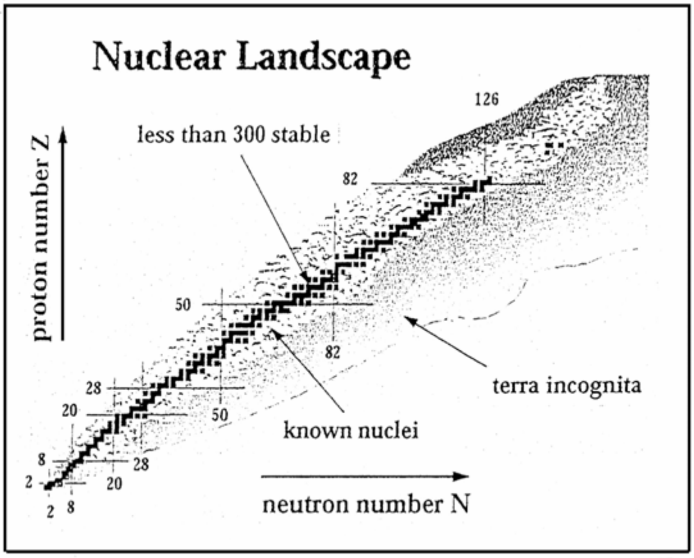

Figure 1 Map of bound nuclear systems as a function of proton number Z (vertical axis) and neutron number N (horizontal axis). The black squares show the nuclei that

are stable, that is, non-radioactive or long-lived with half-lives comparable with the age of the earth. There are fewer than 300 such species. Between the stable nuclei and the driplines, discussed in the text, are thousands of radioactive nuclei, some known but most unknown.

Perhaps the most wonderful science story that has emerged in the past century pertains to the new understanding of the history of the universe since the initial Big Bang, billions of years ago. Nuclear physics led to nuclear astrophysics which underlies much of modern cosmology. The very lightest elements were created in the Big Bang and then the remaining elements arose from the processes involved in the birth, life and death of stars.

In fact with iron constituting the most stable nucleus, all elements with masses greater than iron must have been formed in supernovae explosions (of stars with masses greater than four times the mass of the sun). The detailed understanding of these processes remains a modern challenge for nuclear physics because it requires a knowledge of the low energy nuclear reactions of all nuclei.

Access to the strong nuclear binding energy became a very dramatic development just before the second world war. Looking at the nuclear landscape of Fig. 1, it can be appreciated that the stable nuclei terminate, beyond lead, because the electric repulsion of the protons reduces the total binding energy. As a result, fission is possible in which a heavy nucleus splits into two or more lighter nuclei with a great release of energy. When fission was discovered in 1939 it led rapidly to the development of nuclear weapons and the domain of nuclear physics became highly political, while at the same time the scientific questions of the field made nuclear physics the queen of the sciences. Fortunately nuclear energy can also be harnessed for the production of electricity: the pursuit of clean energy sources as nuclear reactors is another continuing challenge for the field. With the possible emergence of global heating the availability of clean energy sources is indeed of great importance to mankind.

Nuclear Physics and Particle Physics

While quantum mechanics and nuclear physics thrived together a number of other important fields of science were spawned off in mid twentieth century — such as particle physics, condensed matter physics, microelectronics, microbiology, etc. — which rapidly joined nuclear physics on the centre stage of science and achieved their own dominance.

With the applied sciences being much emphasised today, the news media are full of items about information technology and nanotechnology, stemming in turn from particle physics and condensed matter physics, respectively. Though no longer in any sole regal position, the field of nuclear physics remains full of new ideas which promise to carry it into the twenty first century.

The emergence of particle physics as a separate discipline in the second half of the century has had a strong impact on nuclear physics. It is no longer protons and neutrons and electrons which are the basic building blocks of matter, but, according to the Standard Model the building blocks are quarks and leptons. Further, the strong interaction is not the nuclear force between nucleons but rather Quantum Chromo-Dynamics (QCD), the exchange of gluons between quarks. Nuclear physics now pertains to the complex quantal systems (hadrons), including atomic nuclei and collapsed stars, made of strongly interacting quarks. Ordinary matter only consists of the two lightest quarks, the so called “up” and “down” quarks, with perhaps a sprinkling of “strange” quarks in the form of quark-antiquark pairs. With QCD describing systems of quarks, these carry a property called colour. In nature there appear to be only colourless systems of three quarks, the nucleons, and colourless systems of quark antiquark pairs, the mesons. But in principle five quark systems, consisting of three quarks and a quark antiquark pair, and six quark systems can exist. Confirmation of the existence of such multi-quark systems is pursued vigorously.

With nucleons and mesons consisting of quarks bound by gluon exchanges one naturally expects, as in atomic physics, the existence of spectra of exited states. In hadron physics a great deal of effort is spent on unravelling the intricate spectra of nucleons and mesons. And there are some beautiful analogies between the spectrum of energy levels of positronium (an electron-positron pair) and the spectra of energy levels of the quarkonia , like charmonium (a “charm-anticharm” quark pair, with the “charm” quark the second quark of the second family of quarks, the “strange” quark and the “charm” quark)! Nuclear physics is the science of hadronic matter, of nucleons and atomic nuclei, of their properties, their interactions and their constituents. Classical nuclear physics is now moving in new directions towards a more fundamental understanding of extreme states of this most dense form of matter which must have existed in the first instances after the birth of the universe.

The development of nuclear physics over the past decade has increasingly reaffirmed its strong links to particle physics and nuclear astrophysics. The research is closely related to the description of various phases in the early evolution of the universe.

Experiments to describe multi-quark systems in terms of QCD, to determine the three neutrino masses in conjunction with the oscillations between the various neutrino species, to detect the quark-gluon-plasma and to study the abundances of the lightest elements, together with attempts to model the production of heavier nuclei and to determine the equation of state of nuclear matter are all open problems shared by nuclear physics, particle physics, and astrophysics. Dense nuclear matter can take on extreme forms as in neutron stars and possibly strange quark stars. The Standard Model contains too many parameters to be the ultimate theory of matter; the start of the new millennium has seen a great focus on experiments, both in nuclear physics and particle physics, which can give a glimpse of what lies beyond the Standard Model. Nuclear physics and particle physics are beautifully complementary here, with nuclear physics precision experiments searching for very tiny deviations from the predictions of the Standard Model and particle physics experiments probing the energy region where the creation of new particles becomes a possibility.

Calculation of the strong binding force (QCD) between the quarks remains largely intractable at nuclear energies and so phenomenological methods are necessary to describe nuclei. At low energies the nuclear properties are described in terms of nucleons and mesons with empirically deduced interactions. Sophisticated tools have been developed to collect information to provide a phenomenological description.

Unstable Nuclei

In the nuclear landscape of Fig. 1 our present knowledge pertains primarily to that small subset of isotopes which are stable or nearly stable. One needs to know the properties of isotopes which are very heavy or have very large neutron or proton excesses, that is, they are near the driplines. The isotopes in the extreme regions of the landscape have unusual behaviour and most are involved in the creation of the elements in stars. Sophisticated tools have been developed to collect information for a phenomenological description of nuclei. Recent years have seen remarkable progress in synthesising the heaviest man-made nuclei in the region of superheavy elements, and in probing nuclear systems at the dripline regions where the evidence for nuclear halo states (nuclei with an outer skin of only neutrons) has been found. The knowledge of nuclei along the proton dripline is beginning to be excellent with the observation of the long awaited doubly-magic Sn-100 nucleus and many other exotic nuclei showing proton radioactivity. Indeed the process of two-proton radioactivity has recently been observed. Also various other extraneous radioactive doubly-magic nuclei have been produced in the laboratory.

A challenge at the beginning of this new century is to produce nuclei with extreme neutron excess in intermediate and heavy mass regions so that one may approach or may be even reach the neutron dripline in the intermediate mass region. The search for new phenomena in this part of the dripline region is a great challenge and will confront important questions. Are there real neutron skins beyond those observed for the light nuclei? Does nuclear structure change when there are large chunks of nucleon matter of very large isospin? The recent very intense development of radioactive beam facilities, worldwide, will certainly play a key role in this progress.

Future Trends

The new trend in theoretical nuclear physics will certainly also play an important role in acquiring a deeper understanding of nuclear matter. At high energies and temperatures, the substructure of nucleons and mesons in terms of quarks and gluons becomes important. This substructure leads to a challenge: how to find a more basic understanding of nuclei, that is, how does one proceeds from QCD to phenomenological models in terms of nucleons and meson exchange so that one can derive nuclear structure and hadron dynamics at short distances from first principles? One may not be able to find a complete theory but there are many gaps to bridge. New capabilities with energetic and intense electron, photon, and proton beams promise to provide comprehensive studies of this very fundamental goal during the present decade. Some questions of current interest are about the apparent difference in the charge and magnetization distributions of the nucleons, about the strangeness contents of the nucleon, about the distribution of the spin of the nucleon over its constituents, about the shape of the nucleon, and whether the laws of physics are the same for matter and antimatter, to list a few. A vigorous program of constructing large scale nuclear physics facilities with international participation is currently under way.

Most of the studies of nuclear matter, until the present, have explored its properties at or near normal temperatures and pressures. With increasing energy and density, phase transitions are expected and are known to occur in nuclear matter and in the early universe. At intermediate energies liquid-gas transitions occur, after which with increasing energy hadronic gas is formed possessing a density as high as two to three times the normal density of nuclear matter. At the high energy limit we expect to see how nuclear and particle physics merge. Future experiments employing collisions between relativistic heavy ions will allow heating and compression of nuclear matter and will create extreme conditions under which such questions can be explored. The quark-gluon plasma, a very important goal, will certainly be readily available within a few years at several laboratories. By getting access to it one expects that the field of nuclear physics will contribute to the understanding of the early universe. Beyond this there is the question what constitutes dark matter and what is dark energy. Is there the need to introduce another force beyond those that so beautifully provide the current description of matter: the strong force, the electromagnetic force, the weak force and the gravitational force?

Physics Education[1]

Commission 14

Jon Ogborn

Physics Education Reform

The half century since the late 1950s saw a spate of curriculum reform in physics in very many countries, both developed and developing, starting in the USA with the Physical Science Study Committee (PSSC). Reform spread rapidly throughout the world, with many countries establishing curriculum reform projects in physics and other sciences, some set up by governments and others by voluntary agencies.

In developed countries, curriculum change in physics had two main driving forces behind it. One was a perceived need to increase economic competitiveness. It seemed essential to improve the scientific and technological background of the workforce, in an increasingly science and technologically oriented society. The second was to bring the physics curriculum up to date. The essentially nineteenth century divisions of the subject into mechanics, properties of matter (mainly the Young modulus), thermal physics (mainly thermal expansion and calorimetry), light (with much geometrical optics) and sound, and electricity and magnetism, were badly out of date. Physics had moved on. New topics were established, beginning with the introduction of "modern physics" (by then already 50 years old) including radioactivity and the Bohr atom. Then new topic groupings, better suited to the new shape of physics, were developed: for example mechanics, materials, waves, fields and thermodynamics.

In developing countries, the motives for reform were similar, though not quite identical. One strong emphasis was on national economic development; that is, with educating future scientists and engineers. The other was on improving the teaching of basic physics, through providing better facilities and resources, notably low-cost and readily available apparatus for physics teaching. However, learning is not simply by doing, but is by doing and by thinking before during and after doing. Easy though this is to say, it is hard to achieve where class sizes are large and resources are scarce.

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[1] This review draws with gratitude on the review prepared by Paul Black for the previous edition

Important work is being done through UNESCO and other agencies to create national and regional networks to support science teachers in schools and in universities, in Asia, Africa and South America.

Three general lessons emerge from this period of reform. One is that the nature of reform and the way it needs to be implemented differ markedly from one country to another. Education shows much more national, even local, specificity than does physics. The second is that even so, there is a set of common constraints that any such reform needs to address, despite differences in the solutions found. These are, in broad outline:

- Changes in physics itself, which need to be reflected in some way in courses at school level.
- Changes in the way society views physics education and its purposes, and changes in its relation to other subjects, particularly mathematics and other sciences.
- The structure of the education system, particularly whether it is centrally controlled or is devolved to a greater or lesser extent. Does the political system expect or allow diversity, or is uniformity the normal presupposition? This kind of difference affects radically the scale, timing and nature of reform that is possible.
- Who teaches physics at a given level? What do these teachers expect and demand? What kinds of change will they accept? How well prepared are they?
- What are the socio-political pre-occupations of the time – for example, the need for a wider and fairer distribution of education? Are there other relevant concerns – for example global pollution or global energy issues – which science education is expected to address?

The third lesson is that curriculum change takes time. Change diffuses through the education system slowly, and at rates that vary for different kinds of change. Meanwhile, competing traditions continue to coexist.

Updating the Physics Content

It is in the nature of physics (and other sciences, including mathematics) to be dynamic, changing and developing all the time. School curricula sooner or later have to respond, if they are not to give students a fatally flawed view of the subject. And in any case, at high school level, students may well be aware of the most glamorous new developments – for example in particle physics and astronomy – that school courses ignore.

This process of transposing physics at the research level into physics that can be taught in (say) secondary schools is both creative and not at all straightforward. It involves finding the right kinds of simplification, especially of the mathematical language used. It also involves a strong selection so as to present the essence of new ideas from a particular point of view. In this work ("didactic transposition") school teachers play as important a role as university physicists. One of the success stories of the past half century has been the collaboration between noted physicists and teachers in developing such ideas.

Here are a few leading examples of such work. Those working in PSSC showed how to make mechanics a much more experimental subject (less like applied mathematics) and to make it accessible to a wider range of students. Others developed a range of equipment for teaching about radioactivity in schools. Excellent work has been done in many countries on developing new ways of teaching quantum physics, nuclear and particle physics, thermodynamics and relativity, to name but a few topics. A recent successful example is the introduction of microelectronics into some physics curricula.

Future Needs for Updating Content

Physics continues to change, and updating the content of school curricula continues to be needed. There are several such current needs, each having begun to be addressed (for example in the recent UK project *Advancing Physics*) but all yet to be achieved on any widespread scale. One is the move throughout physics to increased use of computation, very clearly in evidence in most of the reports in this volume. Computers are used in physics in experimentation, in modelling, in processing data and in imaging and visualisation. Schools have begun to use computer interfaces for experiments, but few have any experience of teaching computer modelling in physics, or of using modern software for (for example) image processing. Another related need is to recognise the explosion of work in optics and computer imaging. This has transformed many research fields (again, see elsewhere in this volume), and is relatively simple to understand, besides being attractive to many students. A third need is for school physics to recognise the huge developments in miniaturised sensors, now at the heart of almost every control system, indeed present in quantity in every automobile.

The case of optics is of some interest. In many physics courses, geometrical optics (restricted to thin lenses and mirrors, and to paraxial rays), fell by the wayside when new reformed curricula were developed. Now, a different kind of optics needs to be re-introduced; one which responds to the massive new developments in the field.

Change in the Social Context

During the course of the twentieth century, in developed countries, secondary education passed from being something available to a minority of the population to being expected by the great majority. The same process is underway in developing countries. Similarly, whilst college and university education used to be available to only a few percent of the population, they are now available to at least a large minority. These changes strongly affect the social demands made of physics (or science) education.

One response has been, in the interests of serving a broader education, to expect physics courses to pay more attention to the social and technological implications of physics, and to its philosophy, history and characteristic modes of thought and enquiry. However, this rather intellectual response is not obviously well chosen for all students, many of whose interests often focus more on application and use.

A related policy move, in many countries, has been to see the place of physics, at least for the years of compulsory schooling, as a component of either "science" or "physical science". Thus the subject may not have a strongly separate identity, but rather be presented as combined, or co-ordinated (or, in the hands of some teachers, even integrated) with the other natural sciences. This can often be to the advantage of physics, because such combined courses are usually taken by all pupils, so that there is no choice to avoid physics, whilst, because its concepts are fundamental to the other sciences, physics may well receive more than its proportionate share of attention in such courses. However, in some countries, this kind of move, often allied to the difficulty in finding qualified physics teachers, has meant a reduction in the time given to physics.

The wider social context is also very important. Developed countries generally have strong physics research communities, and a substantial technically qualified workforce. It is then argued that physics is needed in the curriculum to sustain the research community, whose work then feeds into economic development. But the argument looks much less plausible in a country that lacks a strong research community. This has led, in many countries, to arguing for school physics as preparing for daily life, as part of the education of confident well-informed citizens.

Research in Physics Education

The past forty years have seen rapid development and growth in research in physics education research worldwide. In some countries, this has been done in specialised departments within or associated with university physics departments. In others, it has developed in university departments of education, with responsibility for training of teachers. International associations and conferences support this now quite large research community.

One focus of research has been on identifying particular difficulties in teaching and in learning physics, and on finding well-founded and well-tested solutions to such difficulties. The best of this research has yielded modest but clear-cut results, drawing the attention of teachers to unexpected problems and potential answers to them. An excellent example is the teaching of optics. French researchers were able to suggest changes to the physics curriculum that constructively addressed simple but fundamental issues of understanding that were systematically missed by traditional teaching of ray optics.

Perhaps the strongest result to emerge from this research has been the fundamental importance of the ideas students hold about the physical world, in deciding how they understand what they are taught. The point is ultimately simple and obvious: everybody understands what they are told as a kind of ‘best fit’ to what they already know. In the process, the learner transforms knowledge so as to make sense of it. The result may differ markedly from what the teacher actually said. The lesson is one that it is essential for physicists, above all, to learn, because what they have to tell is so often counter-intuitive. Newtonian mechanics offers a prime example. Students regularly refuse to believe the First Law, and import into mechanics ideas of their own about a ‘force’ needed to keep objects in motion (this result stands clear in a multitude of studies). Reflect, then, on the many other parts of physics that present the world as quite other than it appears to be, and on the difficulties this inevitably generates.

Research has made it clear that to teach and test factual knowledge alone, with the hope that understanding and use will develop later all by themselves, just does not work. It shows that extensive experience of tackling real problems is essential to learning to solve them. Recent research has emphasised the importance of discussion and argument in learning both skills and concepts, leading to renewed interest in the value of group work and peer assessment. There has been increased traffic between those concerned with physics education and those concerned more generally with cognitive processes, development and change. But this is still an area where “Watch this space” is the best advice.

Other relevant fields of research have been: motivation and choice of subject to study; alternative methods of assessment and testing including effects on learning and the predictive power of tests; bias, particularly gender bias, in textbooks, classroom practices and testing; and the role of practical work and practical investigation.

Much practical work in the sciences has been called into question because students are often required to follow recipes with little opportunity to exercise choice, creativity, or even thoughtfulness about the arts of measurement and experimental inquiry. Effort has gone into developing ways for students to conduct investigational projects of their own, to provide them with some authentic experience of ‘doing physics’. Despite successes (in particular in university courses), such work presents real problems for teachers, especially if they have no experience of it themselves.

As mentioned earlier, an area of growing importance is the use of information technology in physics education. Here there are wide differences between the best teaching one can find, and the average. Excellent use has been made of the computer for modelling, for controlling experiments and acquiring data, for analysing and presenting data, for image and signal analysis, and in supporting internet communication. But such work remains relatively thin on the ground, even in favoured circumstances.

To summarise, the researcher in physics education needs to combine a strong personal background in physics, access to working physicists for further insights into current trends, and an armoury of concepts and methods deriving from the social sciences. The last includes insight into processes of learning and cognition, and into the social processes involved in schooling and indeed in science itself. Mutual respect between physicists and physics educators is crucial, but is not always easily achieved.

Policy and Standards

One pressing policy concern has been the frequent signs of decline in the numbers of students taking up advanced study of physics, and, related to this, a fall in the numbers of those well qualified to teach the subject. Thus there has been much study of the reasons why the subject is unattractive to pupils: one reason is the lack of connection between the topics in the curriculum and the daily lives and interests of students. Another reason is the perceived difficulty of the subject – a perception that can often be supported by evidence that the average student is less likely to do well in physics than in almost any other school subject. However, many physicists who accept that this is the case nevertheless find it difficult to construct courses which are less demanding.

The development in the 1980s and 1990s of prominent national and international comparative surveys of achievements in mathematics and science focused media interest on ‘league tables’ of each country's standing. Unfortunately, commentators were rarely inhibited by the very real dangers of illegitimate interpretation in comparing different educational systems.

There has also been concern in some countries about a perceived decline in standards of attainment. Discussion of this has largely ignored the consequences of huge increases in the numbers of students studying physics at all levels. On balance, there seems to be no firm evidence that standards have declined.

Challenges for the Future

One challenge, obvious from what has been said so far, is to recruit physicists and physics educators to work together on keeping the teaching of this continually evolving subject up to date. Recall that the working life of a physics teacher may be forty years, in which time areas of the subject will have changed out of recognition. This fact underlines the need for continual professional development and in-service training.

A second challenge is to further improve how physics is taught, taking account of the best available understanding of processes of teaching and learning, within the constraints of available resources and the capabilities of teachers.

Perhaps the largest challenge of all is to decide what, out of the large amount of material that could be taught under the umbrella name of physics, should be selected, and for whom. Conflicting expectations in this new era of mass education have somehow to be resolved. The main message from research is that it takes time and effort to teach or learn anything well, so that selection and concentration is unavoidable, indeed desirable. As Philip Morrison once said of the physics curriculum, “Less may be more”.

Atomic, Molecular and Optical Physics

Commission 15

W. A. van Wijngaarden

Historical Perspective

Atomic, molecular and optical physics describes the interaction of electromagnetic radiation with atoms and molecules[1]. Optics is based on the theory of J. Maxwell who predicted in the 1860's that light is a transverse electromagnetic wave. This was confirmed by experiments by H. Hertz and others who demonstrated the existence of nonvisible radiation. The latter included X-rays that were discovered by W. Röntgen. The experiment by A. Michelson and E. Morley measuring the speed of light and finding it to be independent of the Earth's motion did away with the idea of an ether and laid the groundwork for the discovery of special relativity. The modern form of atomic and optical physics originated at the turn of the 19th century when convincing evidence of the quantized nature of light and matter was obtained. J. Thomson discovered the existence of a light negatively charged particle called the electron in 1896. The photon was postulated first by M. Planck to account for the black body radiation spectrum and later used by A. Einstein to explain the photoelectric effect. A. Einstein also gave credence to the idea of atoms or molecules by showing how random molecular collisions account for Brownian motion.

Significant insight into the structure of atoms was provided by E. Rutherford's experiment scattering alpha particles off of a gold foil. This showed that most of the atom's mass was contained in a small positively charged nucleus that was orbited by electrons. The difficulty with this so-called Bohr model of the atom was that it was inconsistent with electromagnetic theory. The latter predicted that electrons

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[1] Also see Atomic, Molecular & Optical Physics Handbook, edited by G. W. F. Drake, published by American Institute of Physics, New York (1996).

accelerated to maintain circular motion should radiate energy. Electrons would then quickly spiral into the nucleus and the atom would collapse.

The resolution of this paradox gave rise in the 1920's to an entirely new theory – quantum mechanics – to describe atoms, molecules and photons. The so-called wave like properties of particles were first postulated by L. de Broglie and later expressed by the famous Heisenberg Uncertainty Relation. It was truly amazing how well the Schrödinger equation could account for the spectra of atoms including the Zeeman and Stark shifts. Indeed, measurements of fine structure permitted the discovery of electron spin by S. Goudsmit and G. Uhlenbeck as well as effects due to special relativity. W. Pauli also discovered the famous exclusion principle that describes the relation between wavefunction symmetry for bosons/fermions. Hyperfine effects due to the nucleus were also discovered, including the 21 cm spectral line in hydrogen, now famous in astronomy as a way of mapping the distribution of hydrogen in the galaxy, which arises from a transition between the ground state hyperfine levels. The bringing together of both quantum mechanics and special relativity was achieved by P. Dirac, leading him to predict the existence of antiparticles. Shortly thereafter, C. Anderson discovered the positron.

In the 1940's, W. Lamb measured a small energy difference between the $2S_{1/2}$ and $2P_{1/2}$ states of hydrogen that was not accounted for by the Dirac equation. This so-called Lamb shift resulted from the effect of virtual particles arising out of the vacuum and was important in the creation of Quantum Electrodynamics (QED) by R. Feynman, J. Schwinger and S. Tomanaga in the late 1940's. This theory continues to be tested in present day high precision experiments. For example, the anomalous magnetic moment of the electron (the amount by which it exceeds the value 2) as measured by H. Demelt agrees extremely exactly with the theoretical value calculated by T. Kinoshita. The success of QED has spurred on the development of the Electroweak theory unifying the electromagnetic and weak interactions and Quantum Chromodynamics to describe the strong nuclear force.

Survey of Recent Developments

Applications of lasers

Lasers are presently used in nearly all atomic physics experiments. The stimulated emission of radiation was first postulated by A. Einstein but it took until the 1950's for the first devices to be made. Microwaves were first amplified using this effect by C. Townes and others, by building a MASER – Microwave Amplification by Stimulated Emission of Radiation. In 1960, T. Maiman created the ruby laser (Light

Amplification by Stimulated Emission of Radiation), the first laser to operate in the visible spectrum. Lasers operating at many different wavelengths and with increasing power and tunability quickly followed. In the 1970's, T. Hänsch and others developed narrow linewidth dye lasers using gratings and etalons. This permitted experiments to make sub-Doppler measurements. J. Hall and others developed techniques to lock a laser to a resonance line (of an atom, ion or molecule) to create ultrastable frequency standards that can be used as atomic clocks and length standards.

The applications of lasers continue to grow exponentially, revolutionizing our daily life. For example, lasers are useful for measuring pollutant concentrations at a distance. Pollutants in car exhaust as well as mercury emitted by power plants can be monitored. Indeed, so-called LIDAR systems have been created that can detect particular molecules tens of kilometers in the atmosphere or even from space. This has permitted the study of the polar ozone hole in the 1990's by A. Carswell and others. Other molecules, such as methane, that significantly contribute to the global greenhouse effect, can also be monitored.

Lasers operating at ultraviolet wavelengths are essential for the lithographic processes used to create computer chips. There continues to be a strong incentive to develop shorter wavelength, even X-ray, lasers in order to produce ever-smaller circuits. Nanostructure devices, containing components such as transistors with dimensions of less than 100 nm, are necessary for faster more powerful computers.

Optical fibers having extremely low attenuation at infrared wavelengths have also been developed. The 1980's and 1990's saw the placement of extensive undersea fibers that have revolutionized telecommunications and now serve as the backbone of the Internet. Fibers have also found uses in medicine for probing the body less invasively, minimizing the effects of surgery and treating disease using photodynamic therapy.

Magnetic resonance imaging (MRI)

Magnetic resonance methods were developed by I Rabi in the 1930's to study the magnetic properties of nuclei, atoms and molecules. This work was furthered by F. Bloch and E. Purcell. In recent decades, this has resulted in techniques that non-invasively image living biological tissues using large spatially varying magnetic fields. In the early 1990's, W. Happer pioneered the use of spin polarized ^{3}He and ^{129}Xe nuclei to obtain high-resolution images of the lungs. These nuclei were polarized using optical pumping techniques first developed by A. Kastler in the

1950's. High power lasers operating at infrared wavelengths permitted the production of macroscopic quantities of polarized alkali atoms. Angular momentum could be exchanged between the alkali valence electron and the noble gas nuclei when the two species form a short lived van der Waals molecule. Polarized targets composed of radioactive nuclei are important for nuclear scattering experiments.

Precision measurements

Atomic Physics has a long record of developing novel techniques for precision measurements. In the 1940's, N. Ramsey developed the so-called separated oscillatory fields method that is now the basis of the cesium atomic clock. Recently, the frequency of the 1s-2s transition in hydrogen has been determined with a precision of 3 parts in 10^{13}. G. Drake has made theoretical advances that permit the accurate determination of nonrelativistic energies of two electron systems. A recent experiment resolved discrepancies in the Li^+ fine structure. Future experiments will test QED and lead to an improved determination of the fine structure constant. A number of experiments by J. Kimble and S. Haroche have also examined cavity QED effects, in which vacuum fluctuations play an important role.

Beginning in the 1970's, work has been done to test the Weinberg-Salam Standard Model of the Electroweak interaction by measuring parity non-conservation (PNC) effects. In 1997, C. Wieman measured PNC in cesium with a precision of 0.35%. This experiment complements results obtained using high energy accelerators.

Accurate atomic and molecular data is critical for progress in a number of disciplines. For example, astrophysics requires accurate measurements of atomic and molecular energy levels, transition probabilities, cross sections and rate coefficients. The same is true for plasmas. An early example is the identification by Edlen of atomic transitions in highly ionized iron and nickel in the spectrum of the solar corona that showed the corona has a temperature of 2×10^6 K.

Quantum cryptography & computing

Quantum entanglement has been known since A. Einstein, B. Podolsky and N. Rosen discussed their famous paradox in 1935. A variety of experiments have confirmed this unusual aspect of quantum mechanics. During the last decade, important possible applications in the fields of communication and even computation have become increasingly hot topics. In 1994, P. Shor showed that quantum information contained in so-called qubits, can in principle be used to process certain computational tasks, such as factoring large numbers into primes, much faster than conventional computing. P. Shor and A. Steane also showed that quantum error correction is possible without needing to learn the state of the qubits. Practical implementation of a quantum computer is difficult but possible schemes involving arrays of ultra-cold trapped ions are being contemplated. The difficult remaining challenge is the rapid decoherence of any system due to collisions and interactions with its surroundings.

Trapping of ions & neutral atoms

A trap isolates an ion or neutral atom from its surroundings and thereby minimizes perturbing collisions. Two very useful ion trap configurations were proposed by F. Penning in the 1930's and W. Paul in the 1950's and have been used to trap a single electron or ion for times as long as weeks. Traps also facilitate the study of radioactive species. Recently, G. Gabrielse was able to trap an antiproton and combine it with a cold positron to create antihydrogen. This will be useful for testing CPT symmetry.

Trapping neutral particles using laser beams was first investigated by A. Ashkin in the 1970's. S. Chu used 3 pairs of counter-propagating laser beams detuned below a transition frequency to achieve optical molasses in the mid 1980's. This was followed by the development of the Magneto Optical Trap (MOT) that today is the workhorse of laser cooling research. Dense clouds of atoms at micro-Kelvin temperatures have enabled the study of collisions between ultra-cold atoms. New cooling mechanisms were discovered, such as polarization gradient cooling by C. Cohen Tannoudji.

During the 1990's, Bose Einstein Condensation (BEC) was observed using magnetic traps and evaporative cooling in Rb (C. Wieman & E. Cornell), Na (W. Ketterle) and Li (E. Cornell). In 1998, D. Kleppner achieved BEC in hydrogen. Work exploring BEC has resulted in an understanding of vortices and the demonstration of the so-called atom laser. Recently, there has been work exploring ultra-cold fermions. L. Hau showed in the late 1990's that light interacting with a BEC can be slowed and even stopped.

Ultrafast lasers

The high power generated by laser pulses allowed the investigation of nonlinear optical phenomena such as frequency doubling in the 1960's. This permitted the generation of visible and ultraviolet laser pulses using infrared laser beams. Pulses of nanosecond duration were first obtained using Q-switching techniques. Later, picosecond pulses were generated by locking the laser modes. In the 1990's, powerful pulses of femtosecond duration were obtained using the technique pioneered by G. Mourou of amplifying frequency-chirped pulses that were later temporally compressed using diffraction gratings. Recently, there has been progress in attaining subfemtosecond pulses by P. Corkum.

These ultra-short pulses are of interest for investigating chemical reactions and generating plasmas including laser fusion. The ultra-high available laser pulse power has opened up an entire new regime for laser material interactions, because the peak laser electric field now exceeds that generated in an atom. Hence, novel ionization effects have been observed.

T. Hänsch has recently shown how a train of femtosecond pulses can generate a so-called comb of well-defined frequencies useful for precision spectroscopy. This permits accurate frequency calibration throughout the visible spectrum eliminating the need for a complicated chain of frequency locked lasers. This will facilitate the use of precision frequency measurements in many laboratories that until now have been the domain of large national standards laboratories.

Looking Ahead

Atomic, molecular and optical physics has a long record of productive research that has changed our outlook on the universe. It has yielded results with important implications for a wide variety of disciplines including astrophysics, condensed matter, nuclear physics, photonics, quantum optics, statistical physics etc. This interdisciplinary tradition is bound to continue with the growing interest in Quantum Information Science. In addition, progress in ultrahigh precision measurements will undoubtedly continue to yield significant results. These demanding experiments will generate technological spin-offs highly relevant for a wide range of applications. It is safe to assume that atomic, molecular and optical physics will remain a hotbed of active research for the foreseeable future.

Plasma Physics

Commission 16

Abhijit Sen

Introduction

While the origins of plasma physics can be traced to the pioneering laboratory studies of oscillations in gaseous discharges in early last century and its initial growth can be linked to the interest of astrophysicists in using it to characterize the state of matter in stars and other astrophysical objects, modern day plasma physics has a very rich and multifaceted character with many fundamental areas of research and a vast number of applications. An apt description of the field is as a *'frontier area of the physics of complex systems'*. This remarkable evolution has come about from a very vigorous and sustained scientific programme of experimental and theoretical studies of plasmas that took place world wide in the second half of the twentieth century. Although a large part of the programme was driven by the goal of attaining controlled thermonuclear fusion in the laboratory, the studies yielded rich dividends in the form of fundamental insights into nonlinear collective phenomena, the understanding of various instabilities and means of controlling them and in general an appreciation of the behaviour of systems that are far from thermodynamic equilibrium.

The effort also sparked new innovations and applications as well as spawning linkages with a large number of other areas of physics and applied mathematics. Today plasma applications range from fusion energy to novel methods of particle acceleration, surface engineering to space propulsion, chemical and biological waste disposal to synthesis of new materials, ultra-thin display panels to pollution control devices, novel stealth technology to new sources of radiation. This list is not exhaustive and continues to grow at a rapid rate.

Likewise at the fundamental science level plasma physics has contributed richly to the understanding of such nonlinear phenomena as chaos, solitons, vortices etc. and has generated much data on turbulence and transport phenomena. It has also given rise to new areas of study like non-neutral plasmas and dusty plasmas, which reveal strong linkages with soft condensed matter studies and strongly coupled systems. Recent laboratory studies with intense short pulse lasers impinging on solid targets have succeeded in producing extremely high material densities and in creating mega gauss magnetic fields. By pushing further along this direction, one is getting close to creating astrophysical conditions in the laboratory and thereby providing a unique opportunity to test some of the early theoretical ideas that helped plasma physics grow up from its infancy.

It is fair to say therefore that plasma physics is today in a very exciting stage of development with many recent accomplishments and the promise of more to come in the near future. In the next few sections we will touch upon some of these advances and future prospects. A good source for looking at updates on various current topics of plasma physics are the various review articles published in the journal *Physics of Plasmas* (an APS publication). In particular the May issues of the past few years carry articles based on the review and invited talks delivered at the Annual meeting of the Plasma Physics Division of APS. Fusion research updates are available on various websites including the ITER site (www.iter.org), the Princeton Plasma Physics Laboratory (www.pppl.gov) and the IAEA site (www.iaea.or.at).

Fusion Research

Fusion energy research has made great strides towards establishing the scientific feasibility of this alternative nuclear energy option which has one of the best potentials for securing the future energy needs of the human society. There are two main approaches to controlled thermonuclear fusion, namely the magnetic confinement fusion (MCF) approach and the inertial confinement fusion (ICF) path. There has been significant advances in both these approaches and ambitious future experiments are in the offing for both programmes.

Magnetically confined plasmas

In the field of magnetically confined plasmas, tokamak experiments like JET, TFTR, JT-60 etc. have obtained spectacular success in achieving high density hot plasmas with good confinement and have thus laid the foundation for the next generation of experiments involving burning plasmas. Over the next decade the major development in the field of fusion research is going to be the construction and operation of ITER – a reactor-scale advanced tokamak device with superconducting magnets designed for long pulse to nearly steady state operation. ITER will have the objective of demonstrating controlled ignition and extended burn of deuterium-tritium plasmas as well as of demonstrating technologies essential to a reactor in an integrated system. It will also perform integrated testing of the high heat flux and nuclear components required to utilize fusion energy for practical purposes. ITER will be a joint international venture between the EU community, Japan, Russia, Canada, the U.S. and China. The recent decision by the U.S. to rejoin ITER and the inclusion of China as an additional member has considerably brightened the prospects of an acclerated pace of development for ITER. It has also injected a surge of excitement in the entire scientific fusion community which is now looking forward to taking this important next step in the advancement of fusion research. Apart from ITER there are significant national programs in the U.S., Europe and Japan as well as in other Asian countries. A new generation of advanced tokamaks with superconducting magnets (but not designed for burning plasmas) are in advanced stages of construction in China, India and Korea. These programs will not only further the scientific understanding of fusion plasmas but they also have the potential of contributing significantly towards the progress and success of ITER through appropriate collaborative ventures.

Inertial fusion energy

There have also been very significant advances in the field of inertial fusion energy (IFE) research using a variety of drivers (lasers, energetic particle beams, z pinch generated x-rays) and target schemes (direct drive, hohlraum, fast ignition etc.). The fast ignition scheme which employs a combination of a direct drive for compressing the pellet and an independent short pulse high power (petawatt) laser to ignite a spark in the central core is a recent innovation which has made a significant impact on the potentialities of developing an IFE reactor. There has also been some remarkable success in the generation of intense x-rays from imploding arrays of z pinches which has generated a great deal of excitement in the field. Among the major future experiments the National Ignition Facility is presently under construction at the Lawrence Livermore Laboratory.

Alternative fusion devices

Apart from these main stream programs in fusion, there is also significant effort in investigating alternative fusion devices which might have a better long term prospect as a reactor configuration. Notable among such devices are the stellarator which generates all components of its equilibrium magnetic fields through external coils (in contrast to tokamaks where a plasma current is excited to generate one of the components) and therefore can be run in a steady state. Spherical tokamaks which are a variant of present day tokamaks but with a lower aspect ratio appear to have better confinement properties. A novel configuration of a dipole magnetic field (created with a levitated current conductor) that is inspired by the earth's magnetic field configuration is being investigated for its potentialy good plasma stability properties.

Space and Astrophysical Plasmas

Space plasma physics

The field of space plasma physics has a history going back to early ground based measurements of ionospheric parameters and radio wave propagation experiments. In recent times the field has grown into a vigorous discipline on a global scale with extremely sophisticated experimental programs involving rocket launches and multi-satellite observations.

The principal fields of investigation comprise:

- study of the Sun's interior using helio-seismology techniques
- dynamics of the solar wind and its interaction with the earth's magnetosphere and ionosphere
- solar flares – their composition, dynamics and statistics (with an eye to prediction)
- magnetospheric disturbances (storms, sub-storms and their prediction)
- waves in the ionosphere and magnetosphere, and their interaction with particles
- generation and dynamics of the aurora, cometary plasmas etc.

The present trend is to adopt an integrated approach, treating the sun-earth system as a closely coupled entity with strong correlations between the solar wind plasma, the magnetosphere and the ionospheric responses. This has given rise to programs like *space weather* studies, a terminology that provides a conceptual framework for analyzing and predicting events like sub-storms for example. The vast amount of data (from satellite observations) and the wide range of space and time scales offer a rich testing ground for theoretical plasma modeling and interpretation. This has been an active and productive area of space plasma physics research involving detailed studies of nonlinear coherent wave structures as well as broadband turbulent spectra in the ionosphere and magnetosphere regions, sheared flow structures in the solar wind and reconnection phenomena in the solar flares as well as in the magnetosphere.

Plasma astrophysics

Despite the very early interest of astrophysicists in the use of plasmas to characterize stellar matter, the field of plasma astrophysics is relatively young. Its recent development is tied to the availability of powerful spacecraft based astronomical observations and an increased awareness of the complex and rich behaviour of plasmas. For example, the recognition of the significant role of electrodynamics in the evolution of a cloud of charged dust has caused a paradigm shift in the study of galaxy dynamics, star formation and planetary structures. The insights developed in the field of dusty plasmas are also yielding rich dividends in understanding novel astrophysical phenomena like the emission of x-rays from comets and galaxy clusters. Plasma physics is also playing an increasingly important role in the attempts to understand such important astrophysical problems as the origin of cosmical magnetic fields, the origin and structure of relativistic jets and the nature of missing matter in the universe.

Fundamental Laboratory Studies

Apart from the major experimental findings in the fusion devices, which have furthered our understanding of such matters as plasma stability, transport and control, there have been a host of exciting and novel basic plasma experiments in non-fusion devices that have truly broadened and enriched the scope of plasma physics. In fact many of these experimental studies have given rise to very active new sub fields in plasma physics.

Non-neutral plasmas

Non-neutral plasmas is one such area, which in the past decade has produced a large amount of exciting new physics. These plasmas have a predominance of one charged species (positive or negative) and can be confined for very long periods in unique traps with the help of a magnetic field and their own inherent electrostatic field. They can be cooled to yield crystal like structures and have provided fundamental insights into the formation of non-linear vortex structures, vortex merging and other pattern formation processes. These plasmas are in thermodynamic equilibrium and hence their properties and configurations have been analysed using very general theoretical principles – something that is very difficult to do for ordinary plasmas. Recent controlled experiments measuring asymmetry-induced transport rates provide valuable clues for understanding anomalous transport induced by magnetic field fluctuations.

Dusty plasmas

The physics of dusty plasmas, which has seen a phenomenal growth in the last decade, continues to explore new grounds. A host of laboratory experiments on crystal formation/melting and experiments carried out in a micro-gravity environment in spacecraft have provided new insights into the behaviour of strongly coupled systems which can be useful in other areas of physics such as colloidal physics and liquid metals. As a system where charge is a dynamical quantity (the dust charge fluctuates with time) dusty plasmas exhibit unique properties and new sources of free energy to drive instabilities. Their study has also proved very useful in applications such as plasma processing and microprocessor manufacturing.

Terawatt laser pulses

The availability of short duration intense laser pulses in the energy range of terawatts and beyond has opened up new avenues of application and fundamental research areas other than laser fusion. One such application is in the acceleration of particles using intense plasma waves excited as wake-fields by the propagation of the laser pulses through matter. Experiments are already in progress at SLAC, USA, to use this technique to boost the energy of LINAC accelerated beams of electrons and positrons to 100 GeV levels and to study their collision. If successful this will extend the reach of SLAC in its quest for the Higgs boson. Another significant new area is the study of extremely high density matter and the creation of ultra-high magnetic fields brought about by the interaction of intense laser pulses with solid targets. The availability of inexpensive table top terawatt lasers has made it possible for many smaller laboratories (including those in developing countries) to undertake novel experiments of a fundamental nature at the frontiers of physics.

Industrial Plasmas

As mentioned in the introduction the practical applications of plasmas span a phenomenally wide range touching upon nearly all major areas of industry and technology. In contrast to fusion plasmas, the plasmas employed for industrial applications are usually of lower densities, lower temperatures and are often partially ionized. A study of their basic properties and the nature of their interaction with solid materials constitutes an important area of investigation. The number of research scientists engaged in the study of industrial plasmas has truly exploded in the past decade largely due to the interdisciplinary nature of the subject and to the handsome commercial payoffs. One of the heartening new directions in this field is the attempt to harness plasma processing for creating a cleaner and better environment to live in and to aid in pursuing a sustainable and healthy development of our society.

Looking Ahead

Given the special multi-faceted character of the field and its present state of vigour, plasma physics can be expected to make significant advances in several directions in the near future. The grand challenge problem in the field has of course always been that of attaining controlled thermonuclear fusion for a new source of nuclear energy – a problem that remains technically unsolved to this day. However the future looks promising, given recent developments regarding ITER and technological advances in other fusion schemes.

At the fundamental level there are still several interesting physics problems that have defied complete solution over many years and continue to attract the attention of both theoretical and experimental investigators. One such problem concerns the creation of currents or annihilation of magnetic fields in the process known as *magnetic reconnection***.** Although widely studied and observed in the context of space plasma and laboratory experiments, the basic mechanism of reconnection is still not fully understood – particularly the physics of the so called fast reconnection process. Recently there has been a great deal of renewed interest in this problem thanks to large-scale numerical simulation efforts that have revealed new insights involving wave dispersion activities at the electron scale lengths.

Plasma turbulence and anomalous transport have been perennial topics of research in plasma physics since they are deemed to be at the heart of understanding the behaviour of confined plasmas in fusion devices. Investigations have benefited from new paradigms based on low dimensional nonlinear dynamics models and have made some important advances in the interpretation of experimental data from tokamaks and other high temperature magnetically confined plasmas. It is expected that this activity will continue to grow leading to further improved physical insights.

One of the major limitations in arriving at a comprehensive understanding of complex plasma behaviour is the lack of fundamental guiding principles for dealing with driven systems that are far from thermodynamic equilibria. There is some concern that present theoretical descriptions of confined plasmas that are based on perturbations around thermal equilibria may be seriously flawed. But there is also hope that with the significant advances being made in characterizing and controlling the behaviour of plasmas we will pick up valuable clues for developing a sounder and more complete theoretical description.

Quantum Electronics

Commission 17

Hans-A. Bachor
and
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Introduction

The laser opened a new area of physics and technology in the early 1960's. It gave access to new optical phenomena, all based on the process of stimulated emission. Initially a curiosity, the laser has rapidly led to many new applications ranging from precision measurements to communications, and from welding to surgery. Their many varied applications have become an integral part of our daily lives.

The laser itself developed rapidly. The early systems were mainly based on gas laser technology, especially the widespread He-Ne, Argon and Krypton lasers for scientific and medical work, and the CO_2 laser for engineering applications. These lasers are reliable but very inefficient and costly in their operation. The last 10 years have seen a complete change in the technology based on all solid-state technology. The semiconductor diode laser appeared initially as an alternative for low power (milliwatt) operation in the red and near infrared regime. This compact laser combines simplicity, small size and low cost.

More recently the quantum cascade laser has extended the availability of compact lasers further into the infrared, out to wavelengths as long as 100 microns. This extended wavelength range spans many of the interesting molecular vibrational modes, resulting in a major new area of quantum cascade laser applications in environmental gas monitoring. Compact, low cost lasers in the red, and more recently in the blue, have become essential components of all optical storage technologies, in particular CDs and DVDs for music and data storage. The requirements for all of these applications require the good beam quality, single mode characteristic, low cost and reliability that can now be provided by many types of semiconductor lasers.

Photonics and Optical Communications

Semiconductor lasers are now widely used in communication systems. Just as electrical signals are controlled and manipulated by electronic devices, so also it is now possible to control and manipulate light signals with optical devices, giving rise to the field of photonics. Photonics technology forms the backbone of the extensive optical communications networks spreading around the globe. Its success initially derived from the development of low-loss single mode optical fibres that transmit optical signals over large distances, e.g. across the oceans. The modulated laser signal is transmitted through the optical fibre and manipulated by optically active signal splitters, combiners and amplifiers.

A major breakthrough in the early 1990s was the development of erbium-doped fibre amplifier, used to compensate for the large losses over hundreds of kilometers of optical fibre. These amplifiers along with optical modulators with speeds as high as 40Gb/s, allow higher data rates over distances up to 4000km. The capacity of these systems has been increased a hundredfold by using wavelength division multiplexing of hundreds of separate wavelength channels in order to achieve staggering total capacities well over a 10^{12} bits/second (Tb/s) on a single fibre. The clever use of the nonlinear properties of fibres through specially shaped pulses, called optical solitons, can increase the capacity and reach of these systems even further.

Information processing at large routers in the Internet and in networks of computers is limited by the electrical interconnects that are presently used. The routers for communication networks that route billions of Internet information packets are approaching throughputs of a terabit/second. The electrical limits are fundamental in nature and limit the interconnect data rates to less than 20Gb/s. Optical interconnects do not suffer from these fundamental limits and will come into more frequent use as the data capacity needs intensify and the cost of integrated photonics circuits continue to decrease. Vertical Cavity Surface Emitting Lasers are now available in large arrays for interconnecting back planes of computers and large electronic routers.

High Power Lasers

Semiconductor lasers have been developed for high power continuous wave operation. The available power per laser increases every year. Diode lasers with powers of hundreds of watts are available. These lasers are ideally suited as optical pump sources for solid state laser systems such as the Nd:YAG laser. This laser operates at a wavelength of 1000 nm. It has an excellent beam quality, very high efficiency and small size. Its high power of more than 100 watts makes it perfectly suited for precision machining. Presently these lasers are replacing the old CO_2 technology in many engineering applications. They are superior in their precision and versatility and are more efficient. Semiconductor lasers are also being used to pump optical fibres to yield optical gain throughout the Raman shifted wavelengths in silica. This provides a tunable optical amplifier with distributed gain, of great value to optical communications systems. These new amplifiers eliminate the restricted wavelength operating range of erbium doped fibre amplifiers and decrease the effective system noise.

The interaction of laser light with nonlinear optical materials leads to a wide variety of new phenomena. The interaction is nonlinear in that the material emits light at a frequency different from the incident signal. For example, frequency doublers emit light at twice the input frequency, and optical parametric oscillators emit light with a frequency equal to the sum or difference of two input signals. This effect can be used to amplify a very weak signal by mixing it with a strong signal. The quality and utility of nonlinear materials have improved dramatically in the last few years, greatly expanding the available wavelength range of solid-state lasers. For example, the frequency-doubled Nd:YAG laser at 500 nm is now a low-cost alternative to the Ar ion laser. Combined with optical parametric oscillators, they provide continuously variable wavelengths both below and above 1000 nm. New materials, such as periodically poled lithium niobate (PPLN), have increased the efficiencies of these wavelength conversions and promise simple and easily tuneable systems.

Very high power lasers with intensities in the petawatt range are revolutionizing the study of nonlinear phenomena and providing new sources of X-rays through harmonic generation. At very high laser intensities the electric and magnetic fields of the light are stronger than atomic and molecular fields so that they dominate the dynamics of electrons in the light beam. This leads to interesting new physics and light generation phenomena. At the highest intensities quantum electrodynamics comes into play. Scattering of light by light, one of the weakest interactions in nature, can now be studied using high intensity lasers. There is also a wide range of plasma generation and laser accelerator physics that are being explored with high intensity lasers.

Ultra-short Laser Pulses

Enormous progress has been made in shortening the length of laser pulses. While in the 1980s pulses shorter than a nanosecond were rare, it is now possible routinely to reach the absolute limit of a few femtoseconds. This corresponds to only a few optical cycles. In order to achieve this limit, new laser media had to be developed that have an extremely broad gain spectrum. In particular the material Ti-sapphire brought a breakthrough. In addition, nonlinear pulse compression techniques, such as nonlinear Kerr mirrors, were invented to further shorten the pulses. Femtosecond pulses are now readily available, allowing the probing of extremely fast biological and chemical processes. Reactions can be observed with an unprecedented time resolution. A parallel development will be the use of pico- and femto-second pulses for the shaping and drilling of materials. Since the material has no time to melt, the fast pulses create perfect edges and holes. Damage centers and photoinduced chemistry may result in the ability to write patterns in glasses or photoresists. In this way ultra-short pulses will find their way into practical engineering. At the edge of research in ultra-short pulses is the generation of atto-second laser pulses using high power lasers that produce short UV and X-ray pulses.

Quantum Optical Processes

Even the simplest laser is based on quantum optical processes. It was known from the beginning that this leads to quantum fluctuations and thus to limitations in the precision of the frequency of laser light. The quantum mechanical intensity fluctuations (shot noise) and the intrinsic laser linewidth are consequences of quantum optics and the uncertainty principle. Since the mid 1980s it has been possible to generate alternative types of light (called squeezed light) that allow an improvement of the measurement of one property of a laser beam, while sacrificing a precise knowledge of the complementary property. Such squeezed light is now available routinely and, apart from fundamental tests of quantum optical principles, can be used to improve the sensitivity of optical sensors beyond the standard quantum limit. Related are ideas for quantum non-demolition measurements, such as counting the number of photons in a cavity without destroying them by absorption in a detector. The use of nonlinear processes can achieve optical measurements without the quantum mechanical disruption of the system, provided that information is lost about the complementary property of the system (in this case, the phase of the light waves).

Laser interferometers have recently been built for the detection of the gravitational waves resulting from cosmological events such as supernovas or the collapse of stars. To obtain the necessary sensitivity, these kilometer-sized instruments have to monitor the position of mirrors with the precision of optical wavelengths, and in addition to measure displacements as small as 10^{-17} meters. The above techniques of quantum optics will give a sensitivity that will ultimately be limited only by the quantum noise of the light.

Single photons

The quantum properties of individual photons continue to be interesting. Since photons have spin 1, they are bosons obeying Bose-Einstein statistics. Because of the quantum correlations this introduces amongst the photons, the detection of one photon affects the properties of the remaining light. As a consequence, the effect of a device that splits a photon beam into two branches is considerably different from that of a junction in a wire that carries fermionic electrons. This can be exploited by encoding information directly onto the properties of the photons, for example by modifying their state of polarisation. Any loss of photons from the signal then has a measurable effect on the remaining light. It therefore becomes impossible, at least in principle, for an intruder to tap information without leaving a trace. This idea for secure quantum cryptography has recently found a very rapid development from theoretical concepts to practical systems. Photon sources have now been demonstrated that can emit single photons on demand. These micro-resonator devices have relatively high efficiency and will further enhance quantum cryptographic technology.

Future quantum optics applications may include sytems to transmit data complete with all their quantum information (optical teleportation), and to use light as the transmitting medium in computers based on quantum states. Quantum computers could be used to simulate large quantum systems or as computers that exceed the performance of classical computers for some tasks. A number of physical systems are being explored to achieve quantum computation. An example from the field of quantum electronics is the development of quantum computational techniques using linear optical components and detection of light. The number of optical elements required increases only polynomially with the number of qubits being processed.

Experimental implementation of these ideas is in progress; however the very high detection efficiencies, efficient single photon sources and very low optical losses required are a tremendous challenge for the future. It is possible to generate more complicated states of correlated photon beams using the optical parametric oscillator. Separate beams emerge, but the photons in the beams are strongly correlated, forming an “entangled state” of light. Because of quantum correlations between photons, measurements of photons in one beam allow conclusions to be drawn about photons in the other beam.

These beams have also been used to test some of the fundamental assumptions of quantum mechanics. For example, the indeterminacy of quantum mechanics could be removed by a more fundamental underlying theory containing local “hidden variables” which determine uniquely the outcome of experiments. Based on an experiment originally proposed by Einstein, Podolski and Rosen, Bell derived a set of inequalities that must be satisfied if local hidden variables exist. However, measurements with photon beams show that Bell's inequalities are violated, thereby ruling out local hidden variable theories. These optical experiments are now the best tests of such foundational principles of quantum mechanics.

Laser - Atom Interactions

Lasers allow the selective interaction with atoms in specific excited states since they can be tuned to a specific transition of a particular atom or molecule. This ability has led to many spectroscopic applications in chemistry. These include extremely sensitive analytical and diagnostic techniques, and the ability to monitor chemical concentrations. A great advantage is that the monitoring can be done remotely by analysing the light scattered back from a laser beam. This so-called LIDAR, in analogy to RADAR, is increasingly used as a tool for the detection of pollution in the atmosphere and for environmental monitoring.

Tuned laser light can also be used to influence or "coherently control" chemical reactions. Coherent control will undoubtedly have significant applications to the industrial processing of chemicals. Already the use of many-photon ionisation for isotope separation is a well-established technique in the current technology for the enrichment of nuclear fuel. The phase properties of light are also being used to control and optimise high harmonic generation and physical properties of semiconductors.

The use of coherent light has led to more complex interactions where the atom is coherently driven. This allows the use of special pulses to completely invert the atom system and to observe coherent phenomena such as photon echoes and optical nutation. The analogy to NMR is very strong and it is possible to build systems that show a variety of coherent effects.

In addition, the interaction between light and atoms changes the atomic momentum. Suitably detuned laser beams can be used to decelerate and even stop atoms. This is equivalent to cooling the atoms, and temperatures as low as micro Kelvins have been achieved. In combination with magnetic fields, it is possible to trap large number of cold atoms. These slow atoms exhibit clearly the wave-like nature associated with large deBroglie wavelengths. Many forms of atom diffraction by both material structures and periodic light fields have been demonstrated. Atom interferometry, which uses a coherent superposition of de Broglie waves, is now a mature technique that can be used for detailed measurements of atomic properties. A potential application is the precision measurement of variations in gravity from point to point on the earth. These gravity gradients are of great interest to geologists in locating mineral deposits and mapping other geological features of the earth.

Since 1995 it has been possible to cool atoms even further and to observe the influence of the bosonic nature of certain atoms. In particular, these atoms can form a Bose-Einstein condensate in which all the atoms enter the same coherent quantum state. The system is then represented by one macroscopic wave function for many atoms. The properties of these condensates are intriguing because they exhibit the quantum nature of matter on a macroscopic level. They have the properties of a superfluid, but with a density low enough that the interactions between the atoms are still weak. For this reason, it is possible to study theoretically the quantised vortices and quantised excitations of these novel systems. One of the most exciting recent advances is the formation of a coherent beam of atoms from the Bose-Einstein condensate to form what amounts to an atom laser—the atomic analogue of an optical laser. This field is still in its infancy, and the potential applications to microelectronics, micro-machining and atomic holography remain to be developed.

The interaction of light with atoms and molecules is making important contributions to biology and medicine. For example, single molecule fluorescence techniques are being used to observe conformal changes in biological molecules. Single living cells can be trapped and manipulated with infrared beams. The Raman spectra of these trapped cells are obtained to give biochemical composition for real time identification and analysis.

Looking Ahead

This overview shows that laser physics and optical technology have made great progress in many parallel directions. All properties of laser light have been dramatically improved and there is no end in sight. At the same time lasers have become simpler, cheaper and more reliable. Today’s applications affect every aspect of our lives and span many areas of technology. Optical technologies complement and sometimes replace conventional electronics. Fibre optics and semiconductor lasers have made a stunning transformation of the communications industry to form an ultra-high capacity global network, including of course, the Internet. Lasers will also play an increasing role in engineering and the chemical industry. Enhanced efficiency detectors may soon make solar energy a significant part of the economy. High efficiency organic light-emitting diodes promise to revolutionize displays of all types and lighting in many applications.

The intrinsic and unique quantum properties of light will lead to new fundamental tests of physics and to further investigations of the macroscopic manifestations of quantum mechanics. The potential applications of just one very recent development, the atom laser, are as difficult to predict as they were for the optical laser when it was first invented, but it is certain to have an important impact in the future. One day we may develop quantum computers and simulation devices that will yet again transform our world.

Mathematical Physics

Commission 18

David J. Rowe[1]

Introduction

Mathematical physics spans every sub-field of physics. Its aim is to apply the most powerful mathematical techniques available to the formulation and solution of physical problems. Mathematics is the language of theoretical physics and, like other languages, it provides a means of organising thought and expressing ideas in a precise and consistent manner. Physicists who are articulate in the language of mathematics have made great contributions to the modern formulations of physics. The list is long and includes such names as Newton, Maxwell, Einstein, Schrödinger, Heisenberg, Weyl, Wigner and Dirac.

Mathematical physics is both interdisciplinary and in the mainstream of physics. Whereas experimental physicists make use of engineering and electronics techniques in their investigations, theoretical physicists make extensive use of mathematics. What is special about mathematical physicists is that they communicate and interact with both physicists and mathematicians. Some address mathematical problems that arise in physics. Others are primarily theoretical physicists who invoke mathematical methods in the interpretation of physical phenomena, e.g., by the development and solution of physical models. What they have in common is an interest in understanding the exciting systems and mathematical challenges that physics uncovers. The results advance physics as a whole and make contributions to mathematics and new technology. Physics is not an isolated activity. It both feeds on and enriches many related areas.

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The value of strong interactions between scientists and mathematicians is underscored by the fact that many scientific revolutions have been linked to corresponding developments in mathematics. In this short essay, it is possible to mention only a few examples.

General Relativity: the Theory of Gravity

In his general theory of relativity, Einstein introduced the revolutionary idea that gravity could be understood as a warping of space-time. This science fiction-like idea emerged as a logical consequence of a simple principle: the principle of equivalence.

For centuries, the study of geometry was restricted to flat spaces. Then, as a result of investigating the consequences of discarding Euclid's axiom about parallel lines never meeting, new curved-space geometries were discovered. These provided a natural, and even simple, language for the conceptually difficult task of describing the curvature of four-dimensional space-time.

General relativity was a theory ahead of its time due to a paucity of experimental evidence. Even by mid-century, it remained unclear if the gravitational waves implied by the linear approximation to general relativity were real and the notion of what we now call a black hole was dismissed as an absurdity.

Then, under the stimulus of advances in astronomy and cosmology, general relativity entered a golden age. Penrose and Hawking applied global techniques to the causal structure of space-time and were able to prove very generally that singularities are inevitable at the endpoint of gravitational collapse and the big bang. Within a few years, understanding of gravitational collapse and black holes progressed from its inchoate beginnings to a sophisticated discipline comparable in elegance, rigour and generality to thermodynamics, a subject that it turned out unexpectedly to resemble.

Insight into the origin of this resemblance came in 1974 with Hawking's discovery that, at the quantum level, black holes are thermodynamic black bodies with characteristic temperatures. Many see this result as a clue to some future synthesis of general relativity, quantum theory and thermodynamics. Its exact nature even now remains a mystery.

A new discipline, numerical relativity, has mushroomed in the last decade thanks to advances in digital technology and refinements in the numerical integration of hyperbolic differential equations. Within the next decade it should become possible to compute the pattern of gravitational waves emitted from a pair of in-spiralling black holes (the "binary black hole grand challenge") and to link these predictions with observational results from several gravitational-wave detectors now going on line.

By geometrising the gravitational field, general relativity introduced a new viewpoint: the aim of describing all the basic forces and elementary particles in terms of some structure more general than Riemannian geometry. Non-commutative geometry, twistors and loop variables all represent gropings in this direction. The most actively pursued program is superstring (or M-) theory. It has been said that string theory is a part of twenty-first century physics that fell by chance into the twentieth century, before the appropriate mathematics had been developed. M-theory calls on the full arsenal of modern mathematics—topology, homotopy, Calabi-Yau spaces, Riemann surfaces, moduli spaces, Kac-Moody algebras, and so on, a symbiosis that can only get closer as the field develops.

Quantum Mechanics

Quantum mechanics has long been a subject of intense investigation in both physics and mathematics. The first steps towards a quantum theory came from the pioneering work of physicists such as Planck, Einstein, and Bohr. The formulation of quantum mechanics, by Heisenberg, Schrödinger, Born, Dirac and others as the fundamental theory of non-relativistic matter, invoked abstract mathematics: linear algebra, infinite-dimensional complex (Hilbert) spaces, non-commmutative algebra, and group theory. Quantum mechanics became a sub-field of mathematics in 1949 with its axiomatic formulation by von Neumann.

Objects like atoms are characterized in quantum mechanics by sets of wave functions and energies, which (in the non-relativistic case) satisfy a differential equation, called the Schrödinger equation. However, following initial success in deriving the energy levels of the hydrogen atom, it soon became clear that exact solutions of the Schrödinger equation are possible only for systems with few particles or for models with special symmetries. Approximate solutions are obtained by separating the problem into two parts such that one part has simple properties and its Schrödinger equation is exactly solvable. It is then assumed that the wave functions for the complete problem can be expanded in terms of the known solutions for the simpler problem. Moreover, by ordering the solutions of the simple equation by increasing energy, one can obtain a sequence of approximations to the full problem, which, if they converge, give accurate results – as found, for example, in numerous applications to atomic physics.

In considering the validity of such an approach, mathematical physicists investigate the properties of differential equations and the completeness of solutions to the Schrödinger equation. A set of wave functions is said to be complete if an arbitrary wave function can be expanded in terms of them. However, completeness is hard to prove for general many-particle systems for which some of the particles may be unbound to the others. It has recently been proved under special conditions.

Fortunately for physics, the physical world has a hierarchical structure that enables condensed matter to be explained in terms of atoms and molecules, which in turn are explained in terms of nuclei and electrons, etc. This stratification suggests the construction of sequences of models in which the building blocks of one model are the objects of study of a more microscopic model. Furthermore, models of complex systems can be constructed, with restricted degrees of freedom, to explain particular phenomena. Useful models are ones with clear mathematical structures, which enable the properties of a model to be inferred from basic assumptions (axioms). Enormous progress has made during the past twenty years using dynamical symmetry (group theory) for such purposes.

Group Theory; Dynamical Systems

In physics, group theory provides a mathematical formalism to classify and study the symmetry properties of a system. The fundamental books of Weyl and Wigner on the theory of groups and quantum mechanics established group theory as an essential tool of quantum mechanics. Between 1928 and 1938, Wigner (sometimes with students) introduced time reversal invariance and made applications to atomic and molecular spectra, properties of crystals and their energy bands, nuclear structure and spectroscopy. In 1929, Bethe introduced the use of finite crystal point groups to the analysis of degeneracies of quantum states in crystals; this led to crystal field theory which in turn played a fundamental role in the design of lasers and fibre-optic communication systems. Of particular significance for later developments was Wigner's 1930 paper on vibrational spectra of molecules. This paper introduced to physics the "Frobenius method", later called "the method of induced representations". In 1938, Wigner used this method to construct all irreducible unitary representations of the Poincaré group for positive mass particles in what is recognised to be a landmark of twentieth century physics. In the forties, Racah laid the foundations for calculating the properties of many-particle quantum systems such as occur in atoms, nuclei and subatomic particles.

The method of induced representations is now a widely used tool in both mathematics and physics, with applications, for example, to the theory of crystal space groups and rotations of molecules and nuclei. Fundamental applications to the theory of Fermi surfaces and the related band structures that underlie the theory of conductors (and semiconductors) have been made in recent years. The theory of induced representations has also been applied extensively in nuclear and other areas of mathematical physics within the framework of coherent-state theory.

An example of a subject investigated initially for purely mathematical reasons is that of Penrose tiling. The problem was to tile a plane aperiodically with tiles of at most two shapes. Solutions to this problem were later invoked to explain the so-called "quasi-crystals" observed in 1984. Such crystals are now known to be quasi-periodic and described by functions with a number of periods greater than the dimension of space.

The last twenty-five years has seen an explosion of uses of dynamical groups and spectrum generating algebras for the construction and solution of models. Advances have followed the recognition that solvable models can usually be expressed in algebraic terms so that the powerful methods of group representation theory can be exploited in their solution. The idea goes back (at least) to a famous 1946 paper of Tomonaga. Modern developments followed the SU(3) model of nuclear rotations and the quark model of baryons and mesons.

That the theory of Lie groups should apply to quantum mechanical problems is natural, considering the fact that Sophus Lie founded his theory for the purpose of solving differential equations like the Schrödinger equation. However, in contrast to the Schrödinger equation, most of the other basic equations of physics are non-linear (e.g., Einstein equations, Yang-Mills equations, Navier-Stokes equations). This has inspired many developments during the last 30 years on the solution of non-linear differential equations. Technical tools have been provided by advances in computer science, i.e. algebraic computing.

A crucial development was the discovery of "solitons", i.e., waves that are stable with respect to mutual collisions. Solitons were found in numerical simulations and, subsequently, for a large class of non-linear equations, now called non-linear integrable partial differential equations. They are widespread in nature. In oceans they are destructive and can interfere with oil drilling. In optical fibres they are used to carry undistorted information.

Another important discovery in non-linear mathematical physics is that of "deterministic chaos". It was shown that systems governed by simple non-linear differential equations, that should be entirely deterministic, actually behave in an unpredictable way over large time periods. The reason for this “non-integrable” behaviour is a very sensitive (exponential in time) dependence of the solutions on the initial data. An example of such a chaotic system is given by the Lorenz equations from meteorology. Deterministic chaos is observed in virtually all complex non-linear systems. Integrable (soliton) systems typically have infinitely many symmetries and a very simple singularity structure. Chaotic ones have little symmetry and exceedingly complicated singularity structures.

Many-Body Theory; Statistical Physics

Many-body theory and statistical physics are attempts to describe the properties of extended matter, which might comprise as many as 10^{24} atoms per cubic centimetre and for which a detailed microscopic description is inconceivable. A central idea of many-body theory is to make expansions that become exact as the inverse of the particle number approaches zero. In statistical physics the behaviour of particles is described by probability theory. In equilibrium statistical mechanics the assumption is that all states of the particles in some fixed volume with a fixed number of particles and fixed energy are equally likely.

A fascinating challenge is to understand and predict properties of phase transitions, such as melting and boiling. A classic discovery of Onsager was that it is possible to find an exact solution for a two-dimensional (Ising) model of a phase transition. Recent discoveries have placed this discovery in a much larger context, relating it to conformal symmetry of two-dimensional systems. Another development is the renormalisation group, whose applications to statistical mechanics were promoted by such pioneers as Ken Wilson. This is an attempt to explain certain universal properties of phase transitions. In particular, it is helping to explain the extraordinary similarities (critical exponents) of phase transitions in very different systems.

Many-body theory and statistical mechanics take on new features when combined with quantum mechanics. In particular, the notion of equally-likely states has to be revised for systems of identical particles. There are two kinds of elementary particle: bosons and fermions. Quantum mechanical wave functions are symmetric under exchange of coordinates of a pair of bosons and antisymmetric under exchange of fermions. A consequence of this is that two fermions are precluded from occupying the same state; this is the exclusion principle.

One of the early predictions for bosons was Bose-Einstein condensation (BEC), a phenomenon that has recently been observed. BEC raises many interesting questions; e.g. does it depend on the symmetry under exchange of bosons or on an absence of the exclusion principle? The observation of BEC for a system of hydrogen atoms would appear to favour the former. This is because a hydrogen atom is not quite a boson; it is a pair of fermions (a proton and an electron). Thus, while hydrogen atoms are symmetric under exchange, they also obey an exclusion principle. The evidence is that correlated pairs of fermions behave in suitable limits as bosons. A dramatic example of this is superconductivity in which electrons combine to form Cooper pairs. Thus, whereas systems of bosons form superfluids at low temperatures, electrons in metals form superconductors.

These phenomena are among the few manifestations of quantum mechanics at a macroscopic level. They have many fascinating properties and commercial applications; they are also of intense mathematical interest. For example, much is learned from them about the nature of phase transitions. Some insights into the nature of superconductivity and the approach to a phase transition in a finite many-body system come from nuclear physics. The suppression of superconductivity in rotating nuclei with increasing angular momentum is particularly relevant because of the mathematical similarity between Coriolis forces and magnetic fields. The problem of explaining superconductivity at a high critical temperature is a current challenge.

Often matter is not in equilibrium. There is a flow of particles or of energy, and often the flow itself is changing in time. This requires a non-equilibrium statistical mechanics. Currently non-equilibrium statistical mechanics is beginning to provide an understanding of the limits of cruder theories of nature, such as macroscopic theories of fluids or plasmas.

Symplectic Geometry; Symplectic Groups

Loosely speaking, symplectic geometry is the mathematics of phase spaces. These are the basic spaces of classical mechanics, with coordinates given by the positions and momenta of particles. They also provide the appropriate framework for the quantisation of classical systems. Because of its practical applications, symplectic geometry is an area where the interaction between mathematics and physics is especially close.

An example is the study of the stability of the solar system. This is a system for which all the relevant laws of physics are known to great precision. However, working out the consequences of those laws is nontrivial. One can integrate the equations of motion step by step to obtain accurate predictions of planetary orbits over time periods of billions of years. Yet it remains an open question as to whether the solar system is bound or not; i.e. if a planet might not some day in the future acquire enough energy to leave the system.

Another example is the recent development showing how the motion of an ideal fluid can be described. This has led to important applications in geophysical fluid dynamics as well as in fluid mechanics.

A fundamental concept of symplectic geometry is the so-called “symplectic form”. This is a concept that expresses the pairing of position and momenta as “canonical variables”. The fundamental relationship between pairs of canonical variables gives rise to the famous conservation law, known as Liouville’s theorem, for the volume of phase space occupied by a system of particles. The content of the theorem is illustrated by the observation that, without removing energy from a system of particles, it is impossible to squeeze them into in a small space by application of a force field without giving them large momenta. A related implication for quantum mechanics is the uncertainty principle; one cannot simultaneously measure the values of a pair of canonical variables, like position and momentum, to better than prescribed limits of accuracy.

Closely linked to symplectic geometry and equally important is the group theory of linear canonical (i.e., symplectic) transformations. These groups have been widely used, for example, for the description of electromagnetic and particle beam optics. An optical lens or a magnetic focusing device corresponds to an element of a group of symplectic transformations. Thus, the effect of a sequence of lenses or focusing devices can be inferred by the standard mathematical rules for composition of group elements. By such means, the aberration effects of optical and particle-beam transport systems can be computed and corrections made to a high level of accuracy. The development of symplectic techniques has revolutionised the design of optical systems.

During the past thirty years, the links between classical and quantum mechanics and the routes from one to the other have been explored in great depth using the methods of “geometric quantisation”. Geometrical quantisation is a series of methods which associate unitary group representations (“quantum mechanics”) to certain Hamiltonian group actions (“classical mechanics”). The approach takes advantage of insights gained in physics to advance the mathematical study of group representations. It has also been used effectively to study the quantisation of collective models, notably in nuclear physics.

Coherent States; Optics

Coherent states are used in many areas of physics and mathematics. They were first defined by Schrödinger in 1926 as minimal uncertainty wave packets and used to exhibit the classical behaviour of a harmonic oscillator within the framework of quantum mechanics. Because of this special "classical behaviour" of quantum harmonic oscillators, coherent states have been used widely, following an influential 1963 paper of Glauber, for describing the coherence properties of electromagnetic radiation; e.g., the light emitted by a laser.

Analysis of optical systems in terms of coherent states is appropriate because, while much of optics can be described by classical theory, some problems require a quantum treatment. Coherent state theory lets one have it both ways. This is particularly important for the theory of quantum interferometers. An interferometer superposes optical beams and the resultant interference effects can be used to infer information about the beams, such as their wavelengths, or about the interferometer, such as the relative phase shift between paths of the interferometer. The minimal wave-packet character of coherent states makes them useful for considering the quantum limits to phase measurements in interferometry. Quantum effects become important for light beams of finite photon number. Interferometers can also be constructed for matter waves, including neutrons and neutral atoms.

Coherent states were generalised and given group theoretical definitions around 1972. Since that time, the mathematical analysis, generalisation, and ever widening set of applications for coherent states has become a field of study in its own right. For example, it has become possible to apply the powerful methods of group representation theory to the analysis of multi-path interferometers. Coherent states associated with a vast number of transformation groups have been constructed; they have been generalised further to quantum groups and even to no groups at all.

Coherent state methods have proved invaluable for constructing representations of Lie groups in the forms needed for applications in many-body quantum mechanics. This use has developed substantially during the past 25 years, including generalisations to vector-valued coherent states.

Spaces of coherent states have interesting geometries and feature in the theory of geometric quantisation. They have been used in path integral constructions, in studying inequalities in statistical physics, and in descriptions of classically chaotic systems. They have been applied, for example, to the quantum Hall effect, atomic and molecular physics, nuclear physics, and particle physics. Future applications may include quantum communications, quantum cryptography, and quantum computation.

A practical development to emerge from coherent state theory is the use of "wavelets" as an alternative to traditional Fourier analysis. The idea was introduced by Morlet in 1983 for analysing seismic waves. It has since been set on a rigorous mathematical footing and has become a powerful tool in electrical engineering for signal processing, and in computer science for data compression.

Quantum Field Theory

Field theory evolved from quantum electrodynamics (QED). It became a theory of particles and fields when it was understood that a relativistic quantum theory of a fixed number of particles is an impossibility.

A problem in QED before the middle of the 20th Century was its prediction of infinite values for a number of physical quantities. It turned out that the infinities were artefacts of expressing the theory in terms of parameters, like the electron mass and charge, which, if computed, would themselves diverge. With the right parameters and techniques for avoiding summations of divergent series, QED achieved extraordinary precision, e.g., in predicting Lamb shifts and the anomalous magnetic moment of the electron. Many names are associated with these adjustments of QED, known as "renormalisation"; the list includes French, Weisskopf, Schwinger, Wheeler, Feynman, Dyson, and Tomonaga. QED now ranks as a major achievement of twentieth century physics. It has had many practical applications in areas as diverse as superconductivity, lasers, transistors and microchips.

The latter half of the century has seen many attempts to generalise QED to other force fields of nature. The most successful is the 1954 non-Abelian gauge theory of Yang and Mills. This theory, which uses sophisticated concepts of differential geometry (e.g., connections on fibre bundles), has had a profound impact on mathematical physics. It interfaces with such diverse topics as spontaneous symmetry breaking, non-integrable phases, integrable systems, solitons, knots, and Kac-Moody algebras. The quantised version of YM theory has been spectacularly successful. It underlies the 1967-68 unified theory of electromagnetic and weak interactions of Glashow, Weinberg, and Salam. Likewise it provides the framework for quantum chromodynamics, a self-consistent theory of the strong interactions that evolved from the 1961-65 quark models of Gell-Man and Ne'eman. These developments show that all the fundamental interactions, including gravity, share a common geometric structure.

A separate remarkable development has been supersymmetric field theory, a theory that unites bosonic and fermionic fields within a common algebraic structure. It is hoped such a field theory will hold the key to the major outstanding problem of the theory of fundamental interactions, which is to quantise gravity and provide the sought-after unification of all the fundamental interactions. String theory, which characterises particles as strings rather than points, presents a promising approach to this difficult problem. But it will be some time in the next century before its success or failure is known.

Astrophysics

Commission 19

Virginia Trimble

Golden Decades

At the beginning of the 20th century, we were thought to be near the centre of a galaxy (the Milky Way) which was, very probably, the entire (static) universe, orbiting a star whose only obvious energy source was gravitational contraction, sufficient to power it for only about 30 million years. The decade beginning in 1919 saw all of this change, partly as a result of the commissioning of new, large optical telescopes at outstanding sites. First, in a series of papers ending in 1919, Harlow Shapley, working from Mt. Wilson, established a distance scale for certain clusters of stars that made it obvious, first, that the Milky Way was about ten times larger than had previous been supposed and, second, that the solar system was about two-thirds of the way out from the centre toward the edge of the disk of stars. Then Edwin Hubble, using data from both Mt. Wilson and Lowell Observatories, established that some of the fuzzy, luminous patches in the sky ("nebulae") were in fact additional whole galaxies, and also that all of the galaxies were moving apart from one another at velocities proportional to their separations, in a large-scale expansion of space time, predictable, in retrospect, from the equations of general relativity. The recognition that the source of solar and stellar energy must be nuclear reactions (then called subatomic energy) also dates from the mid-1920s. Later developments of the detailed reaction networks now enable us to say that we actually understand not just the energetics but also the production of the full range of chemical elements from hydrogen and helium, called nucleosynthesis, in stars.

A second golden decade, partly driven by the opening of the radio, X-ray, and gamma ray windows on the universe, began in 1963 with the discovery of quasars, extremely bright nuclei in otherwise normal galaxies, so compact that they must be fuelled by accretion of gas onto black holes. The cosmic microwave background (2.7 K radiation left from the early hot, dense universe, or Big Bang) was recognized in 1965. Pulsars came along in 1967-68, with Jocelyn Bell of Cambridge University looking very hard at data collected with a low frequency, sensitive, high time-resolution radio array designed by her advisor Anthony Hewish. Most astronomers had converged on a model involving neutron stars within a few months.

The X-ray binary, Scorpius X-l, had actually been seen in a rocket flight in 1962, but the recognition that it, too, was a neutron star, in a close orbit with another star, took longer — until 1964 in the Moscow offices of Yakov Zeldovich and his colleagues, but until about 1967 on the other side of the Oder-Neisse line. Another early rocket discovery, the X-ray source Cygnus X-l, flared up at X-ray, optical, and radio wavelengths in 1971. This permitted recognition of the visible counterpart and measurement of its radial velocity curve, hence a measurement of the mass of the X-ray emitting component. At six times the mass of the sun (a lower limit), this could only be another sort of black hole. The decade ended with the discovery of intense, short bursts of gamma rays coming from random directions in the sky. These were an accidental discovery using gamma ray detectors being flown on Soviet (Kosmos) and American (Vela) satellites with the primary goal of watching for illegal atmospheric bomb tests and were not publicly announced for several years after the first were seen in 1969, until each side could be very sure the other was not responsible.

The first, but firm, announcement from Raymond Davis, Jr. that the number of neutrinos reaching us from the sun is, at most, one third of that expected from the nuclear power source appeared in 1971, as did the Mariner 9 photographs of Mars that provided some initial evidence for liquid water in its past. The first close-up images of Jupiter, from Pioneer 10, arrived in December, 1973, marking the end of that golden decade.

It is easy to argue that we are currently in the midst of a similar period of rapid recognition of new phenomena and greater understanding of old ones, and the remaining sections deal with a small fraction of examples, most of which represent work in progress, on which more can be expected in the next few years. Annual updates on these and other topics appear in *Publications of the Astronomical Society of the Pacific* under the title "Astrophysics in 1991" etc. up to "Astrophysics in 2002" (in press for the May 2003 issue). And we end with some of the possibilities for new problems and new understanding over the next decade or so.

The Solar Neutrino Problem

This can be put in the "solved" file. It turned out to be a problem in weak interaction physics, not astrophysics. The sun really does live on the hydrogen fusion reactions as we had always supposed, but one-half to two-thirds of the neutrinos (depending on their energy) are no longer electron neutrinos – the only kind that Davis could see – by the time that they get to us. They have rotated to one of the other two flavours, or a combination of them. This has been demonstrated by a combination of data (a) on neutrinos produced in the earth's upper atmosphere when cosmic rays hit, (b) on neutrinos produced in nuclear reactors in Japan (whose arrival at the detector depends on which reactors are powered up each day, how far away they are, and on the rotation), and (c) on direct detection of the rotated solar neutrinos by the Sudbury Neutrino Observatory in Canada. What happens next? With luck, detection of neutrinos from additional supernova explosions besides 1987A, and with further luck still, in our own galaxy.

Cosmic Water

That so light a molecule as H_2O is a liquid at room temperature is something of a miracle (one belonging to the field of condensed matter and so in the remit of Commission 10). The astronomical surprise is that water, even liquid water, which we think essential for life, may not be particularly rare. ISO, the European Infrared Space Observatory, provided spectroscopic evidence for water vapour and water ice in the atmospheres of cool stars and in interstellar dust respectively. The imaging evidence for water flow on Mars has been enhanced by higher resolution cameras in orbit around Mars in the past couple of years and augmented by the discovery of some hydrogen-rich substance (almost certainly water ice) a meter or two below the surface in the high latitude regions. Finally, though the surfaces of the large moons of Jupiter and Saturn are a combination of assorted kinds of dirt and ice, images of their surfaces and the way a couple of them interact with the Jovian magnetic field strongly suggest dirty liquid water (brine) underneath.

The Gamma Ray Bursters

A few years after these were announced in 1973, there were more than 100 models in print, ranging from white holes and comets hitting neutron stars in our back yard to devastation in the cores of distant galaxies. It also became clear that there are two classes, with relatively long and relatively short duration, and a dividing line near two seconds. What was needed for further progress was optical identifications and, especially, optical spectroscopy to measure compositions, orbital motion, redshift or whatever.

This finally became possible in 1997, when the Italian X-ray satellite, BeppoSAX began providing accurate positions fast enough for optical telescopes to get to them before the fireworks were over. A few dozen optical, and sometimes radio, counterparts have been studied. All are in rather distant galaxies, which simply means that the events are so rare (perhaps one per galaxy per 10 million years) that we are surveying the whole universe. Most, when they fade, have revealed underlying galaxies with lots of star formation in progress, indicating that the bursters are something that happens to massive, short-lived stars. At least one was associated with an unusually bright supernova explosion (something else that happens to massive, short-lived stars). The current "best buy" model is the collapse of a star core to a rapidly rotating black hole, which collimates beamed, relativistic jets whose radiation we see.

There is a catch, however. All the optical identifications have been for the long duration events, and it remains very possible that the short duration ones have a somewhat different origin, perhaps the mergers of close binary pairs of neutron stars. The SWIFT satellite, scheduled for launch in late 2003, may be able to provide even faster, more accurate positions, allowing for the location of optical counterparts of the short duration class — always supposing that they have them!

Extra-Solar-System Planets

Many decades of searches and false alarms reached a climax in October 1995 with the announcement, by a Swiss group, of a planet-mass object orbiting the solar-type star 51 Pegasi. Early carping about whether it was "really" a planet (in mass, in composition, in structure, in formation process) rather than just a very small star has largely given way to sheer statistics. More than 100 are now known, including several stars with two planets each and at least one (Upsilon Andromedae) with three. All have masses at least as large as that of Saturn and orbit periods of at most a dozen years. These are the current limits of the search techniques and can change only rather slowly. But the real surprise has been that many are "hot Jupiters". That is, they have masses (and compositions) like our Jovian planets, but orbits as close to their stars as Mercury is to the sun, or closer. Others are at our distance from their stars, immediately raising the question of whether they might have moons like Callisto, Ganymede and Europa, but with surface water rather than ice and brine underneath; in other words, potentially habitable moons. Still others are out as far from their stars as Jupiter, so that there might be other, smaller planets closer in. The host stars, including our sun, all have a somewhat larger content of the elements besides hydrogen and helium (about 2%) than the general run of old stars.

You will want to know immediately about the existence of other earth-like planets and the composition of their hydrospheres and atmospheres, if any, but you are going to have to wait. A couple of missions, planned by ESA and NASA for later in this decade, may be able to detect earth-sized orbiters when they temporarily block a bit of the light of their stars, but composition information is probably two technological giant steps away. We will need to be able to separate the reflected planet light from the parent star light very accurately so as to look, for instance, for spectral features due to water, oxygen, and ozone (which produce strong signatures). Weaker features absorbed by carbon dioxide, methane, and chlorophyll (only just recognized in 2002 in earth light reflected back to us by the moon) will probably elude detection even longer, if they exist.

Precision Cosmology

Phrased as "How big is the universe? How old?", cosmological questions have a very long lineage. So do wrong answers. Even Hubble, though he was right about cosmic expansion, had the time scale and distance scales too small by a factor of seven or more, though he thought the error bars were only about 10%. Why, then, do we think we may finally be converging on correct numbers for many (not all!) of the quantities you would like to measure? The most important change is that several very different kinds of data are now converging on the same answers. These include:

a. the observed brightnesses of distant supernovae (good for measuring distances)
b. the X-ray brightness and temperature of gas in clusters of galaxies (good for measuring cluster masses and the fraction of the mass in normal, baryonic, material)
c. gravitational lensing by relatively nearby galaxies, clusters, and larger structures (the last is called cosmic shear) of the light from more distant galaxies, clusters, and larger structures (which tells us about the total density of matter on a range of large scales)
d. the details of the brightness and spectrum of the cosmic microwave background radiation and how they change on different angular scales on the sky (which, amazingly, are useful for measuring age, geometry, and density in different kinds of stuff).

The answers for 2003 (including implications of the observations made with the Wilkinson Microwave Anisotropy Probe, announced in February 2003) are not actually very different from numbers discussed for at least the past six years. But the error bars are getting smaller. First, the universe is quite close to 13.7 Gyr old (don't bet your house on the third digit). Space-time is very close to flat, meaning that it has a critical density when you add up all forms of stuff. Of that stuff, only about 4% is the baryonic material of which you (I assume), I, the earth, sun, and everything else that emits or absorbs electromagnetic radiation are made. Another small smidgeon is non-zero rest mass neutrinos (given the masses implied by the various experiments mentioned above). Close to 23% is dark matter, which exerts normal gravitational forces and responds to them (the equivalence principle) as well as exerting normal, positive pressure. And the remaining 73% is even stranger - a sort of dark energy, quintessence, or (in the language of standard general relativity) cosmological constant, which has positive mass-energy density all right, but exerts negative pressure. And if you want to know what it is, you must ask our friends over in Commission 11 Particles and fields. They have some very promising candidates for dark matter but may be as puzzled as the astronomers about the dark energy.

A very large number of additional things are rapidly becoming clear about the early universe – the spectrum of density-perturbation seeds from which galaxies and clusters have grown, the epoch at which the first stars formed and began to ionise the baryons around them (a good deal earlier than many of us, though not the best theorists, had supposed), and how the baryon tracers found their way into dark matter halos to produce the galaxies, quasars, and all that we now see, though this is the hardest part to calculate or observe.

Looking Ahead

Astronomical discovery did not start with Galileo and will not end with us. One can try to look ahead (perhaps another decade) either by looking at well-known unanswered questions or by looking at what might become available to help answer them. A few such items appear at the ends of previous sections.

There are some astronomical windows that have still not been fully opened. One is that at very low frequencies of less than a few MHz, which can only really be explored with very large (but not necessarily very smooth!) collectors in space. There is also an intermediate gamma ray regime above where the Compton Gamma Ray Observatory reached and below the 0.3 TeV that is the current limit of ground-based Cherenkov and Auger detectors. And there has never been an all-sky submillimeter survey. Another nearly unopened window is X-ray polarimetry. One purpose-build polarimeter has been flown (in 1972) on a rocket (thus providing about five minutes of data), and it looked at one source, the Crab Nebula supernova remnant, which was indeed polarized up to 60%, as expected. Both non-thermal emission processes and scattering can polarize X-rays, and one probably needs sensitivity extending down to 1% or less to probe many sources usefully. At that level, polarimetric data might well settle various issues about the structure of jets in quasars, the nature of emission processes in clusters of galaxies, and so forth. One possible design exists (a Compton-scattered electron comes off in a direction that preserves some information about the polarization of the incident photon); not, unfortunately, a cheap design.

Astrophysics, like the rest of academic physics, is heavily dependent upon computing power both for processing of massive data sets (exabytes from some of the ongoing surveys) and for numerical solution of complex equations (some called "simulations"). The processes of both star formation and galaxy formation currently exceed available facilities (which top out at numerical simulations of about 10^9 particles), limiting our ability to resolve, for instance, formation of binary stars and planetary systems in interstellar clouds. Perhaps in another 4 to 5 Moore's Law doubling times they won't.

Ultra-high-energy cosmic rays (meaning more than 10^{20} eV/amu) are detected routinely, though rarely, from their air showers. Such particles, if they are some sort of baryon, cannot swim far through the cosmic sea of optical and infrared photons, and there are no obvious sources very near the Milky Way. Transport of energy by neutrinos, or even stranger particles, which then interact with dark matter material in the galactic halo to make the particles we detect, has been proposed as a solution. It would be useful to have accurate arrival directions for a much larger number of UHECRs. It seems probable that the solution will involve either new particles or new physics or both. The arrival of TeV gamma rays from a few active galaxies at moderate redshift is similarly somewhat unexpected. The risk to them is pair production when they collide with photons of the microwave background.

Magnetic fields are pervasive, though not dynamically important in very many places except the interstellar medium. Their origins on cosmic scales remain mysterious, with candidates called dynamos (analogous to laboratory ones, but in stars and/or galaxies) and primordial (meaning that it all happened a long time ago). Proposals that start with the very early universe (invoking processes connected with symmetry breaking) and others that start with individual supernovae or gamma ray bursts blowing dynamo flux out into intergalactic space are both to be found in the literature. It would be nice to know which, if either, happened.

The formation of stars and of galaxies both count as unsolved problems, but in slightly different senses. For star formation, we think that all the essential physics is known (gravitation, turbulence, magneto-hydrodynamics, and all the rest), but that the computations are simply too complex to carry out. An extrapolation of Moore's law should take care of this, though not immediately, if one wants to be able to start with molecular gas clouds of 10^5 solar masses and follow their fragmentation down to the level of proto-planetary disks.

The formation of galaxies and larger scale structures presents the same computational difficulties that star formation does. But, in addition, it is not guaranteed that we have all the necessary physics to hand. Obvious examples are the nature and behaviour of the various sorts of dark matter and dark energy and the shape and amplitude (and possible non-Gaussian nature) of the initial spectrum of density perturbations that grew into the structures we see. Various speculations on "what happened before the big bang," including higher dimension theories, multiverses, inflation, M-theory, p-branes, and ekpyrotic universes are conceivably part of the solution here. Or not. In any case, what dark matter and dark energy are, how did galaxies form, and what came before the big bang are probably not independent questions.

Finally, there are all the things the author has not thought of, some of which you will surely think of, and perhaps achieve over the next decade or two.

Computational Physics

Commission 20

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Why Computational Physics?

Computational physics can be traced back to the tremendous calculations of solar system dynamics in the 19th century, but Computational Physics[1] [CP], as the discipline we know today began with the development of programmable computers in the mid 20th century, though significant early work was carried out on hand calculators.

The availability of programmable computers that can carry out endless repetitive calculations has greatly extended the range of problems that can be solved. For example one used to be restricted to solving a very limited range of differential equations and had to make approximations so that the model would fit the method. No longer is there such a restriction. Now the concern is not whether the differential equation can be solved, rather it is to ensure that the numerical method being used is stable.

However one must continually be on the lookout to ensure that computational results are valid. The output from a computer is at most as good as the assumptions fed in. Whenever possible a computer result should be compared with the results of real

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[1] Computational Science and Computer Science

Computational Physics is one of a number of computational sciences, e.g. Computational Chemistry and Computational Biology. In Computational Science computers are used as tools for investigating the laws of nature. In Computer Science it is computers themselves that are studied.

experiments. But that is not always practical, and sometimes not even possible. There are many problems which are too complicated for analytical solution, and where for a variety of reasons a real experiment is impossible or undesirable.

Examples of impossible experiments are simulations of stellar and galactic evolution. Examples of experiments which are undesirable are those which are very expensive or very dangerous. We should all have been better off had the operators at Chernobyl performed a computer simulation. Such computer simulations of large systems, where the underlying physics is well understood, can be very effective, particularly in the training of operators.

An advantage of computational simulation is that one can control conditions much more closely than in a real experiment. An example demonstrating this is the work of Matsuda and colleagues, who were studying flux flow in type II superconductors. Flux flow is strongly influenced by impurities in the superconductor. In the real experiment the impurities lay on a periodic lattice. It was found that there was a highly stable configuration when the lattice of flux lines was commensurate with the impurity lattice. In a computer simulation it is possible to control impurities much more closely than in a real experiment, for example one can ensure that the impurity lattice is truly periodic. However it is important to observe that what is being done here is to use the computer to extend and interpret real experimental results.

A very important reason for using computational physics in problem solving is the speed of the computers. In many applications speed of calculation is essential: as has often been said, one does not want a forecast of yesterday's weather.

The Unexpected

Much of the advance of science is orderly: it advances either by small, incremental experimental steps or by new experiments suggested by theory, for example the observations of the bending of the light by the sun to test Einstein's general theory of relativity. However sometimes the advances are wholly unexpected, such as the discovery of radioactivity. In this respect, computational physics, to some extent resembles experimental physics, in that qualitatively unexpected phenomena are observed.

A major significance of the power to calculate (in a computer intensive way, not by hand!) lies in the possibility of studying non linear equations, whose qualitative behaviours are totally unexpected since we have no analytical, exact, indication of how they should behave. The first impact of the capacity to calculate introduced by computers into the theory was really here, in the possibility of studying the behaviour of systems whose evolution follows laws that we know how to write, but not how to solve. This is not unusual in physics. As massive calculations revealed, it is not unusual even in mechanics, so creating an important divide between the situation before and after the advent of computers.

Well-known examples of this arise in the work of Lorenz and of Feigenbaum, each of whose discoveries was completely unexpected, and each of whose computational experimental discoveries has led to significant advances in theoretical understanding.

Ed Lorenz in the 1960s developed a ‘toy model’ of atmospheric dynamics, and discovered the existence of ‘chaos’ and of strange attractors: who has not heard of ‘The Butterfly Effect’? Feigenbaum, in the 1970s, using a programmable pocket calculator[1], discovered a universality in non-linear mappings, which has led to advances in our understanding of the behaviour of nonlinear dynamical systems. (It may be noted that Feigenbaum had considerable difficulty in getting his discovery published.)

A New Area in Physics

Computational Physics is that methodological branch of physics where a computer is the basic tool for exploring the laws of nature.

Modern computers have developed in a tight symbiosis with computations in physics, and their development has proceeded through mutual interaction. Computational Physics has been rapidly maturing as the third leg of the scientific enterprise alongside Experiment and Theory. The increase in computing power has been so great that it has effectively resulted in a qualitative change in the way computers can be used, and in the emergence of Computational Physics as a distinct methodology.

Traditionally, computational physicists have been self-trained, there having been no formal curricula aimed at educating computationalists. Indeed there really has been little formal discussion of what computational physics is. However, in recent years, many universities have begun undergraduate and graduate-level programs in computational science and engineering. Computational physics plays a vital role in these programs. This development will help ensure a growing cadre of trained computational physicists.

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[1] Not all the results we discuss involve the use of state of the art computers!

Physicists (and other scientists) use computers in a variety of different ways, such as for controlling experiments and gathering data. In general when we talk about Computational Physics, we exclude such uses, but see below *Handling experimental data.*

Computational methods and tools continue to evolve at explosive rates. In the 1970s Moore formulated his ‘Law’ predicting that the power and speed and memory of microcomputers halves or doubles, as appropriate, every 18 months. This halving and doubling continues at the time of writing (2003). Today a personal computer [PC] has a computing speed as fast as that provided by a 10 year old supercomputer and may well have a much larger memory. Indeed many current supercomputers are built up from a large number of PCs.

The democratisation of supercomputing is opening up computational physics to scientists throughout the world, including those in ‘less developed’ countries. We may thus expect far greater use of simulation as a basic tool of physics enquiry in the coming decades.

New Possibilities for Simulations

In the remainder of this chapter we shall describe some topics in Computational Physics. Not all current topics are mentioned. Moreover, Computational Physics is expanding rapidly, and new areas outside the traditional boundaries of physics are continually being developed.

Statistical Physics

In the past few years, researchers have increasingly been able to investigate fundamental questions in physics computationally with unprecedented fidelity and level of detail. For example, fluid dynamics simulations aimed at understanding turbulence have recently been carried out with over 200 billion computational degrees of freedom in three dimensions. This allows the examination of fluctuations over a three-order-of-magnitude span in length scales. Using Monte Carlo methods, researchers can now carry out statistical mechanical simulations with stunning fidelity and detail. For example, with current algorithms on the largest machines they could now carry out simulations of the Ising model with 10^{12} spins in three dimensions. Doing so would allow them to faithfully simulate the behaviour of the Ising model over six orders of magnitude in reduced temperature near the critical point.

However, CP is far more important in statistical physics than just providing better accuracy. CP is crucial for basically all areas: The study of disordered systems, polymers, membranes, glasses, granular materials etc. The whole field of non-equilibrium statistical physics uses CP methods, as they are inevitable for non-linear dynamics, turbulence etc. Whole topics have been initiated by the use of computers such as fractal growth phenomena, and cellular automata modelling. CP substantially contributes to the spectacular broadening of the fields of applications of statistical physics, including areas far beyond the scope of traditional physics, including (i) the description of co-operative phenomena in biological systems and (ii) the analysis and modelling of finance phenomena.

Diffusion Limited Aggregation [DLA]

The traditional computational physics approach is to perform numerical experiments. In such simulations, real experiments are approximated by including a large amount of small-scale detail. Computer models for granular media, including detailed description at the level of the individual grain, are examples of this methodology. A second and more subtle application of computers reflects the novel paradigm of ‘algorithmic modelling’: In this case, the level of small-scale detail is minimised. The large-scale structure of the physical system emerges when a simple algorithm is repeated many times. One example of a structure that is particularly well described by algorithmic modelling is the invasion front of one fluid penetrating into another in a porous medium (diffusion limited aggregation), where models that seems vastly oversimplified actually give quantitatively correct description of the physical process.

The DLA model provides deep insight into a rather common natural phenomenon, one which it is completely impossible to approach by non-computational techniques.

Many Body Systems and Quantum Monte Carlo Methods

Of the computational physics problems of the 21st century, the study of quantum dynamics of many-body systems is one of the deepest, and is often described as insoluble. Recent progress in this field has occurred through the use of operator representation techniques, which allow these problems to be transformed into stochastic equations on a classical-like phase-space, that can then be straightforwardly integrated numerically. Theoretical predictions are directly testable through experiments in quantum and atom optics, which allow control of quantum initial conditions and also of the Hamiltonian that determines time-evolution. An example of this is the prediction and experimental verification of quantum ‘squeezing’ in soliton propagation. Further progress in this area is likely as numerical algorithms and representations improve, along with experimental improvements in quantum optics, atom lasers and mesoscopic solid-state devices.

From Electronic Structure Towards Quantum-based Materials Science

For a long time electronic structure studies of metals, semiconductors, and molecules based on density-functional theories have been one of the fundamental tools of materials science. Important progress has been realised recently in extending the applicability of these techniques to larger, more complex systems and in improving the accuracy (and hence the predictive ability) of these techniques. Only a decade or so ago, simulations of systems containing about 100 valence electrons could be performed only on large supercomputers. Today, thanks to concurrent improvements in the basic algorithms and of computer power, *ab-initio* molecular dynamics studies can be performed on clusters of personal computers for systems with thousand of atoms and ten thousands of electrons. This is opening the way to accurate predictions of material and molecular structures and properties and to simulation of complex processes. Chemical reactions can be simulated "on the fly", *ab-initio* calculated potential-energy surfaces can successfully be used for kinetic modelling of a catalytic process, leading to *ab-initio* predictions of reaction rates. The ideal strength of materials can be calculated from first principles, without any other input than the composition and the atomic numbers of the components. Today, electronic structure theory is on the way towards quantum-based materials design. Electronic structure theory has also acquired a strongly interdisciplinary character, spreading into many areas from geo-science to biology. *Ab-initio* molecular dynamics has been used to calculate the viscosity of liquid iron under the conditions of the earth's core and to determine the chemical reactivity of enzymes, to name only two examples.

The corner-stone of density-functional theory is the simplified, yet for many purposes sufficiently accurate description of the many-electron problem - the most accurate description being provided by Quantum Monte Carlo (QMC) techniques. With today's faster computers and algorithmic improvements for handling the Fermion sign problem, QMC simulations become feasible at large enough scale as to make QMC a viable alternative to post-Hartree-Fock or density-functional calculations when accuracy is paramount. QMC simulations will also provide benchmarks for the development of improved density-functionals.

Quantum Chromo-Dynamics [QCD]

In elementary particle physics, the numerical simulation of theories on a lattice by means of Monte Carlo algorithms was introduced more than 20 years ago by K. Wilson. This has now become one of the most important tools for obtaining predictions from theoretical models. The major field of application is Quantum Chromo-Dynamics (QCD), the theory of the strong interactions. QCD simulations have begun to provide quantitative estimates of important properties of hadronic particles, such as masses and form factors. Moreover, numerical simulations are necessary for determining the fundamental parameters of QCD. Another area of application is the behaviour of matter under extreme conditions, such as in the early history of the universe and in different astrophysical objects like neutron stars. For the theoretical study of nuclear matter in such situations Monte Carlo simulation is an indispensable tool.

Sono-Luminescence and Resistive Magneto-Hydrodynamics

Puzzling phenomena such as sono-luminescence are yielding to understanding through a combination of molecular-dynamic and continuum shock-physics simulations. Four-dimensional, highly detailed simulations combining resistive magneto-hydrodynamics with radiation transport are becoming possible. These tools are aiding us in understanding the life cycle of stars and are being used to design inertial-confinement fusion experiments aimed at net energy gain from fusion in the laboratory.

Biophysics

In biophysics, there is revolutionary progress in simulating the folding of complex proteins. Simulations are helping to unravel the physical processes involved in the informational role of primary DNA structures (the genetic sequence) as well as delving into the role of secondary structures (e.g., detachments and loops) in DNA. Researchers are also modelling with increasing detail the physics of enzymatic catalysis. Key progress is being made in the use of classical density functional theory to model ion channels in cells.

Handling Experimental Data

Computational physics involves more than using simulation to provide insight and interpretation. It involves the acquisition and management and understanding of vast amounts of experimental data. Two areas stand out.

In high-energy physics, the ability to acquire, store and interpret terabyte data sets is becoming a key part of progress in accelerator experiments.

A new approach is pursued by the DataGrid Project. Its objective is to build the next generation computing infrastructure providing intensive computation and analysis of shared large-scale databases, from hundreds of Terabytes to Petabytes, across widely distributed scientific communities.

In geophysical modelling of global climates, satellite data provide critical information on the overall status of global climate as well as key global parameters needed to improve models and to validate theoretical methods. The acquisition and management of these data sets poses grand challenges in real-time data acquisition, in large-scale data management, and in data visualisation.

Prospects for the Future

Looking forward, within the next few years we may expect lattice gauge simulations in QCD to become sufficiently accurate to confirm or eliminate current theoretical models and approximations. In biophysics, we should see great progress in *ab-initio* and classical molecular mechanical simulation of many of the dynamic processes involved in the microscopic evolution of cellular building blocks. In material physics, we should see a revolution in mesoscopic physics enabled by microscopic computer experiments on solids and melts with realistically modelled defects.

In the area of the physics of computing, progress continues in attempts to develop fundamentally new approaches to computation based on quantum computers. The problems to be overcome are extremely formidable. Nevertheless great progress has been made recently and we may expect a rich exploratory development phase to continue to unfold in this area over the next few years.

On a more practical level, the availability of inexpensive, commodity simulation engines with capabilities in the many gigaflops/gigabyte range together with new educational and research initiatives will continue to attract more physicists into the computational arena.

Computational Physics is growing. In sum, the past few years have been the brightest in its history and progress in the next few will eclipse even the accomplishments of the recent past.

Optics

Affiliated Commission 1

Pierre Chavel

Introduction

Lessons from the past may be helpful when thinking about the future. In 1948, the founders of International Commission on Optics selected for their discussions such topics as the accommodation of the human eye and its resolving power, the combination of aberrations and diffraction, the design of microscope objectives, interferometers for testing camera lens aberrations, elements of thin film design, diffraction gratings, and new mineral and polymer glasses. When comparing this list with the scope and state of the art of optics today, two major facts appear quite conspicuously. First, it is indeed true that there has been progress in all of these fields, in the following ways:

- The human retina is being investigated by adaptive optical systems, where a deformable mirror compensates the aberration of ophthalmic media to focus and scan a diffraction limited spot on the retinal cells. Will adaptive optics ever be fitted to our spectacles and provide diffracted limited imaging to everyone?

- The most complex optical systems ever built provide f : 0.5 diffraction limited imaging at ultraviolet wavelengths over several square centimetres for the replication of computer chip masks. Thin films can be designed and fabricated in stacks of nearly one hundred layers to match virtually every conceivable spectral reflectance profile. How far into the X-ray range will they affect future lithography tools for micro- and nano-technologies?

- Interferometers are available in all sizes from submicron Fabry-Perot cavities to sensors with kilometre long arms. Diffraction optics has evolved from gratings into holography and lens achromatisation. Micro-opto-electro-mechanical systems offer, as an example, Michelson interferometers for Fourier transform spectroscopy integrated in square millimetres. Will miniaturisation techniques allow one to fit an optical system in the volume of a microcomputer chip? On the theoretical side, progress on the relation between the emission of light and coherence has been significant with the recent understanding of the role of surface waves and near field effects in the spatial and temporal coherence of thermal sources.

- Optical materials include non-linear crystals, rewritable holographic materials such as photo-refractive crystals, liquid crystals and polymer light emitting diodes. Will white LEDs invade our daily life for better energy yield and longer lifetime of our lamps?

- Ten metre diameter mirror telescopes, all fitted with adaptive optics facilities to compensate for atmospheric turbulence, combine their images coherently over distances larger than 100 m. In 2003, some of the first images from the European Southern Observatory "Very Large Telescope" in Chile provided clear and nearly direct evidence of a black hole in the very centre of our galaxy through analysis of the motion of the visible stars closest to it. Planets outside the solar system are now counted in the hundreds: will the even larger optical arrays currently at the planning stage give us evidence of terrestrial planets where life may exist in a form similar to ours?

Yet, the second obvious fact is that optics now encompasses much more than the great unforeseeable progress on these subjects that were already of interest fifty years ago. In 1948, nobody predicted the advent of the laser that was to occur just twelve years later, or the key role of optics in modern information systems. By emphasising these two domains in the following two sections, we shall undoubtedly miss many forthcoming revolutionary changes. Optical nanostructures, that include in particular the fascinating photonic bandgap materials and the counter-intuitive photon sieves will hardly be touched. Similarly, the significant increase of interest in optical tools for accessing and manipulating biological species down to the level of single molecules would deserve more emphasis. But with the choice of lasers and information optics we may be able to point to some major aspects of optics that are likely to develop in the next decade or so. In the United States, the National Research Council (NRC) has devoted a significant effort to identifying the growth points in optics. A detailed account of the findings of the NRC appointed Committee on Optical Science and Engineering can be found in their report. It presents a much broader overview of optics than these few pages can do.

Lasers

The diversity of lasers is an indication of their wide variety of uses, ranging from basic science to many branches of engineering. We shall examine just a few.

Extremely short pulses have reached the range of attoseconds, at least through nonlinear transients in high power femtosecond pulses. The latter, when obtained through carefully designed mode locking, have shown unexpected reproducibility and offer the promise of the most accurate clock ever thought of, down in the 16 significant digit range.

Laser cooling of atoms

Cold atom experiments and the rise of atom optics, a new field of physics which was recognised by the 1997 Nobel Prize in physics being awarded to S. Chu, C. Cohen-Tannoudji and W. Phillips, rely in part on the mature state of laser instrumentation. Atomic beams, usually of noble gases or alkali metals, are first slowed down by a large number of successive collisions with laser photons. When the atoms have been brought essentially to rest, they are trapped and further cooled by suitable manipulation of additional laser beams and of magnetic fields. The first result is a so-called atomic molasses with typically billions of atoms grouped in a cubic millimetre or so and with a residual temperature below one microkelvin, i.e. speeds in the range of millimetres per second. Further cooling and trapping drives molasses to the coherent state of Bose Einstein condensates, where all atomic wave functions widely overlap and all atoms are in the same quantum state. ”Atomic lasers” derived from such condensates by allowing a small leak through a radio wave frequency magnetic transition may some day turn into the ideal source for single atom nanosciences. At this time, cold atoms provide by far the most sensitive gyrometer, with industrial applications in sight.

High power lasers

Large lasers such those as the National Ignition Facility under development in the United States are the record holders in terms of energy per pulse. The challenge of inertial confinement fusion, for both military and energy applications, is being pursued by irradiating millimetre-sized deuterium-tritium targets with megajoules of 350 nm light produced by tens or hundreds of frequency-tripled, amplified doped glass laser beams. The near term perspective here is more scientific in nature, with a better understanding of dense plasmas. The long-range goal of a cheap energy supply from fusion is at this stage considered unrealistic by most specialists but everyone knows that satisfying the growing energy needs of mankind is one of the top challenges of the century and that no path can be left unexplored.

Other large lasers currently in their final stage of development aim at the optical detection of gravitational waves using the largest interferometers ever designed.

Continuous, frequency stabilised laser beams will feed Michelson interferometers with arm lengths in the range of several kilometres, with the arms themselves being Fabry Perot cavities to increase the effective length of interaction with gravitational waves. A relative path length sensitivity of better than one part in 10^{21} will be needed to observe the expected events. Several projects in Europe, in the United States and in Japan are in various stages of development while plans for an international facility in space have been started. Their combined operation will essentially form a world observatory for gravitational events, providing access to the observation of events further in the past than photons can offer.

Laser miniaturisation

These examples may give the impression that lasers are huge, complex and costly systems. While lasers always belong to high technology, the largest market for lasers lies in the million piece sales of compact disk readers, based on 780 nm compound semiconductor lasers with unit costs down to less than one US dollar, with red supermarket bar code readers in the second place. Yet, laser miniaturisation is still going on with the so-called “vertical cavity” lasers. For about two decades, laser diodes used to be constructed from flat semiconductor chips that emitted light through their edges. A radically new concept imagined in the nineteen-eighties, that took several years to turn into a real device, was to stack a bottom mirror, a sub micrometre-thick gain medium and a top mirror all atop a semiconductor substrate to emit light “vertically”, i.e. perpendicular to the substrate. The total laser volume is reduced to a few cubic micrometers and arrays of a thousand lasers have been built on one chip – with the only difficulty that it is impractical to connect them to thousands of independent electrodes. The technology of VCSELs (Vertical Cavity Surface Emitting Lasers) is one of the aspects of the development of optical microcavities, with industrial possibilities for telecommunications, interconnects, display and storage and scientific development related to the control of spontaneous emission and its application to quantum information processing.

Quantum cascade lasers, consisting of stacked suitably engineered quantum wells are a new fast growing field. While providing a nice example of application of textbook quantum mechanics to technology, they offer high energy efficiency and high design flexibility to obtain emission in a very broad range of the infrared spectrum, from the red limit of the visible spectrum to several hundred of micrometers.

Wide raging uses of lasers

An overview of the field of lasers cannot be given in just one or two pages. We shall therefore only mention in passing such other important aspects as laser cutting and welding, laser ablation, all-solid state lasers, optical parametric oscillators and amplifiers, LIDARs (laser radars) that monitor air quality by measuring the back scattered light from aerosols above polluted areas, ultrafast lasers and their developing application to non-invasive biomedical imaging. There are also applications to fundamental physics such as the use of lasers to explore the dynamics of non-linear physical effects involving chaos, multi-stability, spatial solitons, light bullets and other pattern forming effects in space and time. While lasers are almost ubiquitous in modern optics, progress in optics cannot be reduced to lasers and we should now turn to some other aspects of the field.

Information Optics

For many years, the prospect of optical computers competing with electronic computers was a favourite topic in science journals. It is now apparent that this was a naïve expectation if light is merely used to mimic electronic computers. However, optical signals can be used to improve the performance of computers in other ways. The correct arguments are:

1) Operations in computers get faster when capacitors to be loaded during circuit operation get smaller. This is possible if some of the longer wires are replaced by the propagation of electromagnetic waves through free space or in dielectrics – now an economical challenge that will be facilitated by the already mentioned development of semiconductor lasers and other micro-opto-electronic components.

2) Light in the hundreds of terahertz range has a very broad signal bandwidth, which is still far from being completely exploited today.

3) Light beams can cross each other without cross-talk or interference, allowing more components to be packed into a smaller volume and many optically carried signals to travel in the same waveguide.

Developments in telecommunications

The development of optical telecommunication derives directly from these arguments. Improvement in the absorption and dispersion of optical fibres led to the first optical communication links around 1980. The replacement of multimode fibres by monomodal fibres allowed reduced dispersion and better signal quality. The advent of fibre amplifiers around 1990 provided an efficient way to increase the optical telecommunication bandwidth, since amplifying and regenerating optical signals optically turned out to be better than detecting and re-emitting them using opto-electronic repeaters.

Further progress is now arising from the simultaneous transmission of several signals coded on different wavelength channels in one fibre. Current commercial capacities are expected to increase from 10 to 40 gigabits per second, even in the more demanding undersea networks, and 3 terabits per second links have been demonstrated in the laboratory over thousands of kilometres. For the past twenty years, the time required for the performance of optical communications systems to double has been even shorter than for electronic computers (the so-called Moore's Law). This trend was slowed down by the economic problems of the last few years, which resulted from a substantial overestimation of demand. But the scientific and technological arguments just summarised are nevertheless still valid and consumer demand for more bandwidth keeps growing, so that the question is when, not whether, optical telecommunications will resume their rapid growth. At some stage, everyday life will quite likely be dramatically affected by inexpensive fibre optical connections to the home, making possible high speed internet links.

Quantum information

A new chapter in the story of optical information has opened in the last few years with the development of quantum information as a new branch of physical research. Quantum cryptography in fibres and in free space has been demonstrated over distances of a few kilometres, and experimental industrial links are now available from startup companies. The required sources of controlled single photon emission drive semiconductor nanoelectronic research, but available single photon detectors limit the speed. Faster algorithms using continuous rather than discrete quantum variables have been announced. Optical means for manipulating quantum-bits (q-bits) derive from the field of trapped cold atoms and ions, and the first fully operational two q-bit gates have been demonstrated using the latter.

Conclusion

There is a unity in the broad and diverse field of optics. Other aspects of optics could have been highlighted in this survey, such optical near-field microscopy, or the importance of materials development for optics. The interrelations between optics and micro- and nano-technologies may some day combine with micro-electronics to produce smart opto-electronic detector arrays for full electronic imaging in video and still pictures. Through several examples that would equally well fit under the heading of other IUPAP commissions, this short report has shown that the development of optics is closely intertwined with that of several other branches of physics. Pasteur once said, “there are applications of science, there is no applied science”. Optics is progressing as a branch of science, with its roots deeply in physics; applications of optics are progressing and extend their impact well outside physics. Optics has served as the foundation for many of the advances in physics and engineering that have enriched the field of science at the end of the twentieth century. Optics has also been a direct contributor to the improvement of human life world-wide. The impact and recognition of Optics has been increasing steadily in the last decades and the trend will continue well into the new century.

Gravitational Physics

Affiliated Commission 2

Werner Israel and Robert Wald

General Relativity and Gravity

General relativity, the reigning theory of the gravitational force and the geometrodynamics of space-time, was the brainchild of the most famous scientist of the twentieth century, Albert Einstein. But unlike quantum theory - the other conceptual revolution in which he played a seminal role - Einstein's theory of gravitation languished on the sidelines for nearly half a century after the initial flurry of 1919, because relativistic deviations from Newtonian predictions were almost unmeasurably small under all astrophysical conditions then conceivable. Only after 1960 was it recalled to centre stage, when the discovery of X-ray sources, active galactic nuclei, quasars, pulsars and the cosmic microwave radiation revealed the presence in our universe of strong-gravity regimes and spectacular relativistic effects.

Today the theory is central to our understanding of some of the most exotic realms of science, from black holes to the evolution of the cosmos fractions of a second after the big bang. However, it is not yet the ultimate theory of gravitation. Attempts to reconcile it with quantum principles and to subsume it within a Grand Unified Theory of all the basic forces have encountered obstacles, signalling that general relativity must give way to something more fundamental when space-time curvature becomes so huge that the radius of curvature approaches the Planck length, about 10^{-33} cm. Curvatures of this order are expected only in the deep interior of black holes and at the moment of creation itself. There is increasing consensus that Einstein's original 1916 theory adequately describes all aspects of gravity that will ever be directly observable.

Experimental confirmation of the theory has progressed enormously since 1915. A milestone was the discovery, by Russell Hulse and Joseph Taylor in 1974, of the binary pulsar, a pulsar in an 8-hour non-circular orbit about another neutron star. General-relativistic effects on the orbit are much larger than in the solar system (the total perihelion precession is 4^o/yr!), and all have been confirmed to better than 1%. Most significantly, the orbital period is decreasing at a rate that squares with the loss of energy by gravitational radiation as calculated from Einstein's quadrupole formula. This indirect but compelling evidence for the reality of gravitational waves lends encouragement to international efforts currently under way to detect and analyse such waves directly.

Gravitational Waves

There are a number of detectors which have recently begun operation or are nearing completion that will measure the distortion of spatial geometry due to passage of a gravitational wave by monitoring the separations of suspended mirrors using laser interferometry. The nearest concentration of stars that is large enough to yield wave-bursts in inappreciable numbers (at least a few per year) is the Virgo supercluster, about 60 million light-years from us. To detect such bursts, the interferometers must be sensitive to fractional changes in arm length as small as 10^{-21}.

In 2002, LIGO, the Laser Interferometer Gravitational-wave Observatory, began its first science runs. LIGO consists of two identical interferometers with arms 4 km long, located in Hanford, Washington and Livingston, Lousiana. Smaller instruments (GEO in Hanover, Germany, TAMA in Japan) are also in operation, and VIRGO, a similar interferometer with 3 km arms in Pisa, Italy, is expected to be in operation by late 2003. None of these detectors are presently operating at a sensitivity such that detection of gravitational radiation from known or expected sources would be likely. However, improvements of about a factor of 10 in the currently designed sensitivity of LIGO are planned to be undertaken before the end of the decade ("Advanced LIGO") and, if achieved, should lead to the direct detection of gravitational waves.

Sources with well-defined wave-forms are the most promising for early detection. It is anticipated that the initial observations will be of the last minutes (in-spiral and merging) in the lives of compact binary systems, (a fate that awaits the binary pulsar 100,000 years from now). These immediately pending observations pose a major challenge for theorists to develop numerical simulations of the wave patterns that can then be used as templates to filter the data. This requires use of supercomputers and advances in numerical techniques, which now involve the co-ordinated effort of workers at many centres.

The merging of two compact objects (e.g., a neutron star and a black hole) is also a possible model for the origin of the mysterious gamma-ray bursts. The gravity-wave observations will therefore be awaited with interest by gamma-ray astronomers.

However, coincidences are unlikely to be found immediately, as most gamma-ray bursts are at cosmological distances, far beyond the range of the first generation of interferometers.

For frequencies below 1 Hz, the gravity-wave signal is drowned out by seismic noise, and it is necessary to go into space. The Laser Interferometric Spacecraft (LISA), which it is hoped will be launched early in the next decade as a joint project of ESA and NASA, will consist of 3 spacecraft in solar orbit, arranged in the form of an equilateral triangle with a baseline of 5 million km. It should routinely see gravitational radiation from binary stars in our galaxy. It will be able to study mergers of supermassive black holes in galactic nuclei out to cosmological distances and in such detail as to map the ultra-strong field regime near the horizon. The bad new is that it is unlikely there will be more than a few such events per decade.

A satellite scheduled for launch in late 2003 will carry Gravity Probe B, which will measure "inertial-frame dragging," i.e., the way in which a massive spinning body drags the space around it into a swirling motion like a tornado. In the case of the spinning earth, this effect is very small, a precession of just 40"/yr. in the orbital plane of the satellite. The cryogenically cooled gyroscopes of this experiment, monitored with SQUIDs, will be able to measure this precession to an accuracy better than 1%.

Active Galactic Nuclei, Quasars and Black Holes

Active galactic nuclei and quasars have been suspected since the 1960s of harbouring supermassive black holes, but it is only in the last ten years that strong confirmatory evidence has come to hand. In 1994 the Hubble Space Telescope measured the Doppler shift of spectral lines of gas orbiting 60 light-years from the centre of the giant galaxy M87 in the Virgo cluster. The orbital speed (550 km/s) and Kepler's law lead to the inference that a mass equal to 2 billion solar masses is hidden within this radius!

The centres of our own galaxy and of the peculiar spiral galaxy NGC4258 (distance 20 million light-years) provide the most compelling cases for the presence of massive black holes. In our own galaxy, ordinary light from the stars near the centre of the galaxy is obscured by dust in the galactic plane, so measurements of their motion must be performed in the near-infrared. A number of stars have been tracked and found to follow Keplerian orbits, implying a central mass of 2.5 million solar masses concentrated in a region no larger than about 1000 Schwarzschild radii. The galaxy NGC4258 has in its core a molecular gas disk (average radius about half a light-year) the motion of which can be accurately mapped with VLBI (Very Long Baseline

Interferometry, which has angular resolution 100 times better than the Hubble Telescope) via the 1.3 cm (microwave) maser emission line of H_2O. The mass within the disk, inferred from the (precisely Keplerian) velocity distribution, is 36 million solar masses. If this is not a black hole, it must be something even more exotic: a star cluster as dense as this could not be stable and would rather quickly collapse to a black hole.

If as little as 1% of supernovae form black holes, there should be 10 million stellar-mass black holes in our galaxy. Very few, however, would now be in the accreting environment which would make them candidates for detection as X-ray sources, i.e., in a tight orbit with a normal star. Nevertheless, more than a dozen have so far been found, beginning in 1972 with Cygnus X-1, the first black hole ever discovered.

Theoretical Progress

There is space only for brief allusion to some of the highlights on the theoretical front:

- The recognition, around 30 years ago, that black holes are stereotyped objects, completely specified by their mass, angular momentum and charge. (The last has no astrophysical significance: a charged black hole would be rapidly neutralised by currents from the interstellar plasma.) This so-called "no-hair" property enormously simplifies the task of model builders, and it has formed the basis of all work on black holes by theoretical physicists, astrophysicists and gravity-wave theorists.

- Sophisticated numerical simulations of gravitational collapse have revealed an unexpected and intriguing feature, still poorly understood analytically. The process of black hole formation by certain forms of matter, near its critical point (i.e., when the mass concentration becomes just sufficient for the formation of a black hole), shares many of the properties of a phase transition.

- The celebrated discovery by Hawking in 1974 that black holes are "hot" and evaporate thermally by a quantum tunnelling process. (For astrophysical masses, the temperature is insignificant and the evaporation time practically infinite.) Efforts continue to understand at a deeper level the Bekenstein-Hawking formula, which effectively equates the entropy of a black hole to its area. It has been hailed as one of the triumphs of superstring theory that recently it has proved possible to reproduce this formula for certain classes of black holes, as well as other (scattering) properties of black holes, from the study of strings in a flat space.

- The idea that cold stars appreciably heavier than the sun are gravitationally unstable and should collapse to form neutron stars or black holes was advanced more than 60 years ago by Chandrasekhar, Zwicky and Oppenheimer. For many years it was ignored or ridiculed. Its development since then is one of the success stories of twentieth century science.

- Many exciting new speculative ideas have been proposed in recent years, which may significantly impact our understanding of gravitation and cosmology at a fundamental level. Among these ideas are (i) the "holographic principle", which asserts that the degrees of freedom of a gravitating system are determined by its bounding area rather than its volume and (ii) the idea that space may have additional extra dimensions of a "large" (compared with the Planck scale) size, and that we are confined to a "brane" in a higher dimensional space. Many of these ideas have been spawned by developments in string theory and M-theory.

Dark Matter and Dark Energy

During the past decade, enormous advances have occurred in observational cosmology.

The most dramatic advances have involved precision measurements of the Cosmic Microwave Background (CMB) radiation. The CMB was first discovered in 1965 and was soon recognized to be relic radiation arising from an era when the universe was much hotter and denser. The CMB spectrum is (as far as can be measured) a perfect Planck black body distribution, and the temperature variations across the sky are only 1 part in 100,000. The detailed structure of these temperature variations contains a great deal of cosmological information concerning the large scale properties of our universe and the initial spectrum of density perturbations. The variations in temperature were first detected by the COBE satellite, and have been measured with significantly increasing accuracy (and on smaller and smaller angular scales) by several balloon experiments, and, most recently, by the WMAP satellite. These measurements show that the total energy density in the universe is within a few percent of the "closure density", i.e., that the geometry of space is very nearly flat (as opposed to spherical or hyperbolic). These measurements also confirm that the initial spectrum of density perturbations is of the "scale free" type predicted by inflationary models, according to which a short burst of exponential growth occurred in the very early universe.

Arguments concerning the synthesis of deuterium and other light elements in the early universe – as well as the CMB measurements themselves – show that only about 5% of the total energy density in our universe is in the form of "ordinary matter", i.e., baryons. Thus, 95% of the energy density of our universe consists of as yet unknown forms of matter. Studies of the dynamics of galaxies and clusters of galaxies indicate that of this unknown 95%, approximately 25% is clustered with baryonic matter (providing a “dark matter” halo of galaxies and clusters of galaxies). Therefore, the remaining 70% apparently is distributed relatively uniformly throughout the universe.

An important clue to the nature of this unclustered matter has come from observations of type Ia supernovae. These objects provide excellent “standard candles” that enable a far more accurate determination of the redshift-distance relationship than had previously been possible. These observations strongly indicate that the present universe is actually accelerating, i.e., the rate of change of the scale factor with time is increasing with time rather than decreasing. In order for this behaviour to be compatible with Einstein's equation, there must either be a (positive) cosmological constant term in that equation or there must be a significant component of matter in the universe with negative pressure. One possibility for the latter would be a field whose energy is dominated by potential energy.

The Current State of Cosmology

As a result of all these developments, the current (mid-2003) state of affairs in cosmology is as follows. There is a large body of data (including precision measurements of the CMB, determination of light element abundances, type Ia supernova observations, and observations of the clustering of galaxies) that points to the conclusion that our universe is well described by a homogeneous and isotropic, spatially flat model. Only about 5% of the present energy content of the universe is comprised of known forms of matter. Another 25% of the present energy content of the universe consists of a new form of matter that is essentially pressureless and clusters with galaxies (“cold dark matter”). The leading candidate for this dark matter is some (as yet undiscovered) weakly interacting massive particle (“WIMP”). Laboratory experiments searching for WIMPs are presently intensively underway. The remaining 70% is smoothly distributed and has negative pressure. This component is usually referred to as “dark energy”, and the leading candidates are a cosmological constant or a field whose energy is dominated by potential energy. One of the great puzzles concerning dark energy is that – although it presently dominates the energy density of the universe – its contribution is so tiny compared with any scales set by known fundamental physics (such as the Planck scale or the scales occurring in elementary particle physics) that it appears to be extremely difficult to account for it in any “natural” way.

Conclusion

Gravitational physics and cosmology are experiencing an exciting phase, when the "big picture" is coming into focus for the first time. We can expect a crescendo of discoveries in the new millennium, both in theory and observation, clarifying how our universe began and how it will end, the mystery of what lurks inside black holes, the nature of the foamy substratum that underlies the space-time continuum of our experience, and the composition of the dark matter and dark energy that dominate the energy content our universe. We have many new insights and revelations to look forward to!

Acoustics

Affiliated Commission 3

Lawrence A. Crum

Introduction

Acoustics is one of the broadest of all the sub-fields of physics. Acousticians concern themselves with such diverse topics as the physiology of hearing, the complex vibrations of a musical instrument, the noise produced by a jet engine, the development of speech in an infant, the quality of the sound in a concert hall, the propagation of sound over thousand kilometre distances in the ocean — indeed, acoustics deals with both the physical and the biological, the pure and the applied, the technical and the social. Acoustics is important to us because it plays an important role in our daily lives; we are constantly surrounded by sounds, some of which are important in our communication, some fill us with pleasure, others annoy us. It would take many volumes to overview such a complex discipline. Below we describe just a few of the "hot topics" that have recently gained public attention.

Sonoluminescence

It might seem rather surprising that sound waves can produce light, but indeed this conversion of mechanical energy to electromagnetic energy has been known for some time. When an acoustic wave of moderate pressure amplitude is propagated through an aqueous liquid, light emissions can be observed. Such an effect was totally unexpected. The power density in a sound wave, even of moderate to high amplitude, is only on the order of microwatts/cm^3; yet, in the phenomenon of sonoluminescence, light energy is emitted with such intensity that it can be easily seen with the naked eye from distances of several meters. This conversion of mechanical energy into electromagnetic energy represents an energy amplification per molecule of over twelve orders of magnitude! Recently, it has been discovered that a single, stable, gas bubble acoustically levitated in a liquid, can emit optical emissions each cycle for an unlimited period of time. Presumably, the oscillations of the bubble cause the gas in the interior to be heated to incandescent temperatures during the compression portion of the cycle.

Furthermore, some recent evidence indicates that the lifetime of the optical pulse can be on the order of or less than 50 picoseconds, and that the temperature in the interior of the bubble can exceed 100,000 K. Since conventional explanations expect the bubble to remain compressed and the temperatures to remain elevated in the interior of the bubble for times on the order of tens of nanoseconds, it is likely that some rather unusual physics is occurring. There have even been some suggestions that sonoluminescence may be due to quantum vacuum radiation. The best guess, however, is that a shock wave is created in the gas which is then elevated to high temperatures by inertial confinement. If shock waves are the mechanism for sonoluminescent emission, then optimisation of the process could lead to extraordinary physics, including nuclear fusion.

More realistically, however, single bubble sonoluminescence represents only a very special case of multi-bubble sonoluminescence in which thousands of collapsing gas bubbles are observed to produce light over much of the volume of the high intensity sound field produced within a liquid system. In this case, the presence of light is indicative of the existence of free radical species produced by the high temperatures and pressures within the collapsing gas bubbles. These free radicals have been found to induce a number of unusual chemical reactions — an effect that has given risen to an entirely new discipline: sonochemistry. Perhaps sonoluminescence will be a bridge that links physics and chemistry and leads to many exciting discoveries in the future.

Ocean Acoustic Time-Reversal Mirror:

One of the major problems faced when sound energy is propagated through a real medium (such as human tissue or even the ocean) is the complexity that arises from the individual inhomogeneities that exist within the medium. These inhomogeneities change the local speed of sound and thus a reconstruction of the various sound paths to create an image is influenced by these aberrations, which are generated by the medium itself. One approach to correcting for the complexity of the medium is to propagate a sound wave through the medium and collect not only the intensities of the various sounds that have travelled different paths, but also their phases. Reversing the phases and re-propagating the sound wave over the same path enables one to remove the effect of these inhomogeneities — this process is called phase conjugation and the instrument that accomplishes this effect a time-reversal mirror (TRM). A TRM, also referred to as a phase conjugate array, has been implemented in two experiments conducted in the Mediterranean Sea in April of 1996 and 1997. The experiments were carried out jointly by the Marine Physical Laboratory of the Scripps Institution of Oceanography and the NATO SACLANT Undersea Research Centre.

A TRM focuses acoustics energy to a predetermined spot specified by a probe source, regardless of the time invariant complexity of the medium. Previously, megahertz TRM experiments had been conducted in an ultrasonics laboratory (University of Paris) over ranges of less than one metre. The ocean experiments utilised a vertical source-receiver array (SRA) spanning 77 m of a 125 m water column with 23 sources and receivers and a single source/receiver transponder (SRT) co-located in range with another vertical receiver array (VRA) of 46 elements spanning 90 m of a 145 m water column located from 6.3 km to 30 km from the SRA. The TRM demonstration consisted of transmitting a 50 ms pulse with centre frequency of 445 Hz from the SRT to the SRA, digitising the received signal and retransmitting the time reversed signals from all the sources of the SRA. The retransmitted signal was then received at the VRA. An assortment of runs were made to examine the structure of the focal point region and the temporal stability of the process. The process was extremely robust and stable out to 30 km. This research may lead to new concepts in acoustic ocean imaging, sonar and communications, as well as a mean to improve the images in medical diagnostic ultrasound imaging systems.

Recent Developments in Psychological & Physiological Acoustics

High interest continues in otoacoustic emissions (OAEs), which are low-level sounds generated by the inner ear, either spontaneously or from external stimulation. They are measured using sensitive microphones placed in the external ear canal, and appear to reflect normal, non-linear processes in the cochlea. Their potential as a screening tool for quickly and accurately identifying hearing loss is being assessed in a clinical trial with 7,000 new-borns in the U.S. Exciting recent work on gender and hormonal influences on OAEs may reveal more general processes of brain differentiation during development.

In behavioural research with human listeners, work with head-related transfer functions (HRTFs) is bringing realistic virtual auditory environments closer to reality. An HRTF is the frequency response (filter characteristic) between a sound source in space and the ear, shaped in large part by the external ear, and thus unique to each individual. Although sound reproduction is improved using average HRTFs, people prefer sounds processed with their own HRTF. The first home audio equipment using this technology recently became available.

Other hot topics in psychological acoustics include the inter-related areas of auditory scene analysis, sound-source segregation and auditory selective attention. Considerable progress, including computational models, reflect progress in our understanding of the perplexing question of how listeners parse complex incoming sound fields from multiple sources into relevant and irrelevant auditory signals.

High Intensity Focused Ultrasound

For years acoustic researchers have concentrated on demonstrating that low acoustic intensities used in diagnostic ultrasound produce no or minimal biological effects, therefore making ultrasound imaging safe. The tide is turning. Therapeutic ultrasound researchers intentionally turn up the intensity to produce *beneficial* bio-effects. It has been shown that High Intensity Focused Ultrasound (HIFU) can stop bleeding from injured solid organs and major blood vessels in about a minute ("acoustic haemostasis"). The therapeutic intensities are about 4 orders of magnitude larger than those of the diagnostic ultrasound, i.e. 10,000 W/cm^2 vs. 0.1 W/cm^2. At these intensities, two major effects are caused by ultrasound:

- The thermal effect raises the temperature to above 60 ^{O}C, causing coagulative necrosis of cells and tissues. While this thermal effect is shared by several other energy modalities including lasers, electrical current, and simple hot irons, ultrasound has the distinct advantage that it can produce the thermal effect deep within a tissue, where haemorrhaging may be occurring in a patient with internal bleeding. This effective mechanism has been responsible for the success of HIFU in "deep volume cauterization" of solid organs, around an injury site.

- The mechanical effect, which is unique to ultrasound, is just beginning to be explored. Bulk streaming due to ultrasound radiation pressure can push blood out of the way, perhaps back into a bleeding vessel, for better visualisation of the operating field as well as enhanced energy deposition in the injury site. Also, tissue emulsification as a result of the large pressure oscillations can provide a seal for solid organ wounds, or a plug for vascular lacerations. Such tissue homogenates contain a large concentration of tissue factors that may accelerate coagulation and haemostasis by orders of magnitude.

HIFU may provide haemostasis methods for both surgical and extra-corporeal applications. The surgical applications may include pre-cauterising volumes of tissues that are planned to be removed by surgery ("bloodless resection"), as well as providing a general tool of haemostasis. The extra-corporeal applications may include arrest of bleeding in trauma patients at the scene of an injury, or during transport to the hospital. Such methods would reduce bleeding and improve the outcome of subsequent trauma surgery, where HIFU methods may come to the rescue again. Acoustic haemostasis may provide an effective, limb- and life-saving method in the near future.

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