

Name:

Class:

LUMINESCENCE
It's Cool Light!

Visual Quantum Mechanics

ACTIVITY 1

Exploring Light Emitting Processes

Goal

In this activity, you will investigate the physical properties of different luminescent materials and compare these properties to those associated with a common incandescent lamp.

Matter emits light through various processes that convert other forms of energy to light. For example, light is emitted as a result of heat from the flame of a candle or fireplace. Light is also emitted by energy released by breaking or grinding a substance such as sugar or a piece of candy. Energy created from mixing some chemicals and by some living organisms such as the firefly can emit light. In this unit, we will explore common, everyday materials and devices that utilize these processes to emit light. Later, we will find that the unique, observable properties associated with light-emitting materials and devices can be explained by quantum principles. In the first activity, we will explore materials and devices associated with each light-emitting process.

The most common, everyday light sources other than the sun are incandescent lamps, also known as light bulbs, found in every household and place of business. The light bulb contains a solid tungsten filament that emits light when energy is provided by an external energy source such as a battery or electrical power plant.

? Examine the incandescent lamp that you have been provided. Can you see the filament?

Observe the light emitted by the incandescent lamp provided.

? In the space provided below, describe the color, and intensity of light emitted by the lamp.

Kansas State University

©2001, Physics Education Research Group, Kansas State University. Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

Carefully place your hand near the top of the lamp without touching the lamp.

Be careful not to touch the incandescent lamp especially if it is a household lamp.

? Does the incandescent lamp emit any heat? How can you tell?

The process in which light is emitted by the incandescent lamp is appropriately called incandescence or "hot light". Incandescence is the process by which a heated substance emits light. Inside the lamp, the tungsten filament is heated by electrical energy. Some of this energy becomes the light that you see while the rest of the energy is emitted as heat. A typical incandescent lamp is very inefficient at emitting light. About 5% of the energy becomes light; 95% is emitted as heat.

We will now explore the properties of another device, a light emitting diode (LED), which emits light in a different way. LEDs are typically used as ON/OFF indicator lights in electrical appliances such as televisions, VCR's, and stereos. The numbers in some alarm clocks, radios, and microwave ovens are displayed by LEDs. Large video displays in places of business, sporting events, and concerts utilize LEDs. For example, the music group *U2* during their 1997 *POPMART* tour was using a 56 feet x 170 feet video screen consisting of LEDs. The low voltage requirements needed to operate LEDs as well as their small size and mass makes them an attractive light source to use with these applications.

We will use a small circuit board for this exploration.

Connect the battery snap to the circuit and observe the light emitted by the LED. If no light is emitted, use the small screwdriver to turn the screw on the end of the blue rectangular device until light is emitted.

? In the space provided below, describe the light emitted by the LED in terms of its color and intensity.

Carefully touch the top of the LED.

? How is the LED similar to the incandescent lamp in terms of physical and light properties?

? How are they different?

? What type(s) of energy was (were) required for the LED to emit light?

? Do you think that the light emitted by the LED was due to incandescence? Explain.

A device that uses a similar process to emit light as the LED is the Lime Lite® night-light that emits a faintly glowing green light when plugged into the household power supply.

We will now continue the investigation by exploring other ways in which matter can emit light.

Place a Wint-o-green™ Lifesavers® mint in a plastic sandwich bag and close the bag. Take the bag with the mint and a pair of pliers into a dark location and let your eyes adjust to the darkness. Crush the mint with the pair of pliers and observe what happens.

Be careful not to crush your fingers.

? In the space provided below, describe what you observed.

? What type(s) of energy caused light emission?

? Was the emitted light due to incandescence? Explain.

We will now examine the properties of a light stick. Remove the light stick assigned by your instructor from its wrapper and activate the light stick by bending and snapping it to break the inner glass vial. Shake the contents.

Be careful not to puncture the light stick! Although the contents of the light stick are non-toxic and non-corrosive, the contents may permanently stain your clothing.

- ? In the space provided below, describe your observations.

- ? What type(s) of energy was (were) required for the light stick to emit light?

- ? Did you detect that the light stick changed temperature after it was activated?

- ? Was the light emitted by the light stick due to incandescence? Explain.

- ? Do you know of any other objects that emit light in the same way as the light stick?

We will now observe the light emitted by glow in the dark objects.

Take a ball or other glow-in-the-dark object and observe it in a darkened room. Then take it to a bright light and expose it to the light for awhile and return to the darkened room.

- ? In the space provided below, describe your observations.

? What type of energy caused the glow-in-the-dark object to give off light?

? Was the emitted light due to incandescence?

The LED, Wint-o-green™ mints, glow-in-the-dark objects, and light stick did not involve an appreciable emission of heat or rise in temperature.¹ As a result, the process was not incandescence or “hot light”. To quote Polonius from Hamlet (Act I, Scene 3), “These blazes, give more light than heat.” The process in which light is emitted by a material with very little change in the material’s temperature is called luminescence or “cool” light.

Luminescence can take many forms. As you observed in your exploration, luminescence can involve different forms of energy. Light emission as result of adding electrical energy is called electroluminescence. An LED emits light by the process of electroluminescence.

Light emission caused by adding mechanical energy to a material, such as by crushing Wint-o-green™ Lifesavers®, results in mechanical deformation of the material and is called mechanoluminescence or triboluminescence. Other examples of mechanoluminescent light include that seen by pulling apart adhesives like Curad®-brand bandage wrappers or by grinding table sugar. Flashes of mechanoluminescent light have also been observed during earthquakes when large pieces of rock slide past one another (National Public Radio, 1996).

Glow-in-the-dark objects do not give off light unless they are first exposed to another source of light. The source of energy for these objects is the original light source. When an object absorbs light of one energy or color and then gives off light at a different color or energy this is called photoluminescence. Glow-in-the-dark and fluorescent materials fall under this category. We will explore these two photoluminescent processes in a later activity.

¹ With this discussion of heat and temperature and the 1996 summer release of the movie, Independence Day, one is reminded of the classic science-fiction story of The War of the Worlds by H.G. Wells in which the invading Martians use a powerful heat ray to conquer the people of Earth. Wells describes this heat ray as a “flaming death, this invisible, inevitable sword of heat that caused pine trees to burst into fire and every dry furze bush became with dull thud a mass of flames”. For more information about the book, look for the book at your school library or check out the following web site: <http://fourmilab.ch/etexts/www/warworlds/b1c5.html>.

For the case of the light stick, mechanical energy was supplied to break the glass vial found inside. The emission of light, however, is the result of a spontaneous, energy-producing chemical reaction that occurs when the chemicals in the glass vial mix with those in the rest of the light stick. The energy from the chemical reaction was converted into light and the resulting light emission is called chemiluminescence. Small light sticks can be found in clear golf balls that are used to play golf at night. Light sticks can be found at amusement parks or specialty stores as necklaces and headbands. They can also be found in bait and tackle shops to be used as lures for night fishing.

If a chemical reaction that converts energy into light occurred in a living organism, the organism exhibited bioluminescence. Fireflies and certain types of ocean plankton, bacteria, algae, plants, shrimp, jellyfish, shallow sea creatures (for example, flashlight fish and luminous brittle stars), and deep-sea creatures (for example, squid and lantern fish) emit bioluminescent light. Bioluminescence will be discussed in more detail in Activity 5.

Flashes of blue-green light have been observed when a gas bubble, trapped in a liquid and exposed to sound (audible to ultrasonic), expands and contracts. This type of luminescence, which occurs in bubbles, is called sonoluminescence. Sonoluminescence can continue for hours (Glanz, 1996; Crum, 1994; Barber, 1992).²

Eihard Wiedemann developed a classification chart in 1889 to differentiate between incandescence and luminescence. (See Figure 1-1.) Read the chart from top to bottom. Based on whether the emission of light involved a substantial increase in temperature, use the chart to identify the type of light emission from any lighted object.

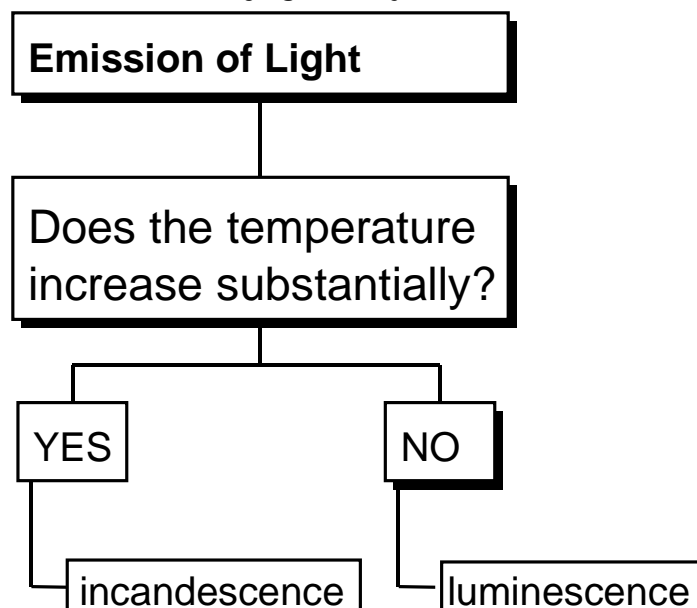


Figure 1-1: Processes of Light Emission

²Sonoluminescence was the subject for the movie, *Chain Reaction*, which was released August of 1996. To learn more about “Hollywood’s” version of sonoluminescence and the movie, investigate the following website: <http://movieweb.com/movie/chainreaction/index.html>.

The chart illustrated in Figure 1-2 expands on Wiedemann's classification scheme and summarizes the results of your exploration.

In this activity, we differentiated between incandescence ("hot light") and luminescence ("cool light") and explored materials that emit light through various types of luminescence. In the next activity, we will continue our exploration of luminescence by focusing on luminescent materials that must absorb light in order to emit light.

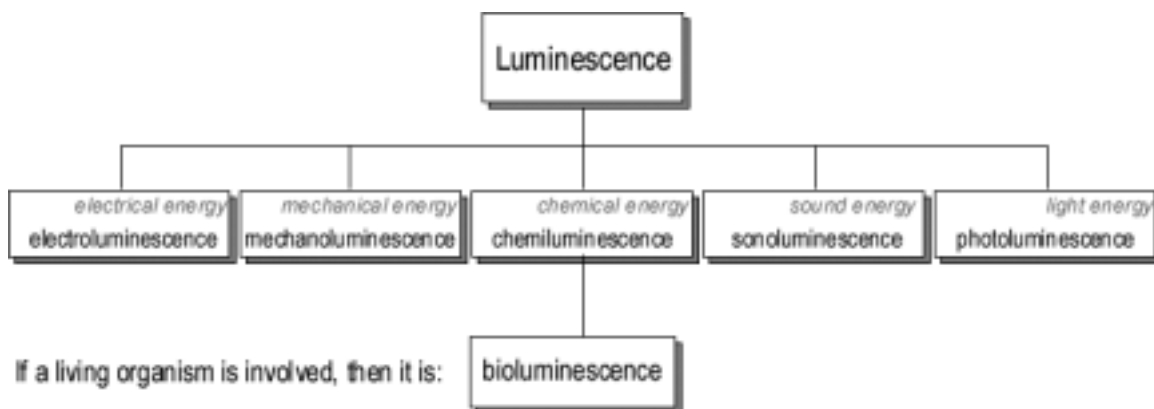


Figure 1-2: Types of Luminescence

Homework Activity:

1. Below each luminescent category of Figure 1-2, identify the investigated object or device that exhibits the corresponding method of light emission.

2. For the luminescent phenomena that you didn't investigate in class, search the Internet or library to learn more about those particular phenomena. Use the recommended Web sites that are found through out this activity as a starting point.

Name:

Class:

LUMINESCENCE
It's Cool Light!

Visual Quantum Mechanics

ACTIVITY 2

Observing Light Patterns

Goal

In this activity, we will continue to investigate the properties of luminescent materials and devices by observing and exploring their light patterns as well as the light patterns from a gas lamp.

In Activity 1 we observed that luminescent devices and materials have different properties and utilize different methods of light emission. To explain the properties and operation of these devices and materials, we will construct a conceptual model of what is going on at the atomic level.

Luminescent materials, with the exception of the chemicals utilized in light sticks, are made up of solids which consist of a large number of atoms that are closely packed together and interact with one another in a complex manner. To begin to understand solids at the atomic level we will start with gases where the atoms are far apart and seldom interact. Once we build an atomic model that can explain the emission of light for gases we will return to luminescent materials and devices. Our model will not only explain the physical properties of the luminescent materials that we investigated in the first two activities but will also explain the spectral properties of these materials as well as light sources made up of gases - called gas lamps or gas discharge tubes. Thus, in order to be able to understand fully the properties of luminescent materials, we need to study the light emitted by both gas lamps and these materials more carefully.

We will use spectrosopes to look at the colors produced by each light emitting device. The spectroscop is a tool that breaks down light into its individual colors. These colors are displayed on a numerical scale.

In our investigations, we will be particularly interested in the energy of the light. Studies of light have revealed that two properties – brightness and color – are related to the energy of the light.

Light is emitted in small packets of energy. Each packet, called a photon, contains an amount of energy that is related to its color. One photon of red light has less energy than one photon of violet light. Other colors are between these extremes.

Our eyes interpret several different energies of photons as one color. For example, we see different shades of red. The spectroscop will help sort out all of the energies related to colors, even shades of the same color.

Kansas State University

©2001, Physics Education Research Group, Kansas State University. Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

Brightness is also a factor in the energy emitted by a light source. Clearly, the sun emits more energy than a candle, a flashlight, or an LED. Brightness is a measure of the number of packets (photons) of light energy. A bright light emits more photons than a dim light of the same color.

In our investigations we will be primarily interested in the energy of individual photons. As we will see, this energy will tell us something about the atoms of a material. Thus, the color of a light will be an important variable. Each photon of visible light carries a very small amount of energy. This energy ranges from about 2.56×10^{-19} Joules for red light to 4.97×10^{-19} Joules for violet. These very small numbers are inconvenient, so we will use a different unit of energy – the electron volt (eV). In these units, visible light energies range from about 1.6 eV (red) to 3.1 eV (violet) – much easier numbers to deal with.

Some spectroscopes provide scales directly in eV. Others show measurements in nanometers (nm) or Ångstroms (Å). If yours use one of these units, recording your observations on the scales provided will enable you to determine the energy value in eV directly.

First, you will use the spectroscope to observe light patterns emitted by hydrogen and mercury gas lamps. Gas lamps can be found everywhere from display signs (for example, neon gas) to streetlights (that is, mercury or sodium gas). In the laboratory, a gas lamp consists of a glass tube filled with a gas (called a gas discharge tube) and a high voltage power supply. When the gas tube is connected to the power supply and the lamp is turned “on”, the gas tube emits light. The voltage applied across the gas tube is typically about 4000 volts.

- Caution:
- 1) Because the gas lamp is a high voltage light source, do not touch the metal contacts that connect the gas tube to the power supply.
 - 2) Never look at the sun with a spectroscope

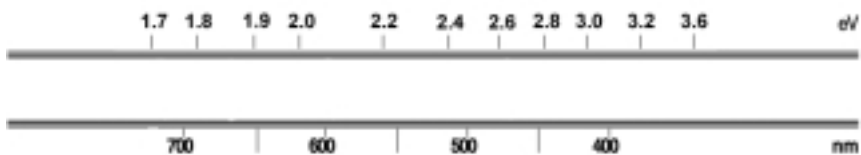
On the following scales, draw the pattern of emitted light observed with the spectroscope for the gas lamps.^{Hint} Use colored pencils or markers to indicate the position of color(s). If necessary, add written descriptions of your observations. Answer the following questions when observing the light patterns of the various gas lamps with the spectroscope:

- ? How many different colors of light are emitted?
- ? What color(s) of light appear to be the brightest or most intense?

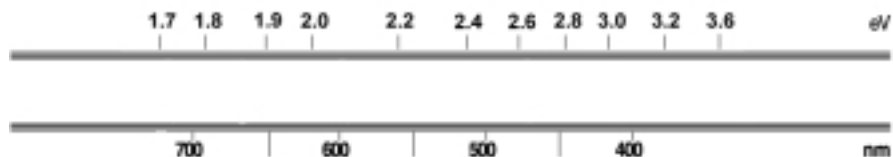
^{Hint} To ensure that the light patterns are clearly visible, position the vertical slit of the spectroscope (found on the end with a screen) so that it is directly facing the light source and, if possible, hold the spectroscope less than a foot away from the light source. Dim the lights of the room so that the light patterns may be seen. The room, however, should be lighted enough for the energy scale to be seen.

Light Patterns Emitted by Gas Lamps

Hydrogen or _____:



Mercury or _____:



In the table below record the color of light that is related to the greatest and least energy per photon emitted by each gas lamp.

Gas Lamp	Greatest Energy	Least Energy

- ? How can you tell which particular color of light emitted by each gas lamp results in the greatest number of photons emitted?

In the table below record the color(s) of light that result in the greatest number of photons emitted by each gas.

Gas Lamp	Greatest Number of Photons

- ? What are the similarities among the light patterns observed for the various gases?

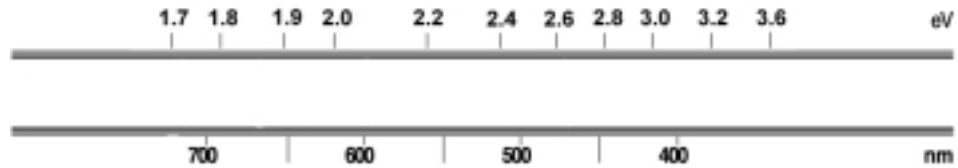
- ? What are the differences?

We will now use the spectroscope to observe the light pattern emitted by the fluorescent lamp. Recall that phosphorescent materials require visible light from a typical fluorescent lamp to emit light. The typical fluorescent lamp is one of the most efficient and economical sources of industrial and commercial lighting. Fluorescent lamps generally have a higher efficiency and longer life than incandescent light sources.

On the following scale, draw the pattern of emitted light observed with the spectroscope for the fluorescent lamp. Use colored pencils or markers to indicate the position of observed colors. If necessary, use written descriptions of your observations. Answer the same questions as before when observing the light patterns of the gas lamps:

- ? How many different colors of light are emitted?
- ? What color (energy) of light appears to be the brightest or most intense?
- ? What energy values (in eV) are observed for the color(s) of light emitted?

Light Pattern(s) Emitted by the Fluorescent Lamp



- ? In terms of the color, intensity, and patterns of light emitted, how is the fluorescent lamp similar to the gas lamps?
- ? How are they different?

The pattern of light emitted by gas lamps is called a *discrete spectrum*. These light patterns appear as a limited number of bright lines of certain colors. The continuous pattern of light observed for the fluorescent lamp is called a *continuous spectrum* for its broad pattern of various colors with no dark regions. The fluorescent lamp emits complex spectra consisting of both a discrete spectrum and a continuous spectrum.

- ? Based on your prior observations of the spectra of gas lamps, what do you think is responsible for the discrete spectrum emitted by the fluorescent lamp? How do you know?

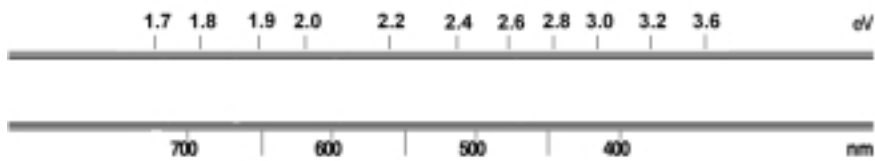
The descriptive name, "fluorescent lamp" provides a clue that the fluorescent lamp must somehow use fluorescence in its emission of light. The question of how fluorescence applies to the emission of light by the fluorescent lamp will be addressed in a later activity.

We will now observe the spectra emitted by other luminescent devices. Use the spectroscope to observe the spectrum of the object assigned by your instructor.

On the following scale, draw the light spectrum as observed with the spectroscope for the luminescent device assigned by the instructor. Use colored pencils or markers to indicate the position of the observed color(s). Answer the following questions when observing the spectrum for the light stick:

- ? How many different colors of light are emitted?
- ? What color (energy) of light appears to be the brightest or most intense?
- ? What energy values (in eV) are observed for the color(s) of light emitted?

Spectrum Emitted by _____



After everyone has completed the investigation, each group should share its results with the entire class. The resulting discussion should focus on the following questions.

? Compare your observations with those of other students who looked at different luminescent devices. How are they similar?

? How are they different?

Summarize the results of all observations in the class and discussion by completing the following table.

Luminescent Device	Color(s) of Light Observed	Energy (in eV) of Brightest Light Observed
<i>light sticks</i>		
<i>LED or Limelight</i>		
<i>phosphorescent object</i>		
<i>fluorescent object</i>		

Summarize the results of your observations of the spectra of the gas lamps, fluorescent lamp, and the luminescent devices by completing the table below with the differences (placed above the gray boxes) and similarities (place below the shaded boxes) among the light sources.

<i>Light Source</i>	Gas Lamps	Fluorescent Lamps	Incandescent Objects
Gas Lamps			
Fluorescent Lamps			
Incandescent Objects			

Your table should show some differences and similarities in the observed spectra emitted by gas lamps, fluorescent lamps, and the other luminescent devices. Spectra can be considered the fingerprints of matter. It allows us to identify not only the material found in artificial light sources (i.e. fluorescent lamps) but also natural ones like the sun and other stars.

The smaller number of colors and discrete nature of gas spectra hints that the emission of light by gases might be easier to understand than luminescent sources. We will now concentrate on gases in the next activity.

Name:

Class:

LUMINESCENCE
It's Cool Light!

Visual Quantum Mechanics

ACTIVITY 3

Introducing Energy Levels in Atoms

Goal

In this activity, we will use the *Gas Lamp Spectroscopy* computer program to understand how the spectral properties of gas lamps leads to discrete energy level models of atoms.

In the previous activity, we found that gas lamps emit distinct colors and therefore energies of light. These energies are emitted by the atoms in the gas. Atoms are the smallest components of a substance that possess the same physical and chemical properties of the substance. Unfortunately, atoms are too small to see so we will use experimental observations in addition to computer simulations to build an atomic model of light emission.

Although the atom is very small, it has a definite structure. Each atom in a gas tube consists of a positively charged nucleus at the center and negatively charged electrons outside the nucleus. As a result of the opposite charges on the electrons and the nucleus they attract each other. This attraction causes the electron to change energy as it approaches the nucleus.

These energy changes must obey the conservation of energy law. When an electron's energy decreases, some other form of energy must appear. For an electron in an atom the energy appears as light. Thus, by looking at the light emitted by gas atoms we are seeing the result of energy changes in atoms.

We will now use *Spectroscopy Lab Suite* to determine what the distinct spectral lines emitted by gases can teach us about the energy change of atom-bound electrons.

In *Spectroscopy Lab Suite*, select *Emission* under *Gas Lamps*. In this program, we can

- Select a gas tube and drag it to the gas lamp socket. The spectra for that gas will appear at the top of the screen.
- Add energy levels for an electron by using the Add Energy Level button.
- Move the energy levels by grabbing them at the left of the energy scale and dragging them to the desired position.

Kansas State University

©2001, Physics Education Research Group, Kansas State University. Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

- Create changes (represented by vertical arrows) by selecting the electron's initial energy (it turns green) and dragging the arrow to the electron's final energy. A colored spectral line on the lower spectrum will indicate the light emitted by the energy change that you have created. If the light is not in the visible spectra, it will not appear on the screen
- To match the energy changes with the gas spectrum you may move the initial and final energies. After inserting the changes you will see the spectral line change in an appropriate fashion.

Drag the figure of the hydrogen gas tube to the gas lamp socket. Look at the top of the right screen to see the spectral lines for hydrogen.

Create a transition that will match a line in the lower spectrum with one of the computer-generated spectral lines of hydrogen.

- ? How many electron energy levels are needed to create one spectral line?
- ? What is the energy of the spectral line as indicated by the eV scale?
- ? What is the difference in energy between the electron's initial total energy and its final total energy?^{H int}

Move the initial energy to a different value.

- ? What happens to the spectral line?

Now, move the final energy until the spectral line returns to the correct position.

- ? What is the energy difference between the initial and final energies?

^{Hint} Use the energy scale found on the right of the potential energy diagram.

The emission of one photon occurs when an electron makes a transition from a higher allowed total energy to any lower allowed total energy. The energy of this photon is equal to the difference of the electron's final and initial allowed total energies. Many such transitions create each spectral line that we see. Thus, the energy of the spectral line will remain constant as long as the difference in the electron's final and initial energies is constant.

Now create and move other energy levels and transitions until the bottom spectrum matches the top spectrum.

Sketch the resulting energy level diagram for hydrogen in the space below.

- ? How many energy levels are needed to create these three spectral lines?

- ? How many electron transitions are needed to create these three spectral lines?

- ? What other, if any, possible electron transitions can take place with the allowed energy levels illustrated on the screen?

Compare your energy diagrams with those of other students.

Describe the similarities and differences.

Repeat the steps to determine the energy levels and transitions necessary to produce the spectral lines emitted by mercury.

Sketch the resulting energy level diagram for the mercury gas in the space below.

? How is the energy level diagram for the mercury gas similar to the diagram for hydrogen?

? How are they different?

An important conclusion from this analysis is that we can explain the spectrum of gas atoms with just a few energy levels and a few transitions. Atoms always emit photons with the same energies, and each type of atom always has the same spectrum. From our matching of the spectra we must conclude that an electron can have only a few of all possible energies in an atom. These energies are called allowed energies.

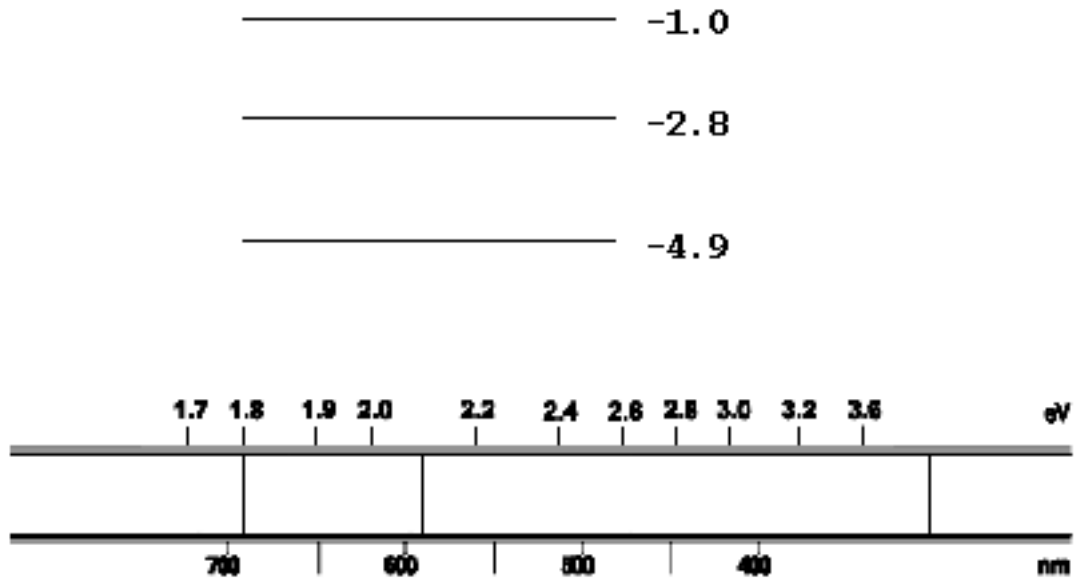
To emit a photon of light an electron moves from one allowed energy to another. The energy of the photon is equal to the difference between the electron's initial and final energy. Because we see photons of only a few energies, we conclude that only a few energy differences exist for each atom.

We also conclude that different types of atoms have different energy levels and transitions. The conclusion arises from the different spectra for each element.

Energy levels in atoms are sometimes described as "quantized", because of their relation to discrete, separated values. The electron transition is a change from one quantized energy to another. Thus, the general study of the behavior of electrons and other small objects is called quantum mechanics.

Homework

- 3-1) Construct the spectrum of light emitted by a gas represented by the following energy level diagram.



- 3-2) Visible light ranges in energy from 1.6 eV (red) to 3.1 eV (violet). How much of the resulting spectrum lies in the visible range?
- 3-3) Confirm your answers by using *Gas Lamp Spectroscopy*.

Name: _____

Class: _____

LUMINESCENCE
It's Cool Light!

Visual Quantum Mechanics

ACTIVITY 4

Applying Energy Levels to Luminescence

Goal

With the help of energy levels diagrams, we have been able to use the spectra to learn about energy in atoms. We will now apply a similar technique to learn how energy levels in luminescent materials are similar to and different from atoms.

Just by viewing various objects we see that some luminescent devices emit light that *looks* similar to gas lamps. Others however seem to emit light that is quite different. In this activity we will look closely (through a spectroscope) at light emitted by some objects. Then we will apply energy levels to understand more about energy in atoms of solids and liquids.

Your instructor will assign your group a device such as an LED, light stick or glow-in-the-dark object. Observe the spectrum of the object and record the results below.

Object: _____



Describe the spectrum in words.

Compare your observations with those of other groups.

Kansas State University

©2001, Physics Education Research Group, Kansas State University. Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

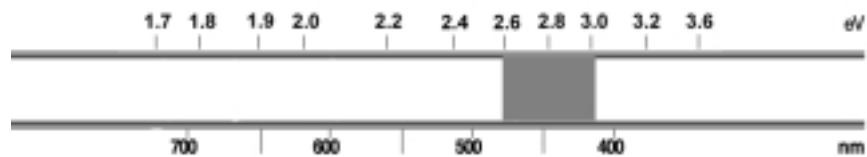
- ? How are the spectra similar?
- ? How are they different?
- ? Do you see any similarities between these spectra and those of gases?
- ? Do you see a difference?

Now, we will see what these observations can tell us about energies in solids and lights. To begin we will pretend that these objects have gas atoms. So, we will try to use the gas model to build a set of energy levels and explain these spectra.

Open *Emission* under *Gas Lamps* in the *Spectroscopy Lab Suite* and place the unknown gas tube in the gas lamp socket.

Click on the Edit button and type in the energy values for the computer-generated spectral pattern that will appear on the top black screen which illustrates the spectrum that you have just observed.

Use the program to produce an energy level diagram that would result in the following spectrum.



- ? In the space below sketch your energy level diagram.

Compare your results and those of your fellow students' with previous energy level diagrams that were drawn in the previous activity. The resulting discussion should focus on answering the following questions.

? How are the allowed energies in your above diagram similar to ones drawn in the previous activity?

? How are they different?

Placing the energy levels close together gives us a spectrum that approximates the spectrum of the luminescent objects. To create energy diagrams that come closer we would need to use more energy levels. Putting in all of the transitions would be tedious. So we will just note an important conclusion: A spectrum which is continuous and covers part of the visible spectrum leads us to conclude that initial energies of the electrons are very close together. The final energies are also close together. The light energy is related to the energy levels as shown in Figure 4-1.

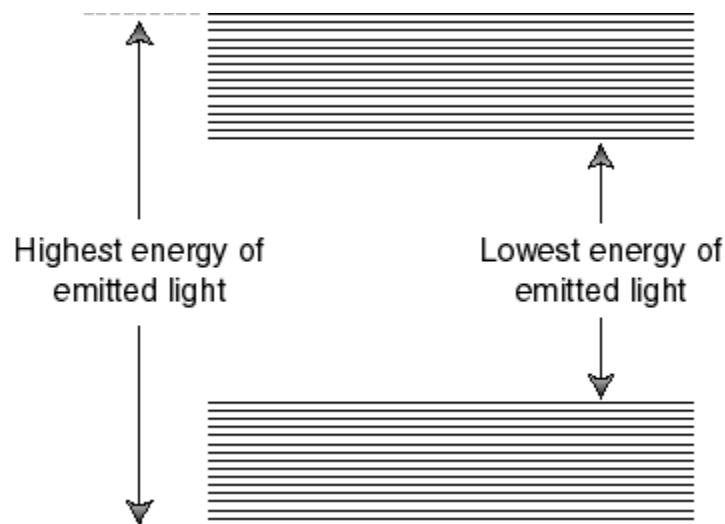


Figure 4-1: An approximation to the energy level diagram for an LED or lightstick.

To improve the approximation we add more energies. As we add the energies the diagram will look as Figure 4-2.

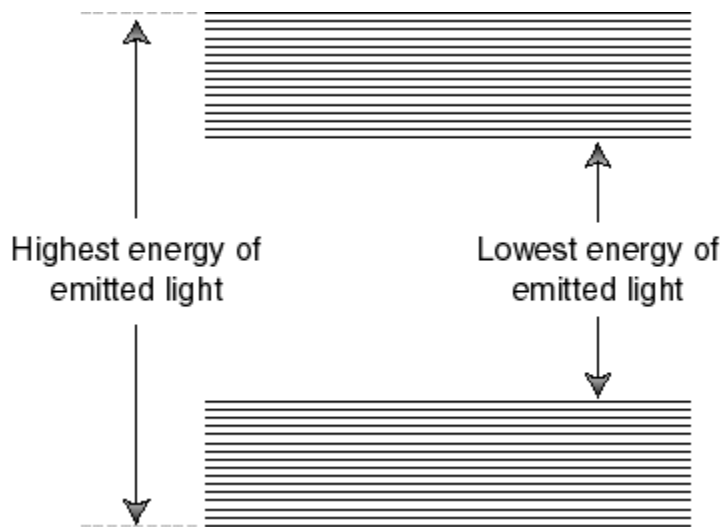


Figure 4-2: Energy bands for a solid.

When the energies become so close together that we cannot distinguish individual levels we say that we have *energy bands*. These bands are separated by an *energy gap*. The bands are given names as shown in Figure 4-3.

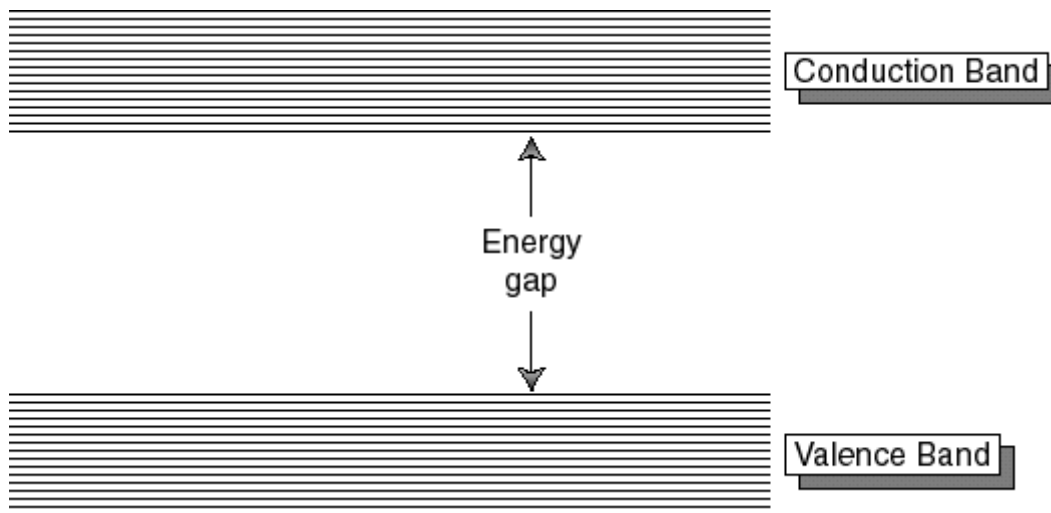


Figure 4-3: The names of the bands and gap.

Now we will use another program in the *Spectroscopy Lab Suite* to understand LEDs and how the bands and gap are related to spectra. Begin by selecting LEDs in the program.

Drag the figure of the LED that is closest in color to the object you observed to the socket. The computer-generated spectrum emitted by the LED should appear at the top of the screen.

Click the Add Conduction Band button. A red rectangle that represents this band should appear near the top of the energy scale.

Click on the Add Valence Band button. A faded-red rectangle that represents this band will appear near the bottom of the energy scale. The spectrum that results from these energy bands is displayed on the lower spectrum.

The broad, orange vertical arrow represents the allowed transitions for electrons in the LED as they move from energy levels in the conduction band to energy levels in the valence band. As these electrons make transitions, they lose energy in the form of light.

Place the cursor in the center of one of the bands. The band turns green and a hand symbol appears. You may change the energy of the selected band by dragging it.

Place the cursor on the top or bottom edges of one of the bands. The band turns green and arrows that point up and down appear. You may now change the energy of the selected edge of the band.

Now adjust the energy bands and their edges until the bottom LED spectrum matches the spectrum illustrated on the top.

In the space provided below sketch the resulting energy band diagram and indicate the LED and the range of energy values (in eV) for each band and the energy gap.

After everyone has sketched the energy band diagram for their LED, each group should share its results with the class. The resulting discussion should focus on answering the following question.

? How is the value of the energy gap related to the color of light emitted by the LED?

We are now able to apply energy level diagrams to the spectra of the electroluminescent device—an LED. The spectra emitted by LEDs is the result of electrons making transitions from a large number of energy levels in the conduction band to a large number of energy levels in the valence band (See Figure 4-4.). The maximum energy for electron transitions is from the highest energy level of the conduction band to the lowest energy level of the valence band (See A of Figure 4-4.). The lowest energy transitions are from the lowest energy level of the conduction band to the highest energy levels of the valence band (See B of Figure 4-4.). Transitions between these extremes result in the emission of a continuous spectrum that is concentrated on a

few colors (and thus energies) of light. The size of the energy gap of the solid determines the lowest energy of light emitted by the LED. Thus, if we know the spectra of light emitted by an LED or any other luminescent device we can predict its energy gap.

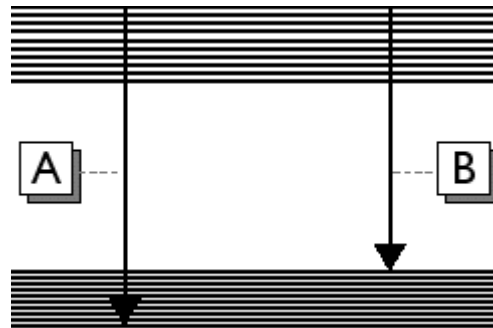
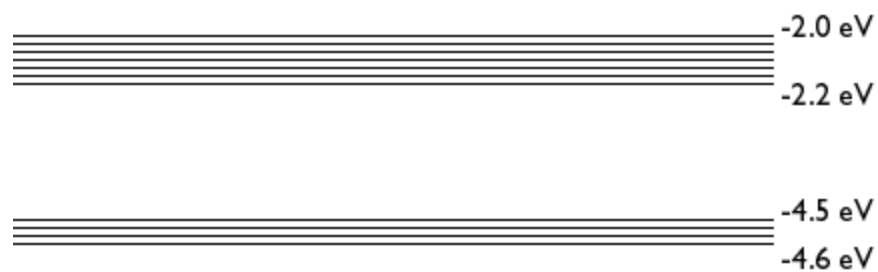


Figure 4-4: Ranges of Allowed Transitions for a Solid that Makes Up an LED

As stated earlier, the interactions among atoms in solids and liquids are more complex than in gases. In terms of allowed energies, gases have individual energy levels whereas solids have a number of energy levels grouped in bands. Although this model can be used to understand the properties of luminescent materials made up of solids, the energy band model is not sufficient to describe the properties and operation of a light stick. The light stick consists of liquids that involve more complex types of interactions than the ones we have discussed for atoms of solids. Thus, our model cannot and should not be used to describe the mechanism in which the light stick operates. However, since the light stick emits a spectrum similar to that of a solid luminescent object, the light stick is a very appropriate source to study in this unit. We will return to it later.

Homework

4-1) A phosphorescent toy is created with a solid which has the energy bands and gaps shown below:



- a) What is the energy gap of the solid?

- b) Explain, using the diagram, the possible transitions for electrons in this solid.

- c) Describe the spectrum of visible light emitted by this glow-in-the-dark toy in terms of energy and color.

Name:

Class:

LUMINESCENCE
It's Cool Light!

Visual Quantum Mechanics

ACTIVITY 5

Exploring Photoluminescence

Goal

In the previous activity, we explored several types of luminescence and compared it with incandescence. In this activity, we will investigate luminescent materials that require light to emit light. These materials are called photoluminescent.

In a dark room, open the black envelope labeled "A" assigned by your instructor that contains an object that has been placed in it overnight. Take the object out of the envelope.

? Does object "A" emit light? If it does, in the space provided below describe the emitted light.

Turn on the lights and expose the object to the light. After a few seconds, turn off the lights.

? Does object "A" seem to emit light when the lights are on?

? Now, turn the light off again. Does light come from object "A"? If it does, in the space provided below describe the characteristics of the emitted light.

Photoluminescence, unlike the other types of luminescence, requires light in order to emit light. As a result, the chart used in the first activity to identify the different types of luminescence (Figure 1-3) needs to be expanded to include Figure 5-1 illustrated on the following page.

Kansas State University

@2001, Physics Education Research Group, Kansas State University. Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

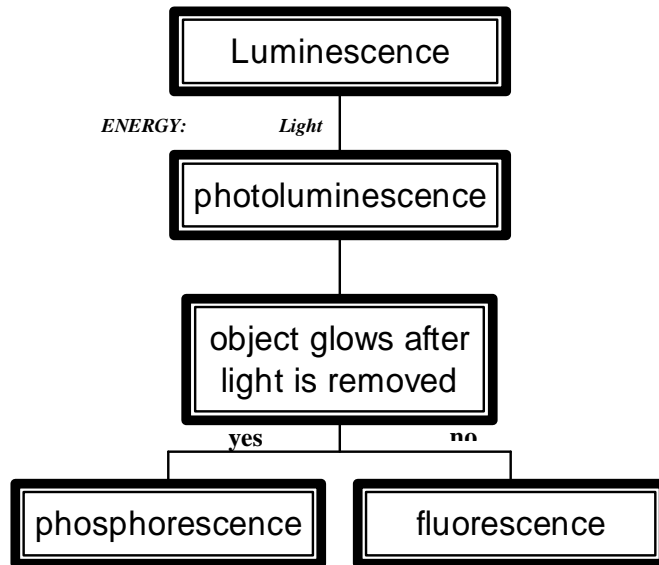


Figure 5-1: Photoluminescence Addition to Luminescence Chart

According to Figure 5-1, a photoluminescent object emits light or glows as a result of shining light on the object. An object that utilizes phosphorescence will glow-in-the-dark after the lights have been turned “off”. A fluorescent object emits light only in the presence of light.

? Using the chart, what process of photoluminescence does object “A” utilize to emit light? Explain.

Caution: The UV light emitted from some black lights has the potential to cause eye damage! Don’t look directly at the light and always wear safety goggles when using the black light.

In this part of the investigation, we will be using a fluorescent lamp and a black light. The fluorescent lamp emits visible light and is a common light source found in many businesses, schools, and homes. The black light is a special type of fluorescent lamp that emits nearly invisible and invisible light of high energy, called ultraviolet (UV) light.

Now, we are using the light from fluorescent tubes to study other photoluminescent objects. As you might suspect, fluorescent tubes use the fluorescence process. We said that light produced by fluorescence does not require electricity, yet a fluorescent lamp does. The process in which the fluorescent lamp operates will be explained in later activities.

The photoluminescent objects under investigation have been stored in a black plastic bag for a few days.

In a darkened room place the two objects, one at a time, on a piece of black paper. Turn on the fluorescent lamp and observe the appearance of each object in the light. After making the observations for one object, remove the object from the paper and place another object in its place. Your investigation should focus on answering the following questions:

- ? Does the color and appearance of the object change when the light strikes it?
 - ? How does the brightness change after the light is turned "off"?
 - ? How long is the light emitted by the object visible?
- ? In the space provided below, record your observations for each object.

Repeat the same procedures to illuminate the same two objects, but this time expose them to different colors of visible light (red, green, and blue) by using color filters. Color filters absorb all the colors of light emitted by "white light" source (i.e. fluorescent lamp) except for the color of light that is identical to the color of the filter. The color filter transmits this particular color of light. For example, a red color filter allows red light from the fluorescent lamp to be transmitted to the object. Your investigation should focus on answering the following questions:

- ? Does the color and appearance of the object change when the light strikes it?
- ? How does the brightness change after the light is turned off?
- ? How long is the light emitted by the object visible?

In the table provided below, record your observations for each object.

Color of Light	Object #1	Object #2
<i>Red</i>		
<i>Green</i>		
<i>Blue</i>		

Remove the color filters and now illuminate the two objects with the black light. Your investigation should focus on the same questions:

- ? Does the color and appearance of the object change when the light strikes it?
- ? How does the brightness change after the light is turned off?
- ? How long is the light emitted by the object visible?

In the space provided below, record your observations for each object.

After completing the investigation, as a group use your observations and Figure 5-1 to identify the process of light emission for both objects. Record the results in the space provided below.

After each group has identified its photoluminescent objects as being either phosphorescent or fluorescent, each group should share its results with the entire class. The resulting discussion should focus on completing the following table and answering the following questions.

Phosphorescent Objects	Fluorescent Objects
glow-in-the dark toys	light sticks
watches	paraffin wax
toothbrushes	laundry detergent with whiteners
vinyl sheets	colored glass
stickers	fluorescent minerals
posters	clipboards
etc.	etc.

- ? Describe the characteristics (such as color, brightness, and duration) of light emitted by the phosphorescent objects.

- ? What conditions were required for light emission by the phosphorescent objects?

- ? Describe the characteristics of light emitted by fluorescent objects.

- ? What conditions were required for light emission by the fluorescent objects?

? How are phosphorescent and fluorescent objects similar?

? How are they different?

Fluorescent objects emit light immediately after absorbing light. When the light source is removed, the object immediately ceases to glow.

Phosphorescent objects continue to glow for some time even after the light source has been removed. Thus, phosphorescent objects are said to glow-in-the-dark. A phosphorescent surface exposed to visible light continues to glow even after the light is turned "off" because the energy absorbed from the light is released over a period of time. For example, phosphorescent ink is used to paint the hands of some watches. The paint absorbs light when illuminated and glows when the lights are turned "off".

While the visible light emitted by the fluorescent lamp can activate phosphorescent materials, fluorescent materials require UV light to produce their characteristic glow.

One practical application of phosphorescent materials is glow-in-the-dark tapes and signs used to identify escape routes during emergencies when visibility is reduced (Hanovia, 1996).

A practical application of fluorescence involves fluorescent markings on credit cards to determine whether the cards are real or counterfeit.

The U.S. Treasury Department is redesigning currency to make counterfeiting more difficult. One of the security features found on the new bills is a fluorescent thread found inside the paper. The thread's relative position indicates the currency denomination and glows red when exposed to UV light. This thread and other security features (such as micro-printing, color-shifting ink, portrait enlargement, and concentric fine lines) will eventually be added on all bills of \$20 or greater.

The black light used in this activity is an artificial source of UV light. Other sources of UV light include tanning lamps, the lamps used to sterilize medical instruments, and the sun. Tanning and sterilization lamps emit light that is higher in energy than the UV light emitted by a "black light".

Only 1% of the UV from the sun is able to penetrate the earth's atmosphere. Fortunately, the ozone in the atmosphere prevents the very high energy UV light that can cause severe damage to our bodies from reaching us. Unfortunately, scientific studies have reported a reduction in the ozone concentrations in the atmosphere, which means more of the very high energy UV can now reach us.

Recall that UV light is higher in energy than visible light. Overexposure to UV in sunlight can cause sunburns that can eventually lead to skin cancer. Directly looking at UV light can also cause damage to the retina of the eye. As a result, one should not look directly into a source of UV light such as the sun or a “black light”.

UV light has been used to examine fine art or old colored glassware that exhibit fluorescent properties. This colored glass, known by various names (*Canary, Vaseline, Topaz, Depression, Teaberry Gum, Burmese, and Pedal ware*) has been produced since the 1870's and comes in a variety of colors and shapes (Salman & Repko, 1996). Most of this glass exhibits strong fluorescence when exposed to UV light and is radioactive because of the uranium salts used to give the glass its characteristic color.

While humans cannot see UV light, researchers have found that birds and certain insects can see special colors in ultraviolet. For example, birds use natural UV light to select their mates. These special colors are produced when UV light bounces off their feathers. Researchers have found that female zebra finches prefer mates with particular patterns of these colors, among other characteristics (*Science News, 1996*).

Insects such as bees can also see special colors in ultraviolet. Since some flowers, which look alike in visible light, display very distinctive colors in UV light, bees are able to distinguish easily among flowers which look very similar to us (Schissel, 1996).

In this activity, we were able to examine the properties and applications of photoluminescent materials. In the previous activity, we explored the other processes of luminescence (that is electroluminescence, mechanoluminescence, chemiluminescence, and bioluminescence) and compared these processes of light emission with incandescence. The chart illustrated in Figure 5-4 summarizes the types of luminescence that we have investigated.

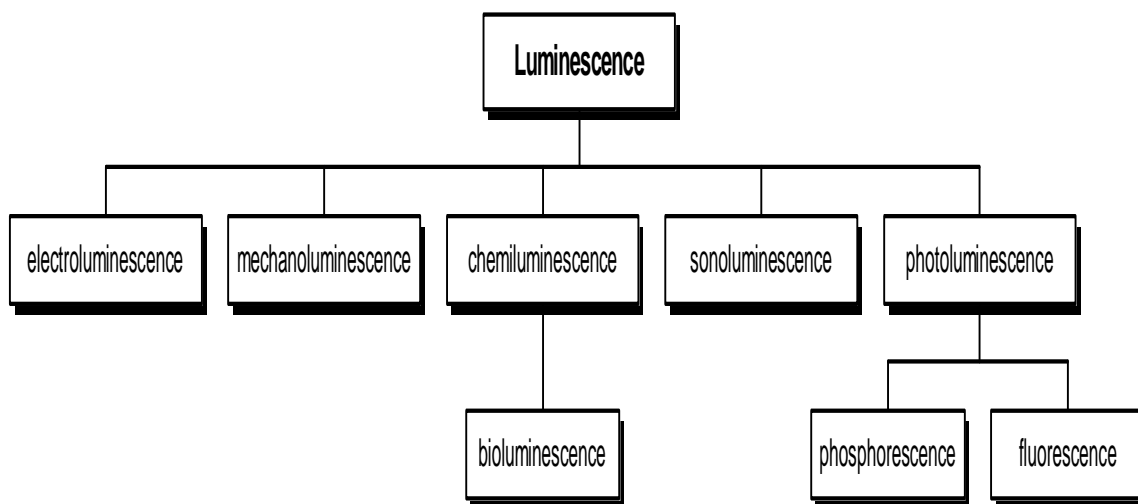


Figure 5-4: Types of Luminescence

In future activities, we will construct models to explain the properties observed for luminescent materials and the fluorescent lamp. Atoms that make up these materials play a key role in these models. In order to fully understand how atoms contribute to the operation of luminescent materials, we will study the light properties of these materials more carefully.

Optional Application Activity

Unlike birds and certain insects, humans cannot see UV light. We, however, can use special plastic beads to detect UV light. Some of these plastic beads have been stored in a black envelope or plastic bag.

Remove one of the beads provided by your instructor and expose it to the UV light emitted by the black light.

Remove another bead from the container and now expose it to the light emitted by a fluorescent lamp.

Remove another bead from the container and expose it to the natural light emitted by the sun.

? What happens to the beads when they are exposed to the light emitted by the black light?

? What happens to the beads when they are exposed to the light emitted by the fluorescent lamp?

? As a result of what happens to the bead when it was exposed to the light emitted by the fluorescent lamp, does the fluorescent lamp emit UV light?

? What happens to the beads when they are exposed to the light emitted by the sun?

? As a result of what happens to the bead when it was exposed to sunlight, does sunlight contain UV light? Explain.

Name:

Class:

LUMINESCENCE
It's Cool Light!

Visual Quantum Mechanics

ACTIVITY 6

Introducing the Potential Energy Diagram as a Model of the Atom

Goal

Now we will introduce an atomic model that we will use to explain luminescent processes. This model will describe an atom in terms of potential energies.

Atoms are extremely small objects that we cannot see directly. So, to understand atoms we complete experiments such as those in the previous activities and use the observation to build our understanding and make predictions. The ideas that we create to help us understand and make predictions are called models. These models give us a representation of the behavior of the object we are studying. This representation does not need to look like the actual object. It is not a model in the way that a Hot Wheels car is a miniature version of the real thing. Instead, it may be quite different from "the real thing" in form but similar in behavior.

We do not have a good "picture" of an atom because we do not see them directly. Instead we build models to help us explain the observations. The model that will be introduced in this activity can provide an understanding of how light is produced by atoms and why different objects emit different types of light.

Our model is based on the knowledge that electrons have a negative electrical charge while the nucleus of an atom has a positive charge. Opposite charges attract, so the atom is held together by electrical forces.

All of our observations have involved light – a form of energy – coming from the materials. We have assumed that atoms in the material emit this light. The process of emitting the light involves changing energy from some other form into light. Thus our model needs to include energy and its conservation.

We begin by looking at the electrical potential energy versus distance for

- one dimension in space,
- a positive electrical charge at 0,
- a small negative electrical charge elsewhere,

Kansas State University

©2001, Physics Education Research Group, Kansas State University. Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

- the positive charge cannot move, and
- negative energies indicate an attraction between two objects.

The graph of the potential energy vs. distance is shown in Figure 6-1. If atoms were one-dimensional, this graph would represent the potential energy of an electron in an atom. The atom is not one-dimensional, but we want the simplest possible model. So, we begin with a one-dimensional model and see what we can learn.

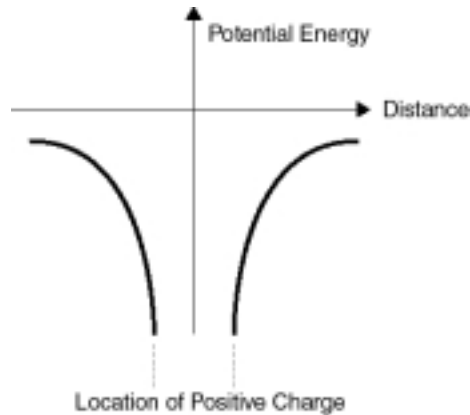


Figure 6-1: Example of the Potential Energy Diagram that Represents a Single Atom. (The dots indicate that the potential energy continues with more negative numbers.)

The graph in Figure 6-1 is an example of a potential energy diagram.

Although the potential energy diagram illustrated in Figure 6-1 does not look like an atom, it does effectively describe the interaction that occurs between an electron and a nucleus. As we shall see, the diagram also allows us to predict some of the atom's behaviors. Thus, Figure 6-1 could be used to represent a single atom.

To get Figure 6-1 as the potential energy representation we made several assumptions to simplify our model. Now, we will make one more – that Figure 6-2 is a good approximation to Figure 6-1.

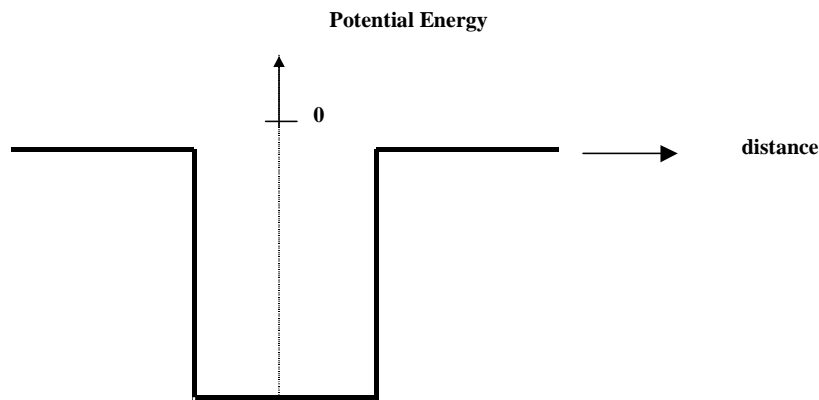


Figure 6-2: Simplified potential energy diagram that we will use to represent a single atom.

This statement is an *assumption*. If we are able to use this model to explain our observations of luminescence, then we conclude that the assumption was good. If the model gives results different from our observations, then the assumption is not so good.

(The change from the curves to the straight line is primarily to allow the computer to calculate faster. As we shall see, it works for most of what we need but it has some limitations.)

In the patterns of light observed through the spectroscope for the gas lamps, we observed distinct lines of different colors. Recall that for this discrete spectrum each line of a different color corresponds to light of a different energy. For each gas lamp, we saw a different number of lines with distinct colors. From this observation, we concluded that atoms of a gas, like hydrogen and mercury atoms, emit only a few distinct energies that can be used to identify these gases. In this and the next activity, we will use computer programs to see how these energies of light are related to the allowed energies for an electron in the atom.

The computer program *Energy Band Creator* does the mathematics to determine the value of the energy for each of the discrete energies in our simple model of the atom. We do not need to know how the math works; we will just look at potential energy diagrams of the results.

To see how it works we will begin with a situation similar to gas atoms. In a gas the atoms interact very little with each other.

Start the *Energy Band Creator* computer program. Click on the Default button. A single potential energy diagram similar to Figure 6-2 will appear on the screen.

The program can determine the allowed energies for the atom represented by this potential energy diagram. Click the Find Energies button. You can enlarge the diagram by clicking inside the potential energy diagram. Click on the magnifying glass with a negative sign to return to the original size.

In the space below, sketch the allowed energies for this situation.

-27 eV ———

-81 eV ———

To see the effect on the energy values, change the lowest value of the potential energy diagram from -100 eV to -200 eV by either using the mouse to drag the green triangle found below the eV scale or by typing 200 in the box to the right of Depth (eV). If you type in the new value, click on the Update Graph button. The potential energy diagram that would represent a different single atom appears on the screen.

Find the allowed energies for this potential energy diagram and sketch them in the space below.

? What is the effect of changing only the depth of the potential energy diagram from -100 eV to -200 eV on the number and values for the allowed energies?

Now investigate changes in the region. Keep the lowest energy at -200 eV and change the width from 0.1 nm to 0.2 nm.

In the space below sketch the allowed energies for the "atom" represented by this diagram.

Describe the effect on the values of allowed energies of changing the width of the potential energy diagram from 0.1 nm to 0.2 nm when the lowest energy is held constant.

The lowest energy and width of this diagram depends on the electrical charge of the nucleus and the number of electrons in the atom. We will not look at details for different elements here. However, we see that changing the lowest energy and width of the potential energy diagram changes the number and location of the possible energies. These changes are similar to ones that we see for energy levels in real atoms.

The horizontal lines on the potential energy diagram represent the allowed *total* energies that an electron in that potential energy can possess. The vertical position represents the electron's total energy. Figure 6-3 (without the axes) is an example of what is called an energy level diagram, and it shows the electron's allowed total energies (dashed lines). Once the diagram contains the allowed energies of the an electron, the diagram becomes an *energy level diagram*.

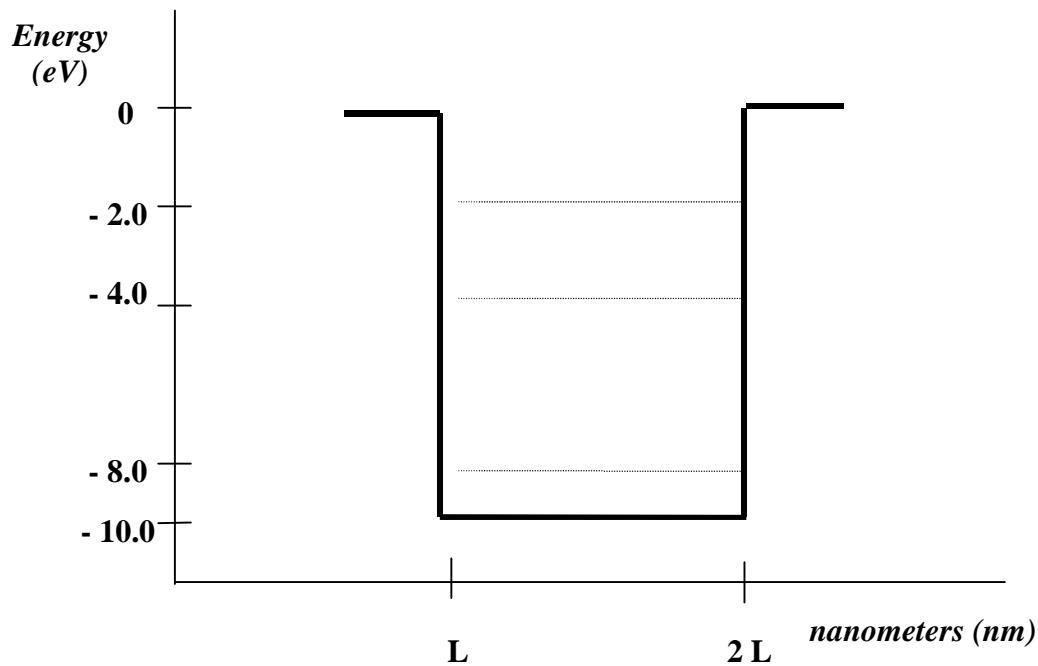


Figure 6-3: Energy Level Diagram

Notice that the total allowed energies have negative values. We use negative values to represent that the electron is attached (bound) to the atom. In Figure 6-3 the value -8.0 eV represents a situation in which an electron has the lowest energy and is attached. The value -2.0 eV represents a situation in which an electron has the greatest energy and is more loosely bound. For the electron to be free and no longer be attached to the atom, the electron must have at least a total energy of 0.0 eV.

The idea of a negative energy may seem rather strange at first. However, the zero for a potential energy can be set at any place that we choose. Then we make all measurements relative to that value. We have chosen the zero of potential energy to be that energy which determines if the electron is attached to the "atom". Positive total energies indicate that it is not attached; negatives that it is. This choice is a matter of convenience.

So far, we have looked at a representation of a single atom and seen how the energy levels change when the parameters (lowest energy and width) are changed. You can see how this representation is similar to the diagrams that you created to describe energy changes that gave us spectra. Both the energies for spectra and the energies in the potential energy diagram exist at only certain allowed values. Different elements have different allowed energies and, thus, different spectra. The potential energy diagram seems to fit our observation of gas atoms. We will now see how it is applied to explain the observations of solid light sources.

Name:

Class:

LUMINESCENCE
It's Cool Light!

Visual Quantum Mechanics

ACTIVITY 7

Applying Potential Energy Diagrams to Solids

Goal

We continue to use the potential energy diagram as a representation of atoms. By bringing these "atoms" close together we see how spectrum from solids are created.

For the model of the atom to represent solids it must include many atoms which are relatively close together. In a solid these atoms interact with each other. The result of those interactions create the properties that we associate with solids. They also create the conditions that enable some solids to emit the light that we have seen

To understand how interacting atoms in solids lead to the broad spectrum of LEDs and other solids we will use the *Energy Band Creator*.

Open the *Energy Band Creator* computer program.

Use the program to create a single potential energy diagram that has a width of 0.1 nm and a depth of - 400 eV.

Use the program to determine the allowed energies for this potential energy diagram.

Sketch below the allowed energy values for the single potential energy diagram as displayed by the program.

Kansas State University

@2001, Physics Education Research Group, Kansas State University. Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

To represent two atoms in this space, add a second potential energy diagram. In the Regular Solid folder found on the bottom of the screen, type "2" in the box labeled Number of Atoms and set the Separation distance to 0.5 nm. Keep the same depth and width as before.

Find the allowed energies for these two potential energy diagrams and sketch them in the space below.

- ? How do the allowed energies of the two potential energy diagrams placed together compare with that of an individual diagram?

Now move these potential energy diagrams closer together. Keeping the depth and the width of the potential energy diagrams the same, decrease the separation to 0.15 nm.

Find the allowed energies for these potential energy diagrams and sketch them below. (Use the zoom-in function of the program to get a closer look at the allowed energies.)

- ? How do the allowed energies of the two potential energy diagrams change when they are brought closer?

We have seen what happens to the allowed energies when two atoms represented by potential energy diagrams are brought close together. Now explore what happens when the number of "atoms" increases.

Use the program to increase the number of potential energy diagrams to the number assigned by the instructor by keeping the depth, width, and separation distance constant. Use the Update Graph button to determine the allowed energies in each case.

Describe, using words and sketches, what happens to the allowed energies as the number of potential energy diagrams increase to the assigned number. Again, you will need to use the zoom function to look closely at each set of energy levels.

Compare your results with other students who were assigned different numbers. The resulting discussions should focus on answering the following questions:

- ? How are the allowed energies in your diagram similar to the others?
- ? How are they different?

The atoms in a solid are relatively close together as in the diagrams we just explored. For instance, the 15 potential energy diagrams are a representation of a 15 atom solid. Such a solid is incredibly smaller than a real solid. For example, the small solid inside an LED has over 10^{23} atoms. However, our less dense solids can give us some idea of how the energies of several closely spaced atoms differ from the energies of isolated gas atoms.

Describe the similarities and differences between the allowed energies of atoms in a solid and those of a gas.

The trend that we saw when we increased the number of atoms continues for very large numbers of atoms in a solid. The energy level diagram for such a solid is shown in Figure 7-1. When the number of atoms increases, the energies merge into groups with no energies allowed between these groups. These allowed energy groups are called *energy bands* and are separated by *energy gaps*.

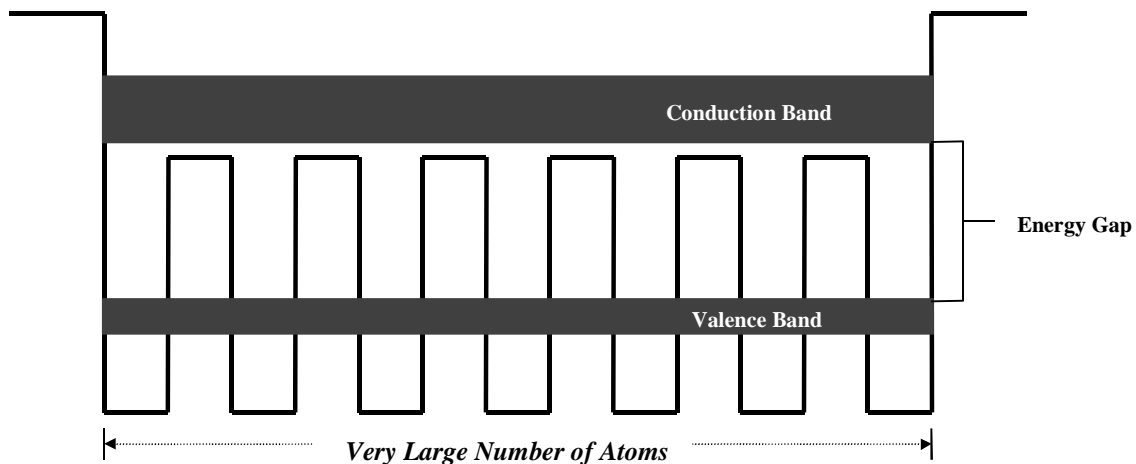


Figure 7-1: Energy diagram with a very large number of solid atoms. Only the upper two energy bands are shown.

Electrons with total energies represented near the top of the energy diagrams are relatively energetic. They are not firmly attached to their respective atoms and can wander about freely throughout the solid. These electrons have energies in the *conduction band*. Notice from Figure 7-1 that the conduction band is located above the individual potential energy diagrams that make up the solid (to represent that the electrons with these energies can move from one atom to the next inside the solid) but are inside the two potential energy diagrams found at the edges (to represent that the electrons with these energies are still bound to this solid).

Recall that the values of the allowed energies for an electron are negative because the electron is bound to the atom. Electrons in the conduction band have relatively small negative values of energy. Other electrons have lower total energies. These electrons are bound to their respective atoms more strongly. These electrons are associated with the next lower energy band that is called the *valence band*.

Figure 7-1 illustrates the energy bands which have the greatest energy and which are important in explaining the physical properties of a solid. Solids also have allowed energies in addition to those found in the conduction and valence bands. Electrons with these lower allowed energies, however, do not influence the overall solid's properties in which we are interested.

These energy bands are similar to the bands that you needed to create to explain the spectrum of the LEDs. When you created those bands, you needed to do it to explain your observations. Now, we see that a relatively simple model of the atom leads to the same conclusions — the energies in solids are grouped in bands with energy gaps between them.

As a brief review Figure 7-2 shows how energy bands and gaps explain the continuous spectrum of luminescent objects.

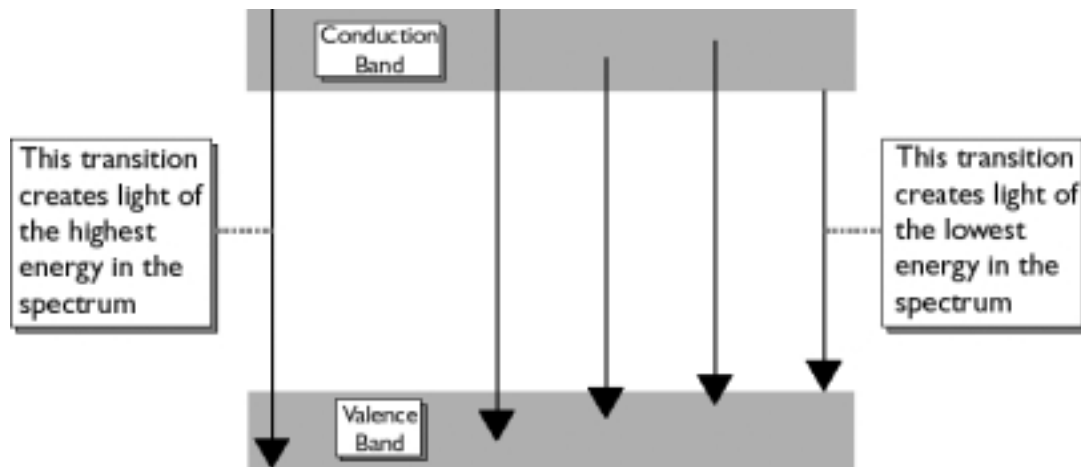


Figure 7-2: Energy bands and energy gaps can explain the spectra of luminescent objects.

Our simple model of representing atoms with squared off potential energy diagrams is not as complex as a real atom. However, it is able to explain our observation of spectra.

At this time we have concluded that energy bands and gaps are consistent with our observations of the spectra which is emitted by solids. We have not, however, explained differences in the various types of light emission. Our model does not allow us to understand why some solids glow in the dark and others do not. So, we need to take the model one step further and look at additional features. We do that in future activities.

Appendix

Energy Bands, Energy Gaps, Conductors & Insulators

If you have studied either the conduction of electrical or thermal energy in solids, you probably have guessed that the name "conduction band" is related to conductors and insulators.

The electric current that flows through a solid consists of electrons with energies associated with the conduction band. Solids that conduct heat or electric current (called *conductors*) will have many electrons with energies associated with the conduction band. Solids that do not readily conduct heat or electric current (called *insulators*) will have few electrons with energies in the conduction band. Thus, the electrons for insulators are found mostly in the valence band. Solids that are good conductors will have many electrons in the valence band because these materials have enough electrons to fill the valence band and many left over to occupy the conduction band.

In addition to the difference in the number of electrons found in their respective conduction bands, conductors and insulators also differ in the size of their respective energy gaps. For conductors, the two bands either overlap or are so close together that electrons from the valence band can easily acquire enough energy to move to conduction band. Insulators, on the other hand, have energy gaps that are so large that thermal or light energy would not be sufficient for electrons to move to the conduction band from the valence band.

Name:

Class:

LUMINESCENCE
It's Cool Light!

Visual Quantum Mechanics

ACTIVITY 8

Using Light Sticks to Predict the Effects of Changing Temperature on the Light Emitted by Fireflies

Goal

We will investigate the relationship between temperature and emission of light by light sticks. Then, we will apply the energy band model to explain this relationship

If you live east of the Rocky Mountains, you may enjoy chasing, catching, and putting fireflies in a glass jar during a warm summer evening. Fireflies emit an eerie yellow-green light. Despite the name, "fireflies" do not use fire or heat to emit light. Instead, fireflies convert energy from a chemical reaction into light. Thus, they produce light by chemiluminescence. Because this chemiluminescence occurs in a living organism, the production of light by a firefly is also classified as bioluminescence.

Fireflies, also known as "lightning bugs", emit light from their bellies by using two chemicals called luciferin and luciferase. These chemicals take the chemical energy stored in the firefly's cells and convert it into a yellow-green light.

Near the ocean, we can find bioluminescent sea creatures. The oceans are filled with tiny plants and animals called plankton, which are too small to see with the naked eye. Some plankton also contain luciferin and luciferase. Late at night, the water along parts of the coast will glow with an eerie blue light. If you drag a stick through dark, ocean water, sometimes the plankton will leave a blue glow along the path of the stick.

Kansas State University

©2001, Physics Education Research Group, Kansas State University. Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

In addition to fireflies and plankton, certain types of bacteria^{1,2}, algae, plants, shrimp, jellyfish³, shallow sea creatures (for example, flashlight fish and luminous brittle stars), and some deep-sea creatures (such as squid and lantern fish) emit light due to bioluminescence. The great majority of luminescent organisms inhabit the seas, mainly in the deepest parts. Scientists estimate more than 70% of all organisms below 400 meters are luminescent. Some fish become luminescent when they are alarmed and swim away from danger, but do not emit light when they are motionless. Unlike fireflies, some squid emit visible light to become invisible. To fool predators, these squid use light to camouflage themselves by controlling the intensity of emitted light to match the intensity of sun light at their depth.

Underwater researchers have found that hydrothermal vents at the bottom of the sea, like deep sea organisms, emit faint light. Physicists maintain that although some of the light may be created by intense heat, much of it must be attributed to some as-yet-unknown process. Biologists believe that these vents produce enough light for photosynthesis to take place.

Fireflies are not actually flies, but male beetles that produce light in body segments near the end of the abdomen. Fireflies use their flash to attract their female counterparts who cannot fly. For at least one species of firefly, the faster the male flashes, the more likely he is to lure a female.

An organ called a lantern that is found on the underside of the firefly's abdomen produces the flashing light emitted by these male beetles. To produce the light, a chemical reaction takes place in the lantern in which two compounds — luciferin and the enzyme luciferase — react with oxygen.⁴ Thus, the firefly's light becomes dimmer when it is trapped in a closed glass jar because the supply of oxygen has been decreased.

Nearly 100% of the energy given off by this chemical reaction appears as light. The firefly controls the intensity of the flashing by controlling the amount of air that is supplied to the lantern organ. A distinct flashing pattern is characteristic of each species of firefly, and is used to attract a mate of its own species.

¹ In March of 1996 after the death of a British Columbia man, a Canadian food inspector cautioned the public not to eat seafood that “glows-in-the-dark” because of some harmful luminescent bacteria that may be found in raw seafood (Kansas City Star, 9/4/96).

² Bacterial luminescence provides an inexpensive, direct method of detecting potentially biohazardous materials in water (Thomulka, Peck, & McGee, 1993).

³ Plant biochemists are experimenting with a protein that causes certain marine creatures, such as the jellyfish, to emit light in the hopes that it can be used to develop luminescent blue plants which may someday provide an early-warning system that will alert farmers to infection and herbivore attack in time for defensive measures. For more info, check out the following web site: <http://www.sigmaxi.org/amsci/issues/Sciobs96/Sciobs96-01DavidB.html>

⁴ The biological mechanism that causes fireflies and other luminescent organisms to “glow” is being used by inspectors to help detect the presence of deadly bacteria in meat and other foods. For more information, see the following web site: <http://www.uoguelph.ca/atguelph/95-11-29/orlux.html>

Normally we see fireflies on warm summer evenings. In the space provided below, predict what would happen to a firefly's light if the surrounding temperature suddenly becomes very hot. Because you have not yet studied the effects of temperature on chemiluminescence, your prediction will be based on other experiences. Describe those experiences in your explanation.

In the space below, predict what will happen to a firefly's light if the surrounding temperature were suddenly to become very cold. Explain based on any appropriate experience.

Unfortunately, using real fireflies to test your predictions would be difficult. For example, the current season could be in the middle of winter. In scientific investigations, experimenting with biological organisms is not always feasible, practical, or ethical. Instead, scientists often use some similar, non-living system to represent the subject under investigation and then apply the results to the real subject. In this activity, we will use the light stick, which utilizes chemiluminescence to emit light, to act as a model of the firefly. To investigate the effects of changing temperature on the light stick, we will then apply the results to the firefly.

A light stick is made of a sealed plastic tube that contains a solution of fluorescent dye and phenyl oxalate ester. Floating in this solution is a thin glass vial filled with a solution of dilute hydrogen peroxide. (See Figure 8-1.) When the plastic tube is bent enough to break the glass vial, the two solutions mix, react, and give off energy in the form of visible light.

In a previous activity, we observed that a light stick would glow when exposed to UV light even if the light stick were previously activated. This observation provides evidence that the dye found in the light stick is indeed fluorescent and is not "used up" during the chemical reaction that produces the emitted light.



Figure 8-1: Light Stick

To investigate the effects of temperature on the light emitted by light sticks, we will compare light from light sticks at room temperature, placed in warm water, and placed in ice water.

Obtain the following materials: 3 small identical light sticks, 2 beakers, warm water (65°C), ice water (4°C), 3 thermometers, and a watch.

Examine the light sticks and wrappers to be sure that they are identical. They should have identical colors, time for light emission and intensity. (Some will be labeled high intensity; others do not have intensity listed.)

Fill one beaker with warm water (approximately 65°C) and another with ice water til each is about 75% full.

In the space provided below, record room temperature and the temperature of each beaker.

- Take the filled beakers and the other equipment into a darkened room.
- Activate each light stick and note if they are at the same intensity.
- Then place each light stick in the appropriate beaker location and start timing.

Observe the brightness of the light emitted by each light stick for 10 minutes. In the table provided below, record the following during your investigation:

- Any changes in the intensity of light emitted by each light stick.
- The time it takes each light stick to lose its characteristic glow.

Light Stick	Intensity of Light	Duration of Light Emission
in ice-water (° C)		
at room temperature (° C)		
in warm water (° C)		

After everyone has completed his/her investigations, each group should share its results with the entire class. The resulting discussion should focus on completing the following:

List the 3 light sticks identified by their respective temperatures, in order of brightness. List the dimmest first.

List the 3 light sticks identified by their respective temperatures, in order of duration. List first the light stick which loses its "glow" the fastest.

? With respect to temperature, what is the most effective way to make a light stick glow for the longest period of time?

? With respect to temperature, what is the most effective way to make a light stick glow the brightest?

? Apply the results of this investigation to fireflies. What effect, if any, would changing temperature have on the light emitted by fireflies? Explain.

? What problems, if any, would result in applying these results to fireflies? Explain.

? How could we conduct this investigation with real fireflies? Explain.

In this activity, we found that the temperature affects, not only the intensity of light emitted, but also the duration of light that is emitted by the light stick. The light stick utilizes a chemical reaction to emit light and temperature must have an effect on the rate of this chemical reaction. Recall that a light stick contains two solutions — a dilute hydrogen peroxide solution that is found in the glass vial and a solution that consists of fluorescent dye and phenyl oxalate ester. The ester and hydrogen peroxide react first, producing a reaction that transfers energy to the dye. As a result, the electrons in the dye gain energy. Recall from the previous activity that electrons like to have the lowest possible allowed and available energy. If the electrons gain energy by heat, chemical reactions, mechanical manipulations or any other means they will naturally return to the lowest energy level and lose the gained energy in the form of light. The glow is visible as the electrons in the dye lose energy and return to their lowest possible allowed energy.

The chemical reaction between the dye and the ester cause the dye molecules to gain energy. That energy is then released in the form of visible light. We can apply the energy bands and gaps model to this process.

Name:

Class:

LUMINESCENCE
It's Cool Light!

Visual Quantum Mechanics

ACTIVITY 9

Constructing a Model to Explain the Fluorescent Lamp

Goal

We will apply our knowledge of energy bands to construct a model that explains light emission from a fluorescent lamp.

In the previous activity, we learned that in solids the energy bands are separated by an energy gap that results from the interactions of numerous closely spaced atoms. These energy bands and gap play a very important role in the light emission process of luminescent materials and devices because most of these materials and devices consist of solids.

If electrons in the valence band are supplied enough energy — mechanical, chemical, electrical, or light — they change to energy levels in the conduction band. These electrons can lose this recently acquired energy in the form of light by changing from energy levels in the conduction band to energy levels in the valence band. Up to this point, we have assumed that the energy supplied to these valence electrons equals the energy of the light emitted by the luminescent solid. In some cases only a fraction of the incoming energy goes out as light.

Fluorescence, for example, involves a luminescent solid absorbing energy in the form of ultraviolet (UV) light and emitting visible light. The UV light has higher energy than the visible light. Our energy band and gap model cannot explain this change in energy. Thus, our energy band model needs to be modified so that it can explain fluorescent materials.

Notice that each atom of the solid is represented by a single potential energy diagram that has the same depth. As a result, each nucleus of each atom contained in this solid has the same magnitude of charge. Thus, each atom in this solid has similar properties. In representing a solid, we have assumed that every atom is the same. This assumption does not hold true for most solids.

Kansas State University

©2001, Physics Education Research Group, Kansas State University. Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

We represent atoms of different types by using different potential energy diagrams. We modify potential energy diagrams by changing either the lowest possible energy or the width. For example, Figure 9-1A *might* represent a sodium atom while Figure 9-1B could represent a chlorine atom.

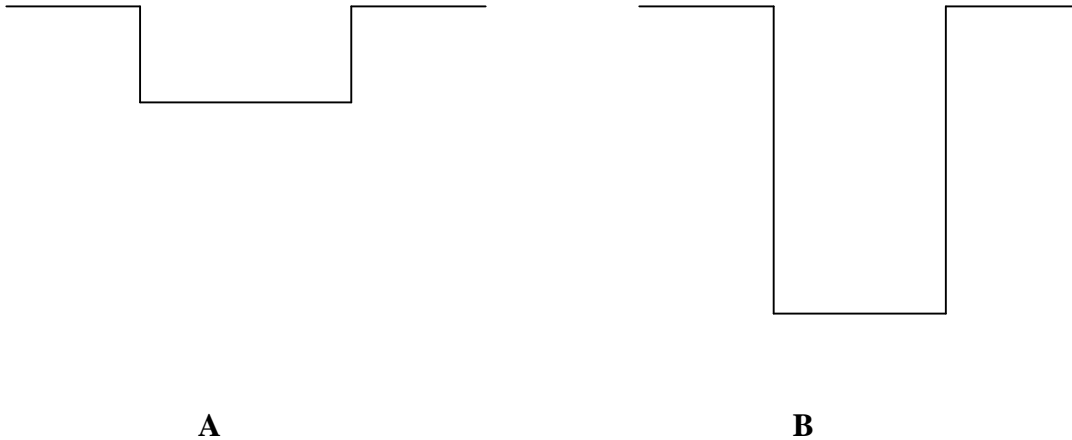


Figure 9-1: Potential energy diagram with different minimum energies and different widths represent different types of atoms.

Sketch, in the space provided below, how the potential energy diagrams (the diagrams without the energy bands) would look for a very large number of atoms in which all atoms were identical except one which as a nucleus with a larger electrical charge than the other atoms.

We will now use the *Energy Band Creator* computer program to determine the effect on energy levels in a solid with a single atom whose nucleus has an electrical charge that is larger than the rest.

In the Regular Solid folder of the program, create 10 potential energy diagrams that have a depth of -300 eV, a width of 0.1 nm, and a separation distance of 0.15 nm.

You have created a solid with ten identical atoms. We now want to replace one of these atoms

with an atom of a different type. This process is called adding an impurity. Click on the Impurity tab. In this folder you have the option of adding a number of impurity atoms (of specified depth, width, and impurity concentration) to the regular solid .

Change the Impurity Concentration from 0 to 1. Notice that one of the regular solid potential energy diagrams has turned green. However, it still represents an atom that is identical to the others because its potential energy diagram is identical. To create an impurity, change the depth to -340 eV so that this atom's potential energy is slightly lower than the potential energies. Keep the width at 0.100 nm. Figure 9-2 illustrates the resulting potential energy diagram representation of the solid with a single impurity atom.

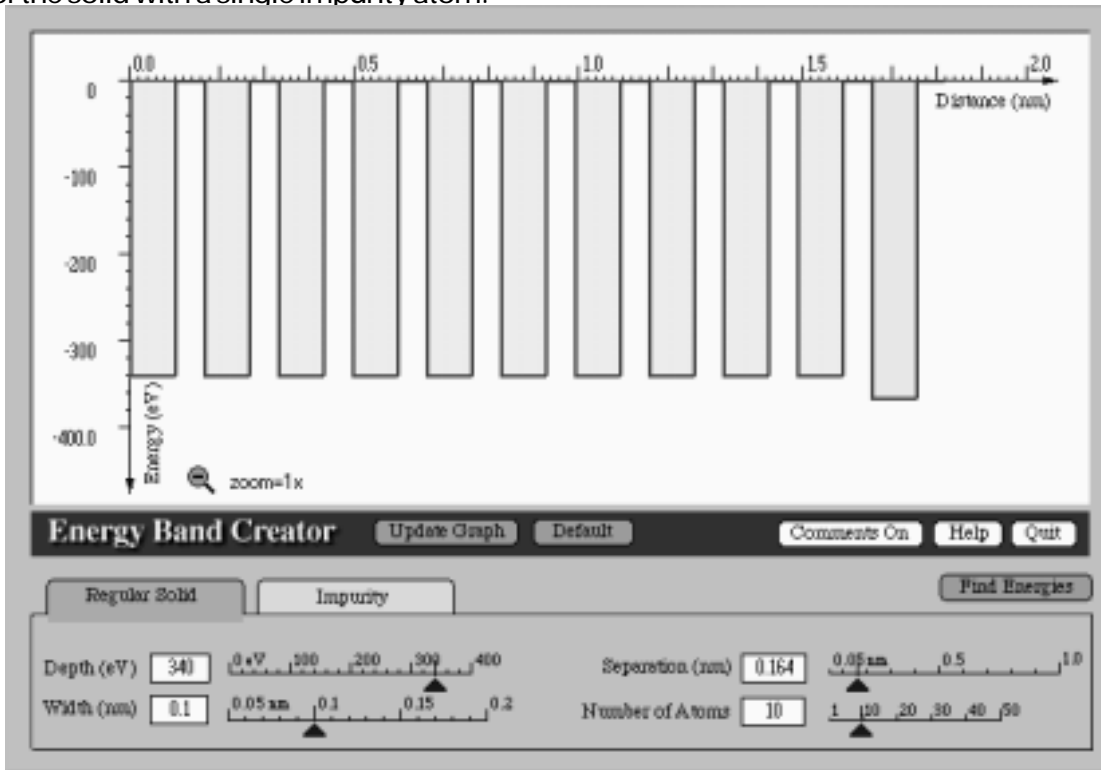


Figure 9-2: Potential Energy Diagram Representation of a Solid with a Single “ Impurity” Atom

Use the program to search for the allowed energies for the impurity potential energy diagram. The red allowed, energy lines result from the interaction of the regular solid potential energy diagrams and the green allowed, energy lines result from the impurity potential energy diagram. Sketch the resulting allowed energies in Figure 9-2.

Notice in your results that the allowed energies related to the impurity are found inside the energy gap (between the conduction and valence bands).

Recall that energies below the valence band are not needed to explain the light emitting properties of the solid. As a result, the energies below the valence band can be ignored. The allowed energies found in the energy gap result from the addition of impurities to the solid.

Your results illustrate the effect of adding an impurity atom with a nucleus of larger charge to the other atoms. The result is the formation of an allowed energy that is slightly below the excited state band. The placement of this allowed energy in the energy gap depends on the magnitude of nuclear charge of the added impurity atom.

We will now use the *Energy Band Creator* computer program to change the depth of the impurity potential energy to a depth of -260 eV. Do not change the width and impurity concentration. The resulting potential energy diagrams represent a solid that contains a group of similar atoms and an impurity atom that has a nucleus with a smaller electrical charge than the other nuclei in the solid.

Search for the allowed energies for this representation of a solid and sketch, in the space provided below, the resulting allowed energies and their respective values. Label the placement of the conduction band, valence band, and any allowed energies inside the energy gap that result from the addition of the impurity.

Suppose that we were to add several more impurity atoms to the solid. Predict how the energies would change if the impurities have a greater charge than other atoms in the solid. Sketch, in the space provided below, the allowed energies for a solid in which several impurity atoms have been added.

Modify the solid represented in the computer program to contain 6 impurity atoms represented by potential energy diagrams that have a lowest energy of - 340 eV. Search for the allowed energies and sketch, in the space provided below, the resulting energies and their respective values.

If your prediction was not consistent with the computer-generated energy diagram, discuss the results with your teacher.

? How is this energy diagram, which represents a solid with 6 impurity atoms, different than an energy diagram that represents a solid with a single impurity atom?

If a large number of impurity atoms are added to the solid, the result is a formation of a band of energies found inside the band gap of the material. The placement of this band of energies depends on the nuclear charge of the impurity atoms found in the solid. This band of energies, which we will call the impurity band, along with the conduction (excited state) and valence (ground state) bands are characteristic of the luminescent solids that make up objects such as fluorescent minerals, phosphorescent toothbrushes, and the coating found inside fluorescent tubes.

For this activity we have used an extremely large concentration of impurities so that we could emphasize how the additional (impurity) band is created. In real solids, the impurity concentration is not as high as the amount indicated in the computer program. In real solids, the impurity concentration is typically one-millionth of the number of regular atoms that make up the solid.

Now that we see how an extra energy band can be created, we will use the idea to understand fluorescence.

The *Fluorescence Spectroscopy* computer program applies the concept of energy bands to explain the light emission from fluorescent lamps.

Open the *Spectroscopy Lab Suite* software package and select Fluorescence from the *Luminescence* category of the main menu.

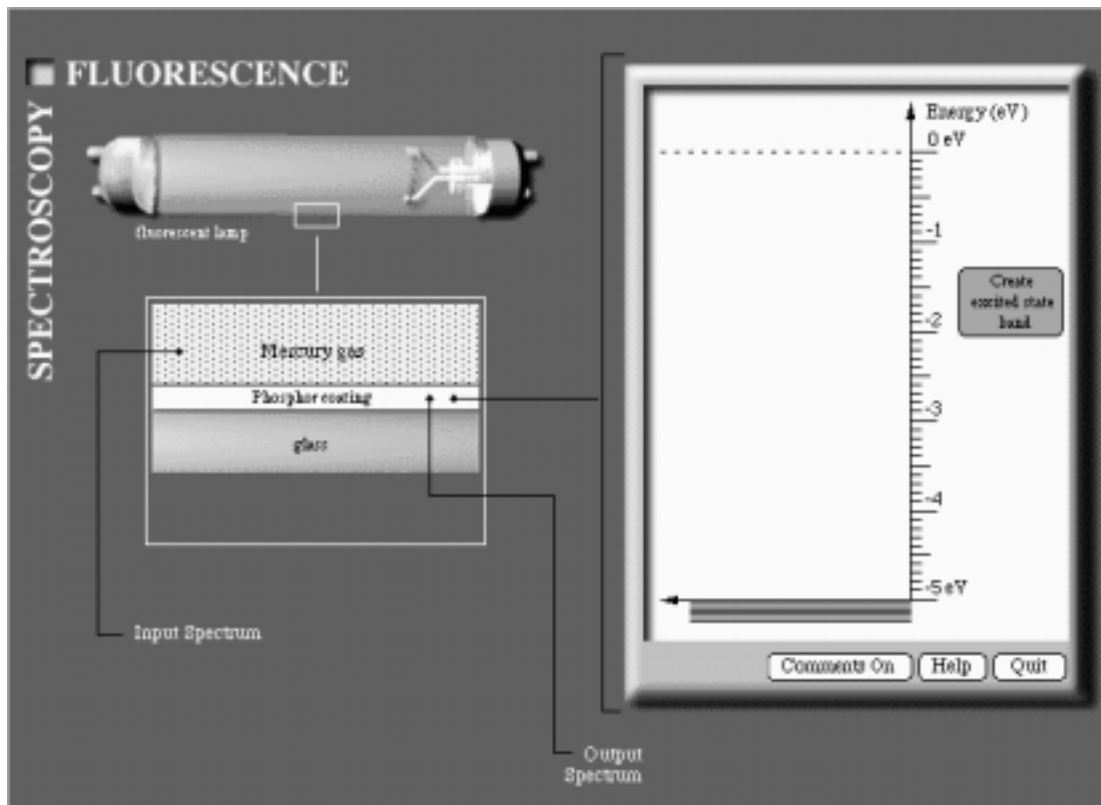


Figure 9-3: *Fluorescence Spectroscopy* Computer Program

Notice the figure of a fluorescent lamp and the diagram of the tube's cross section below the lamp on the left of the screen. The cross section represents the mercury gas contained inside the tube, the solid material coating (called phosphor) found on the inside of the glass tube, and the glass tube.

The energy diagram on the right of the computer screen represents the material in the phosphor. It has a black set of horizontal lines located at -5 eV. These lines represent the valence band of the phosphor coating.

Click on the *Create Excited State Band* (conduction band) button. Notice that a set of gray horizontal lines representing this band appears next to the energy scale. Click on the *Create Impurity State Band* button. A set of gray horizontal lines representing this band appears in the energy gap of the phosphor coating. You may drag the energy bands to other values.

An energy scale labeled *Input Spectrum* should now appear below the cross section of the fluorescent tube. The input spectrum corresponds to the energy of light emitted by the mercury gas. The light of high energy (in the UV range) emitted by the gas is absorbed by the phosphor coating while the visible light passes through the glass tube. The light that passes through the glass tube is characteristic of the mercury gas spectrum. The high energy of the UV light is supplied to the ground state (valence) electrons of the phosphor coating.

Click on the middle of the cursor located below the input spectrum energy scale and drag it through various energy values. Notice that the color of the input spectrum matches the color of the mercury gas illustrated in the cross section. As the cursor is moved, a gold arrow moves up and down the energy scale of the energy diagram .

Place the cursor on an energy that is greater than the highest energy for the excited state band. Click on the *Turn on the Lamp* button.

Try several different Input Spectrum energies. For each energy click Turn on Lamp. Record your results below. Be sure to include at least two energies which turn on the lamp and two which do not.

Energy of Excited State (Conduction) Band: _____ eV

Energy of Impurity Band: _____ eV

Input Energy (eV)

Does the light turn on?

Change the energies of the impurity and conduction bands. Then repeat the process and record your results below.

Energy of Excited State (Conduction) Band: _____ eV

Energy of Impurity Band: _____ eV

Input Energy (eV)

Does the light turn on?

Use your results to describe in the space below the conditions necessary for the lamp to turn on.

The first step in a light emitting process is to give electrons enough energy to change to a higher energy level (Figure 9-4). Recall that electrons in higher energy bands will naturally lose energy and eventually return to the ground state band. The electrons, however, do not necessarily lose all their energy at once and return directly to the ground state. Instead, these electrons lose enough energy to nearby atoms that they move from the conduction band into the impurity band. This transition is represented by a dashed downward arrow which is illustrated in Figure 9-5.

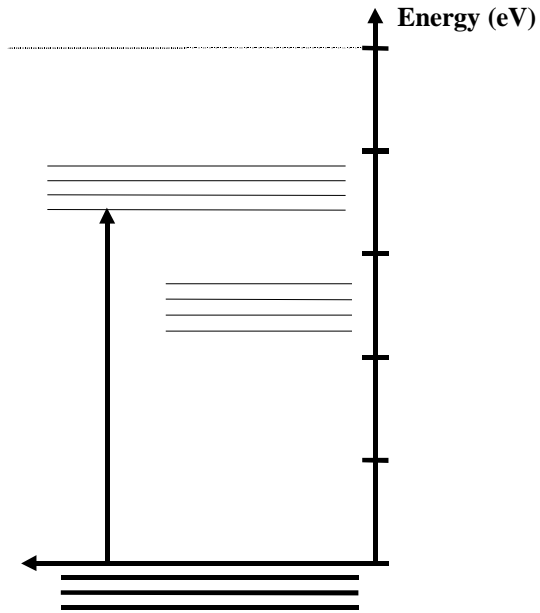


Figure 9-4: Electrons in solid phosphor coating make a transition to excited state band by absorbing ultraviolet light from the mercury gas.

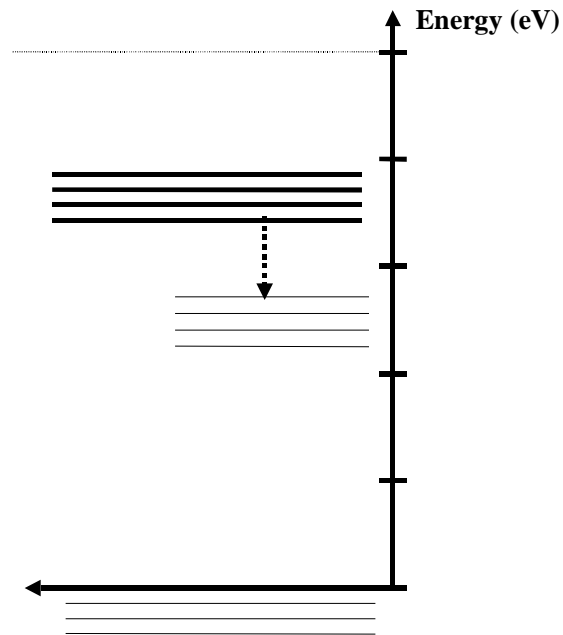


Figure 9-5: Electrons lose energy to neighboring atoms and make a transition to impurity state band. Light is not emitted.

The output spectrum which we see is the result of electrons losing energy as they move from the impurity state band to the ground state band, a transition represented by a solid downward arrow (see Figure 9-6).

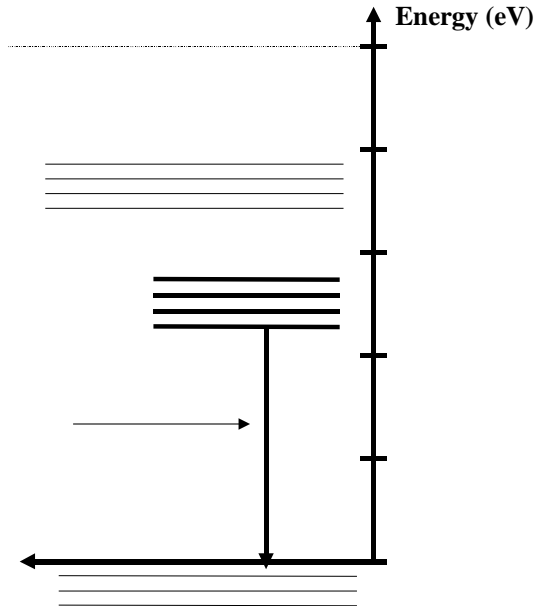


Figure 9-6: Electrons losing energy and making a transition to ground state band.

Ordinary fluorescent tubes operate when an electric current passes through a tube filled with mercury gas. The excited mercury atoms emit visible and UV light. The UV light emitted by the mercury gas has an energy of about 4.8 eV which is much greater in energy than of visible light (1.6 - 3.1 eV). The ultraviolet light is not visible to the naked eye. The process illustrated in Figure 9-4 to 9-6 describe the process by which the UV light is converted to visible light.

Fluorescent tubes are available in several different colors. You have probably seen grow-lights for house plants which emit a much different color than the "white" tubes used in most houses and schools. Even among the white tubes variations exist. "Cool white," for example, has more red than "Daylight" tubes. The variation in color is determined by the impurity states in the phosphor.

We will now use the computer program to model the operation of a typical "cool white" fluorescent lamp. Click the Edit Properties button. Set the input spectrum of the light to approximately 4.8 eV. Notice the color pattern indicated on the scale. The colored pattern represents UV light.

Use the mouse to drag the excited state band, which is illustrated on the energy diagram screen, to an appropriate energy.

Since typical fluorescent lamps emit visible light which has an energy range of 1.6 eV to 3.1 eV, use the mouse to move the impurity state band to the appropriate energy. Remember Cool White lamps have a lot of red. Assume that the resulting visible light will have an energy equal to the average energy for this range of values.

Sketch, in the space provided below, the resulting energy band diagram with the respective energy values. Identify each resulting transition.

? How would the bands change for a "Daylight" (more blue) lamp?

In this activity, we have learned how the addition of impurities affects the allowed energy bands for a solid. We then applied this knowledge to understand the light emission of the fluorescent lamp. In the next activity, we will apply our model to explain the operation and properties of fluorescent and phosphorescent objects previously explored.

Application Activity:

By using different types of phosphor materials to coat the fluorescent tubes, the tubes can be engineered to emit light in a wide range of colors and energies from the near-UV region of the spectrum to the orange-red region. The black light used in previous investigations emitted light in the violet and near-UV regions with an energy of approximately 3.5 eV.

Common fluorescent lamps, black lights, grow lights, and tanning lights all have the same mercury gas inside them. As a result, the excited mercury atoms emit light energy of 4.8 eV.

Use the *Fluorescence Spectroscopy* computer program and the values of 4.8 eV for the input spectrum and 3.5 eV for the output spectrum to construct an energy band model for the black light. Sketch, in the space provided below, the resulting energy band diagram with the respective energy values.

? How is the energy diagram for the black light similar to the energy diagram for the “cool white” fluorescent lamp?

? How are they different?

Name:

Class:

LUMINESCENCE
It's Cool Light!

Visual Quantum Mechanics

ACTIVITY 10

Constructing Models to Explain Photoluminescence

Goal

We have learned how impurities affect the allowed energies for a solid and have applied this knowledge to understand how a fluorescent lamp operates. We will now apply the energy diagram model to explain the properties of photoluminescent materials like the fluorescent and phosphorescent materials and devices previously explored.

Recall that photoluminescent objects glow when light is shined upon them. A photoluminescent object may emit light due to the process of phosphorescence or fluorescence. See Figure 10-1.

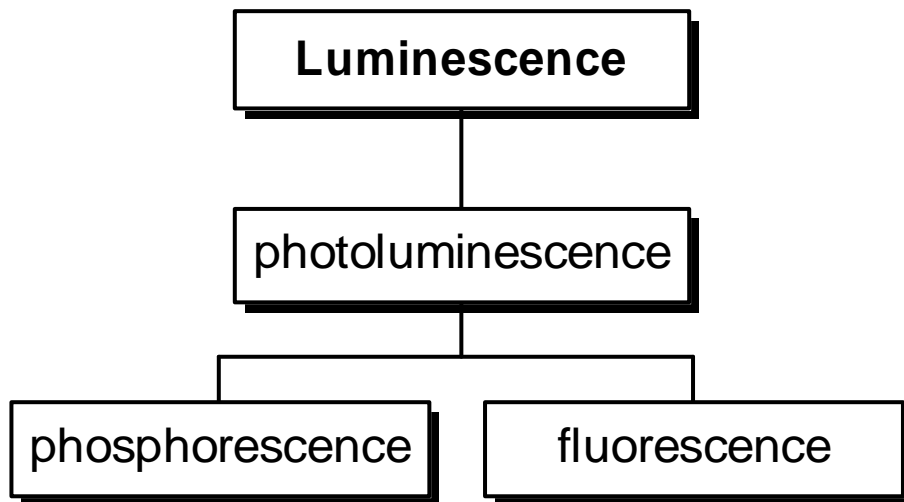


Figure 10-1: Photoluminescence

Kansas State University

©2001, Physics Education Research Group, Kansas State University. Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

Photoluminescent materials such as the phosphor coating found on fluorescent tubes, fluorescent minerals, and phosphorescent toothbrushes contain many solid atoms. As a result, these materials have valence and conduction energy bands that are separated by an energy gap. As we have seen, photoluminescent solids also contain many impurity atoms which result in the formation of a band of energy levels found inside the energy gap of the solid material.

As a brief review, Figure 10-2 represents an energy band diagram for the phosphor coating found in a typical "white" fluorescent lamp that emits visible light (1.6 - 3.1 eV).

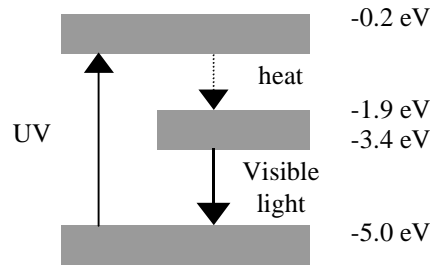


Figure 10-2: Sample Energy Band Diagram for a "White" Fluorescent Lamp

Some fluorescent minerals only emit a small part of the visible spectrum. Using Figure 10-2 as template, sketch in the space provided below an energy band diagram for a fluorescent mineral that only emits red light (1.6 - 2.0 eV) as it is exposed to UV light (3.5 eV) provided by a black light. Explain your reasoning.

In the exploration during the first activities, we found that phosphorescent materials (i.e. glow-in-the-dark paint on watches), unlike fluorescent minerals, require visible light (1.6 - 3.1 eV) to emit their characteristic faint, greenish-yellow glow (2.3 eV) after the light source is turned "off".

Based on the investigations performed on glow-in-the-dark objects and our knowledge of energy band diagrams for the fluorescent lamp and materials, create in small groups a possible energy band diagram for the phosphorescent hands of the watch. In the space provided below, sketch your prediction of the resulting energy band diagram for the glow-in-the-dark watch. Then sketch the electron transitions on your model.

You will now check your predictions by using the *Phosphorescence Spectroscopy* computer program to construct a model that will explain the properties of glow-in-the-dark objects.

Phosphorescent objects, like fluorescent materials, consists of many solid atoms with a number of impurities. As a result, energy diagrams of phosphorescent materials have an impurity state energy band located somewhere between the conduction and valence energy bands.

Open the *Spectroscopy Lab Suite* and select Phosphorescence from the *Luminescence* category of the main menu. A figure of a glow-in-the-dark toothbrush will appear on the left part of the screen and an energy scale will appear on the right part of the screen.

The energy scale contains a black set of horizontal lines located at -5 eV. These lines represent the valence (ground state) band of the phosphorescent material in the toothbrush.

Click on the Create Excited State Band button. A set of gray horizontal lines representing the excited state band (conduction band) appears next to the energy scale.

Create an impurity state band. A set of gray horizontal lines representing this energy band should appear inside the energy gap of the toothbrush. The energy band diagram is illustrated in Figure 10-3.

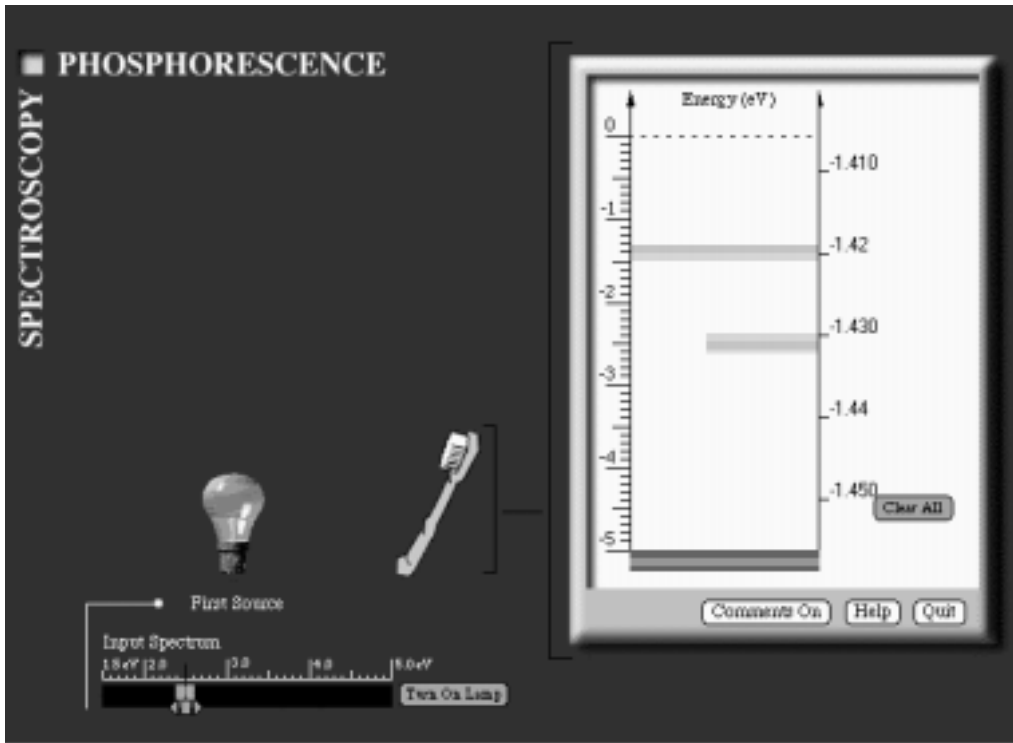


Figure 10-3: Initial Energy Band Diagram Crop of the Glow-in-the-Dark Toothbrush

The computer screen is somewhat small for representing the energies involved here. The impurity band energy is very close to the energy of the conduction band. As Figure 10-4 shows, the difference between the energies of these two bands is about 0.01 eV.

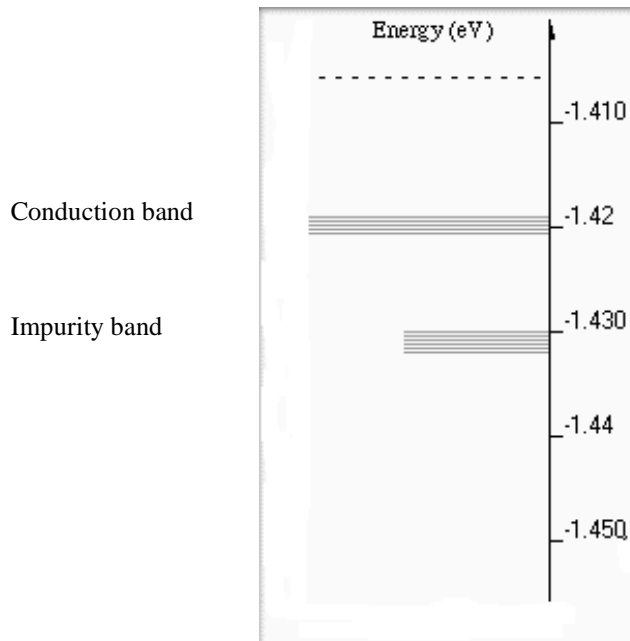


Figure 10-4: A display of the energies of the conduction band and the impurity band.

The difference between the energy of the conduction band and the valence band is much greater than that energy difference between impurity and conduction band. Figure 10-5 shows that the energy difference between the conduction and valence bands is about 3.5 eV.

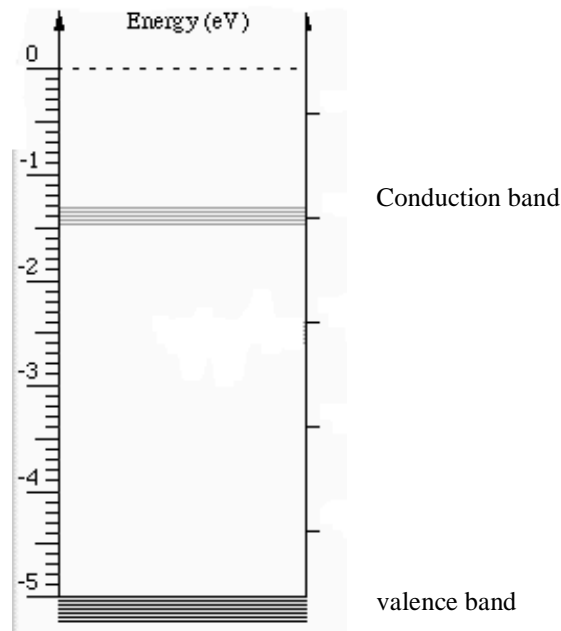


Figure 10-5: A display of the energies of the conduction and valence bands.

We run into difficulty when we attempt to display all three energies on one computer screen. If we use an energy that separates the conduction and impurity band energies, the valence band energy would be off the bottom of the screen — near your feet. On the other hand, if we display the energies of the conduction and valence band energies, the impurity band energy is so close to the conduction band energy that we cannot distinguish them.

To see all three energies conveniently we need a compromise. Our solution is to display two energy scales. The one on the right shows the correct energies for the conduction and impurity bands while the one on the left displays valence and conduction band energies. (Figure 10-6) To help you remember the bands touch only the energy scale relevant to them.

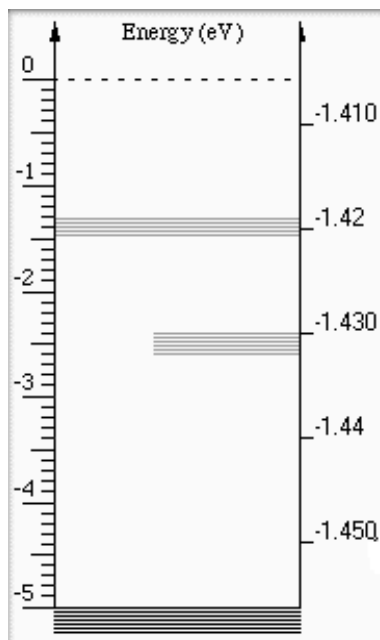


Figure 10-6: The compromise so that we can see conveniently the energies of all three energy bands.

Once the three bands are created, a lamp with variable spectrum appears on the bottom left of the screen. The input spectrum represents the energy of light absorbed by the toothbrush.

Change this energy by dragging the cursor located below the input spectrum energy scale. As you drag the cursor, a gold arrow moves up and down the energy scale of the energy diagram.

Turn on the lamp for several different energies of its spectrum.

? What energies cause transitions from the valence band to conduction band?

If you can, explain your conclusion. If you cannot, discuss your result with your instructor.

Notice that after a transition occurs, the valence band turns gray and the conduction band turns black. This change illustrates that electrons now have energies in the conduction band.

If possible, electrons will naturally lose energy. The excited electrons in the glow-in-the-dark toothbrush, however, do not necessarily lose all their energy at once. Instead these electrons lose enough energy to nearby atoms to make the transition from the conduction band to the impurity band.

A dashed downward arrow represents this transition. After this transition occurs, the conduction band turns gray and the impurity band turns black. This change indicates that electrons have lost some energy and now have energies associated with the impurity band. The change in energy is small and is generally thermal energy.

In fluorescent materials electrons have energies in the impurity state band for a very short time (10^{-9} to 10^{-6} seconds). Then, they emit light as their energy changes to energy in the valence band. As a result, fluorescent materials will only glow while light of sufficient energy shine on them. In phosphorescent objects like the glow-in-the-dark toothbrush, the electrons remain in the impurity band. After this time delay the electrons emit light as their energy changes. Thus, phosphorescent materials emit light using energy that was absorbed at an earlier time. When all energy is converted to light, the object stops glowing in the dark.

Some older watch dials glow-in-the-dark indefinitely, not because of a long time delay associated with common phosphorescent objects, but because they contain radium or some other radioactive substance which continuously supplies energy to keep the process going. Fortunately, such dials are no longer used because of the potential harm of the radioactive material.

In phosphorescence, the emission of light by the glow-in-the-dark object is more complex than for fluorescence. Phosphorescent materials emit light as a result of electrons making transitions from the conduction band to the valence band. Thus, in addition to the original light, phosphorescence must involve a second external source of energy. Phosphorescence is temperature dependent. In other words, the temperature of a glow-in-the-dark toothbrush determines the degree of phosphorescence.

Because the thermal energy in a room is sufficient to cause these transitions, showing the temperature dependence is difficult. With the computer program, we can simulate much lower temperatures than you can achieve in your classroom. As demonstrated in the program, the toothbrush is dipped in liquid nitrogen that has a temperature of -196°C . The temperature of the toothbrush is about -200°C when it is brought near the heat lamp.

Use the cursor to change the temperature values. As before, a gold arrow will move up and down the energy scale of the energy band diagram illustrated on the right of the screen.

Turn on the heat lamp for several different temperatures. Experiment with the energies until you can give an answer and explanation for the following:

- ? How is the temperature at which an object glows in the dark related to the energy differences between the conduction and impurity energy bands? If you cannot explain why, discuss your results with your instructor.

If the heat supplied to the toothbrush provides enough energy for the toothbrush's electrons to move from the impurity band to the conduction band, a transition represented by the dashed arrow illustrated in Figure 10-7 is possible.

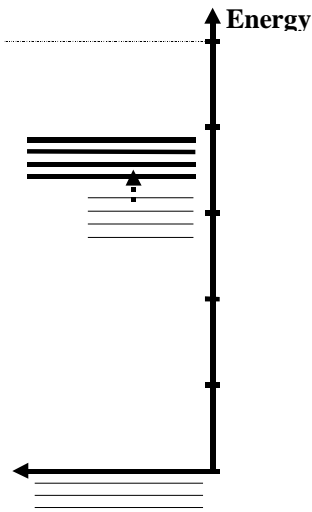


Figure 10-7: Electrons absorb thermal energy from the surrounding and make a transition back to the conduction band.

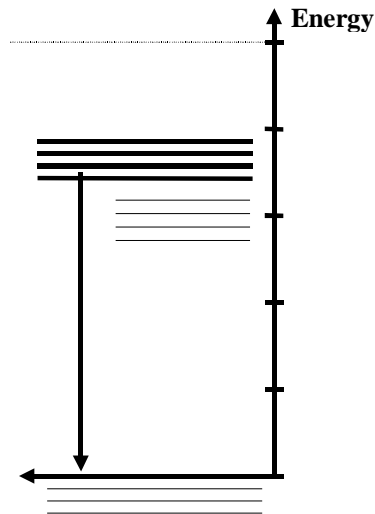


Figure 10-8: Electrons lose energy by emitting visible light and make a transition to the valence band.

The electrons in the conduction band now lose energy and return to the valence band. The output spectrum is the result of the electrons making transitions from the conduction band to the valence band (See Figure 10-8.).

Now use the computer program to create an energy band model that would produce an output spectrum characteristic of a glow-in-the-dark toothbrush at room temperature. Recall that the phosphorescent materials require visible light (1.6 – 3.1 eV) to emit their characteristic faint, greenish-yellow (2.1 – 2.6 eV) glow.

In the space provided below, sketch an energy band diagram for this situation.

When you explored the properties of glow-in-the-dark objects, you found that ultraviolet light is also effective in causing phosphorescence. You will now look at this process with the software.

In the computer program, create an energy band diagram of the glow-in-the-dark toothbrush that utilizes light (3.5 eV) from a black light UV source.

In the space provided below, sketch an energy band diagram for this situation.

? How is this energy band diagram similar to and different from the energy band diagram used to describe the glow-in-the-dark toothbrush when it is exposed to visible light?

? Is the resulting energy band diagram for the phosphorescent toothbrush that is exposed to UV light consistent with the law of the conservation of energy? Explain.

In our explorations we found that phosphorescent objects do not glow after being exposed to red light. According to the model used to explain phosphorescence, red light (1.6 - 2.0 eV) does not have enough energy for the electrons to make the transition from the valence to the conduction band. When the material is exposed to green light (2.3 – 2.6 eV), however, the light provides enough energy to a relatively few electrons that make the transition. When the material is exposed to blue light (about 3.1 eV) or UV light (about 3.5 eV), more electrons attain enough energy to make the transitions to the allowed energies in the conduction band. Thus, the resulting light emission is much brighter when an UV light source, rather than a visible light source, is used.

In this unit, we have explored the physical properties of various luminescent materials and devices including glow-in-the-dark toothbrushes; fireflies; light sticks; Lifesavers®; and fluorescent lamps and objects. The quantum model of energy band diagrams explained these materials and devices. The development of this comprehensive model started with atoms of gases to explain the properties of gas lamps and ended with the atoms of solids with impurities to explain luminescent materials and the fluorescent lamp. We could say that the quantum model is very “cool” because it allows us to see everyday phenomena in a new “light” and gives us a deeper understanding and appreciation for the various processes in which matter emits light.

Appendix: Thermoluminescence

Although phosphorescence can be classified as a form of photoluminescence, it can also be classified as a special type of luminescence called thermoluminescence. Thermoluminescence is a form of light emission that occurs when the temperature of the object is increased after exposure to some form of energy. The process of thermoluminescence has been used as a means to estimate the history and age of rocks and archaeological objects. Thermoluminescence can also be used as a tool for prospecting for uranium.

For a phosphorescent object, the energy used to stimulate light emissions is provided by the light shining on the object. For other thermoluminescent objects such as minerals found near radioactive deposits, the original addition of energy may have come from high-energy radioactive matter or cosmic radiation many years before the temperature increase resulted in thermoluminescence. These thermoluminescent objects, unlike phosphorescent objects, may require very high temperatures (400 - 500 °C) for light emission to occur.

When limestone or granite has been heated in a dark place, the emission of light can be observed during a period of rising temperature. If the rock is cooled and heated again, no light emission is observed. The rock, after having been once heated, needs to be exposed to high energy light in the form of X-rays or gamma rays in order for it to exhibit thermoluminescence. Some minerals, when taken from the ground have a color that disappears upon heating. The color will be restored after the mineral has been exposed to high energy light. Thermoluminescence can also be stimulated in solids by mechanical crushing. Crystals of sodium chloride that show no thermoluminescence can be ground up, after which they show thermoluminescence.

The emission of light may involve one or more forms of luminescence. Our chart that summarizes the different types of luminescence does not completely illustrate the relationships involved with the various forms of luminescence. We now have to expand our chart to include thermoluminescence (see Figure 10-9).

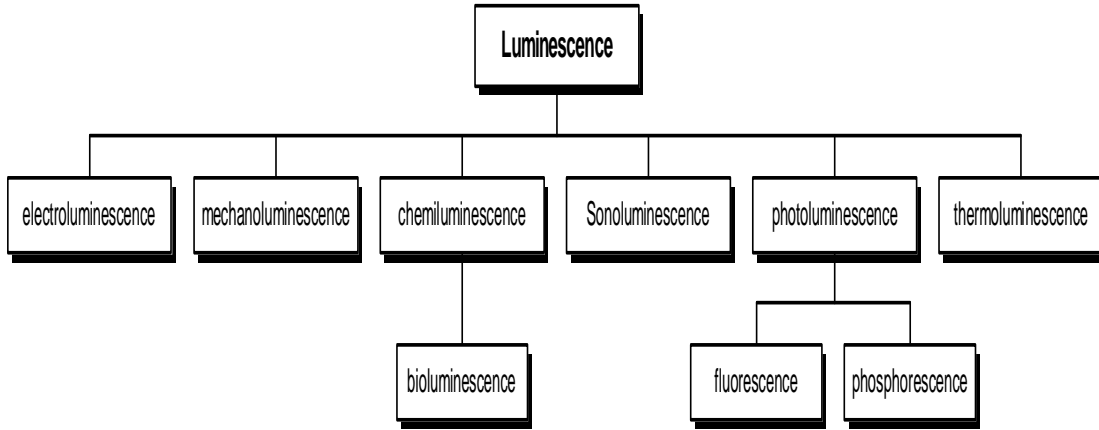


Figure 10-9: Types of Luminescence

The temperature dependency of luminescent objects does not contradict the distinction that was made between incandescence and luminescence. Recall that the key difference between these two processes of light emission is that luminescence, unlike incandescence, does not use heat as the primary mechanism for light emission.

Name:

Class:

LUMINESCENCE
It's Cool Light!

Visual Quantum Mechanics

ACTIVITY 11

Exploring the Properties of the TV Monitor and Remote Control

Goal

We now explore the properties of a small device that allows us to see infrared light.

Preparation:

In this activity we will use a remote control such as the one used to operate a TV or VCR. To prepare for this activity you should learn a little about how the remote control communicates with the TV or VCR. To do so complete the following activities at home.

This part of the investigation can be done at home.

- ? Most remote controls have a plastic section that is dark but different from the black plastic that covers the rest of the remote. The signal leaves the remote through this section. Cover this part of the remote control. Does the TV still respond?

- ? Usually you can find the place where the signal is received. It will have dark material covering it. Does the TV respond when it is covered?

- ? Will the TV respond if someone stands between the remote control and the TV? Try several different positions.

Kansas State University

©2001, Physics Education Research Group, Kansas State University. Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

- ? Can the TV be controlled if the signal is transmitted through glass and bounced off a mirror?
- ? Based on these results describe how the signal coming from the remote is similar to and different from visible light.

The answers to these questions indicate that signal coming out of the remote behaves as light does. No light is visible when you activate the remote. However, the remote is sending out a low-energy light signal to communicate with the TV. Most remote controls emit infrared (IR) light, for which each photon has an energy that is less than 1.6 eV. When the remote is activated, pulses of infrared light leave the remote control. When this light is received by the device, it is interpreted and the TV, VCR, or CD player responds.

Large amounts of infrared light may be detected as heat. The heat you feel from a fireplace, sunlight, or the ground is all sources of infrared light. The eyes of some living organisms like rattlesnakes are sensitive to infrared light. Thus, they see very small temperature variations in their environment. However, the amount of infrared light coming from a remote control is very small, so we do not feel any heat.

Sometimes remote controls fail to function correctly. The first check that is made by repair people is to see if the remote control is emitting infrared light. Of course, the repair people cannot see infrared light, and carrying rattlesnakes is considered impractical.

Fortunately, a small material enables them to “see” indirectly the infrared light. This IR detecting material converts infrared signals to visible light. At first the process may seem similar to fluorescence because it is converting light of one energy to light of another energy. However, IR detection is different from fluorescence in one very important way. In fluorescence a solid emits a lower energy photon than it absorbs; the rest of the energy goes to other forms. In IR detection the material is emitting *higher* energy photons than it absorbs. (Figure 11-1)

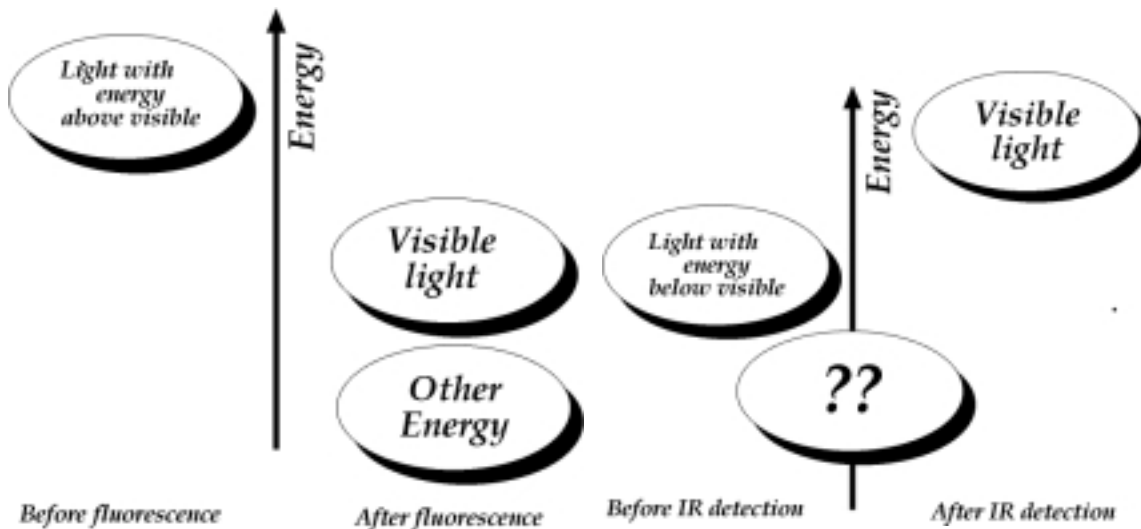


Figure 11-1: The difference between fluorescence and infrared detection is in the changes in the energy of photons. We have included a question mark because you do not yet know how the energy changes in the IR detection process.

To begin your investigations use either a remote control or an LED which emits infrared light. Expose the card with the IR detecting material to room light for a few minutes. Then activate the remote or increase the voltage on the LED. Describe below what you see coming from the material.

Now, expose the IR detector card to an infrared heat lamp. This lamp emits very little visible light and a very large amount of infrared light. Once you have exposed the card to intense IR be careful to keep it out of visible light. Then, hold the infrared detector card close to the activated remote control for about 10 seconds. In the space provided below, record your observations.

Now allow some room light to fall on the card. Then, in a dark room expose the card to IR light from a remote control. Describe below what happens.

Now, allow some room light to fall on the card. Then, in a dark room expose the card to IR light from a remote control. Describe below what happens.

? Leave the IR light on. Does the light from the card decrease with time?

Expose the detecting material to the intense IR source again. Before exposing the material to visible light, cover one-half of the detecting material with the colored transparent material. Your instructor will tell you which color to use. While holding this transparency in place, expose the IR card to visible light.

Return to the dark. Then, activate the remote control and describe the results.

Color of Transparency _____

Results:

Compare your results with others who used other colors of the transparencies. Summarize the results below.

? Speculate about other sources of energy that might be involved in the emission of visible light from the card. Explain

? Speculate why the light emitted by the card decreases after a period of time in the dark room even though the IR light from the remote control is kept on it.

The IR detector card, like the fluorescent and phosphorescent materials, consists of solids with impurity atoms. An energy band model can explain the observed properties of the card.

Discuss in small groups how a possible energy band diagram could explain the properties of the IR detector card.

In the space provided below, sketch your prediction and identify the energy bands of the materials and the energy or energies absorbed by the card (along with their sources) as well as the energy emitted by the card.

In the next activity, we will use a computer program to construct a model that explains the operation of the IR detector card.

Homework

The television itself also displays some luminescence. In this homework assignment you can investigate the light emitting properties of the TV.

The general definition of a phosphor is a solid material which when provided sufficient energy emits light due to luminescence. Phosphors can be found in phosphorescent materials as well as inside the glass tubes of fluorescent lamps. Phosphors made of the same material as phosphorescent objects like glow-in-the-dark toothbrushes can also be found in electroluminescent materials. The green, faintly glowing night-lights that can be plugged into the household electrical outlet and the Timex® Indiglo® watches utilize the process of electroluminescence to emit this characteristic light.

Turn on a television or computer monitor. Keep it on for a few minutes. Make the room as dark as possible and then turn off the TV or the monitor.

- ? What happens to the screen after you turn it "off"?

- ? Approximately how long could this phenomenon be seen?

? What process does the TV screen use to emit light after it is first turned off? Explain.

The face of the TV screen or computer monitor is lined with phosphors. The TV screen is slightly phosphorescent in that the glow disappears rather quickly. When the TV is turned on, the phosphor coating absorbs high-energy electrons that are directed at them by a device inside the TV. The phosphor releases this energy over time in the form of visible light. This process of light emission is called cathodoluminescence. The name comes from cathode rays — a term used about 100 years ago to describe a beam of electrons. Our chart used to classify the different types of luminescence now has been modified to include cathodoluminescence. See Figure 11-2.

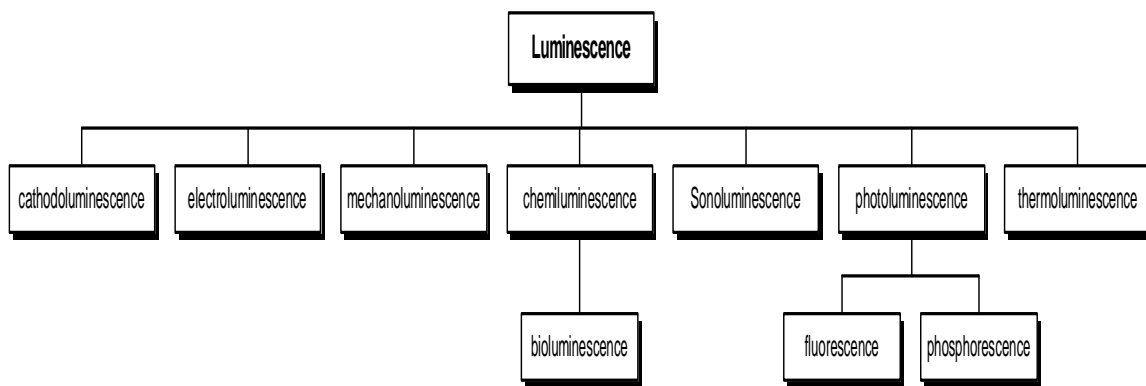


Figure 11-2: Types of Luminescence

Name: _____

Class: _____

LUMINESCENCE
It's Cool Light!

Visual Quantum Mechanics

ACTIVITY 12

Constructing a Model to Explain the IR Detector Card

Goal

We use *IR Detector Card Spectroscopy* to construct a model that explains the properties of the IR detector card.

In the previous activity you completed several experiments using infrared detection material. Each of the experiments were directed toward understanding how the material can absorb infrared light and then emit higher energy visible light. In this activity you will work with a computer program that uses energy bands to create a model of the IR detecting material. By changing variables in the program you will be able to see how the model explains each of the observations in the previous activity.

Open the *Spectroscopy Lab Suite* and select IR Detector under *Luminescence*. A figure of the IR detector card will appear on the left part of the screen and an energy scale will appear on the right part of the screen.

Notice that the energy scale contains a black set of horizontal lines located at -5 eV. These lines represent the valence band of the IR detection material.

Create an Excited State Band (conduction band). A set of gray horizontal lines representing the excited state band appears next to the energy scale.

Click on the Create Impurity State Band button. A set of gray horizontal lines appears in the energy gap.

The material that makes up the IR detector card consists of many solid atoms, including some impurities. Interactions occur among solid atoms that are relatively close together. Electrons bound to these atoms have allowable energies that are in both excited and ground state bands. The impurities create additional allowable energies in the impurity state band.

Kansas State University

©2001, Physics Education Research Group, Kansas State University. Visual Quantum Mechanics is supported by the National Science Foundation under grants ESI 945782 and DUE 965288. Opinions expressed are those of the authors and not necessarily of the Foundation.

The program begins with a simulated IR detection material that is similar to material that has been exposed to an intense IR source. So, it must be exposed to some visible light before it will function. The Input Spectrum represents the source of this visible light.

Figures of the IR detector card and the first energy source appear on the bottom left of the screen along with an energy scale labeled Input Spectrum. The Input Spectrum indicates the energy of light emitted by the visible source and absorbed by the computer-simulated IR detector card.

As you have for models of other types of luminescence, complete investigations by varying the energies of the source, the conduction band, and the valence band.

? What relation must you have for the electrons to make a transition from the valence band to the conduction band?

If the light emitted by the first source provides enough energy for the electrons in the card to change energies from the ground state band to the excited state band, a transition (represented by solid black arrow) is possible. Recall that you performed this experiment in the previous activity by placing colored transparencies over the IR detector card.

As with other computer models of solids the gray and black illustrate that the electrons have changed energy.

? Set up a situation in which transitions occur and electrons change energies. How much energy did the electrons in the detecting material lose as they made the transition from the excited state band to the impurity band? Explain how you determined this value.

The general scheme here is similar to that of phosphorescence. However, the change in energy when electrons move from the conduction band to impurity band is much greater here. Similar to phosphorescence the IR detector requires a second source of energy. In this case, of course, the second source is visible light. We will now look at the energy band model for this process.

On the left of the computer screen is a diagram of an LED and an energy scale labeled Input Spectrum for the Second Source. As with the Input Spectrum for the first source, select the energy (color) of the LED.

Choose several energies for the light emitted by the LED. Describe the energy required for electrons to change energy to the conduction band.

Some electrons with energies in the conduction band will lose all their energy and make a transition to the valence band. These atoms emit the light that we see coming from the detecting material.

- ? How much energy did electrons in the card lose as they made the transition from the excited state band to the ground state band? Explain how you determined this energy.

- ? What is the energy and color of light emitted by the IR detector card?

- ? How is the energy band model that is used to explain the IR detection process, consistent with the law of conservation of energy?

We will now use the computer program to create a model that is consistent with your observations. In the previous activity we saw that the IR detector card

- a) was able to detect IR only after exposure to visible light
- b) was not effective if exposed only to red light but is effective when exposed to other colors
- c) decreased its effectiveness over time when not exposed to visible light, and
- d) emits only a reddish orange light.

Use the computer program to create an energy band model that can explain as many of these observations as possible. In the space below, sketch your model and label the energies.

Describe how your model is consistent with each of the observations listed above. If your model does not explain an observation, explain why.

In the previous activities, we used energy band models to explain fluorescent and phosphorescent materials. How is the energy band model used to explain the IR detector card similar to the energy band model used to explain fluorescence?

? How are these models different?

? How is the energy band model used to explain the IR detector material similar to the model used to explain phosphorescence?

? How are these models different?

The process by which the IR detector card works is summarized in Figures 12-1 to 12-4.

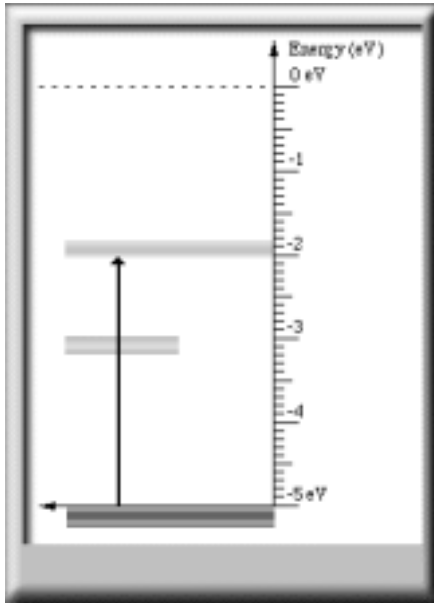


Figure 12-1: Electrons absorb energy from visible light and make a transition to the conduction band.

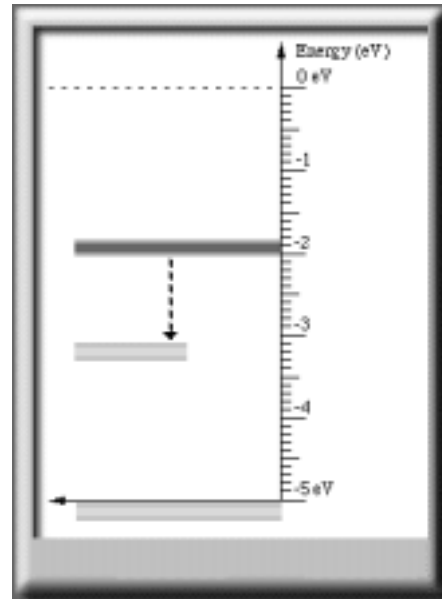


Figure 12-2: Electrons losing energy to neighboring atoms and making a transition to the impurity state band.

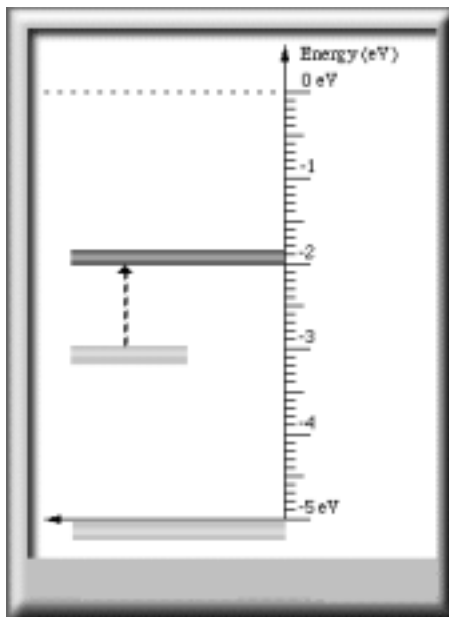


Figure 12-3: Electrons absorb energy from infrared photons and make a transition back to the excited state band.

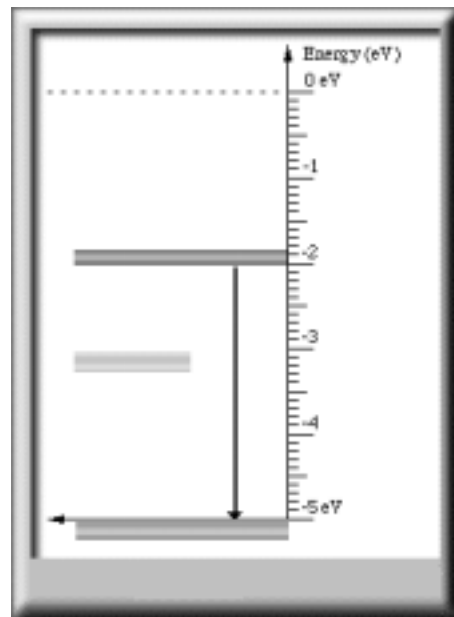


Figure 12-4: Electrons lose energy by emitting visible photons and make a transition to the ground state band.

In terms of energy in and energy out, infrared detection is described in Figure 12-5.

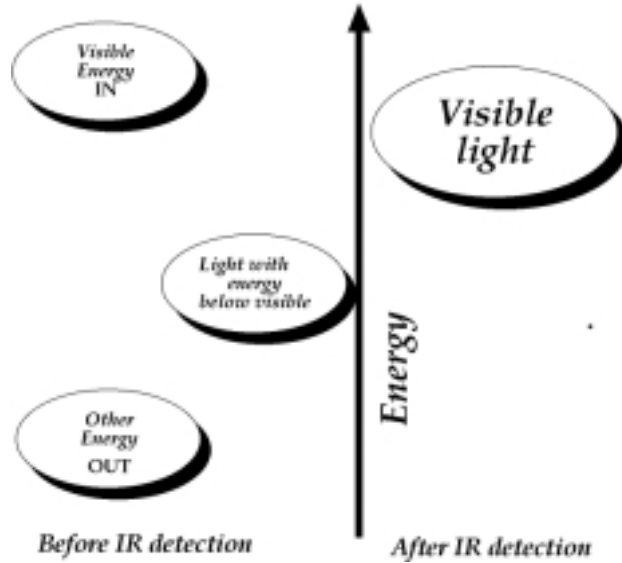


Figure 12-5: A summary of the energies needed to cause the infrared detector material to work.

In this unit, we have explored the physical properties of various luminescent materials and devices including "glow-in-the-dark" toothbrushes; fireflies; light sticks; Lifesavers®; and fluorescent markers & minerals; fluorescent lamps; and IR detector cards. The quantum mechanics model that involves energy bands explains how these materials and devices emit light. The development of this comprehensive model started with atoms of gases to explain the properties of gas lamps and ended with the atoms of solids with impurities to explain luminescent materials such as the fluorescent lamp and the IR detector card. We could say that the quantum mechanics model is very "cool" because it allows us to see everyday phenomena in a new "light" and gives us a deeper understanding and appreciation for the various processes in which matter emits light.

Homework

1. Researchers who investigate the properties of light use materials similar to the IR detector card. However, they sometimes need to detect only a small range of the energies in the infrared. Suppose such a card is created and it detects only photons with energies between 1.1 eV and 1.2 eV. Describe the energies of the bands of this material. Explain your conclusions. (Such materials exist but are much more expensive than the IR detector that you used.)

2. A rock music group has decided to use IR detector cards as part of its light show during concerts. Each ticket for the concert will have some infrared detecting material on it. During the concert big infrared lamps will flash; ticket holders will see nothing but light coming from the tickets. However, the leader of the group would like some tickets to emit red, some to emit green and some to emit blue light. As the scientific consultant to the group your job is to determine whether this process is possible. Your first step will be to see if you can arrange energy bands and gaps so that the IR detection material can emit only green photons or only blue photons. (We already know about red because we saw it happen.) What advice would you give the group?