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.

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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.

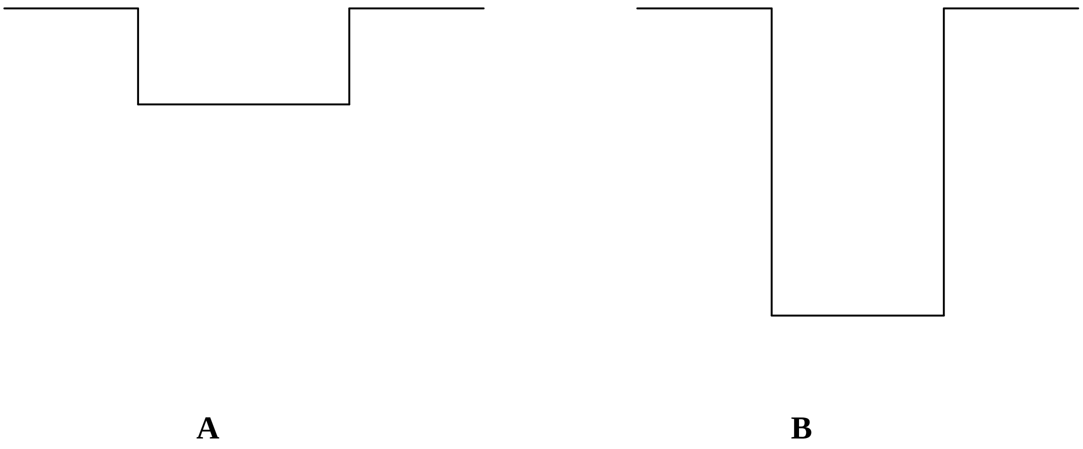


Figure 9-1: Potential energy diagram with different minimum energies and different widths represent different types of atoms.

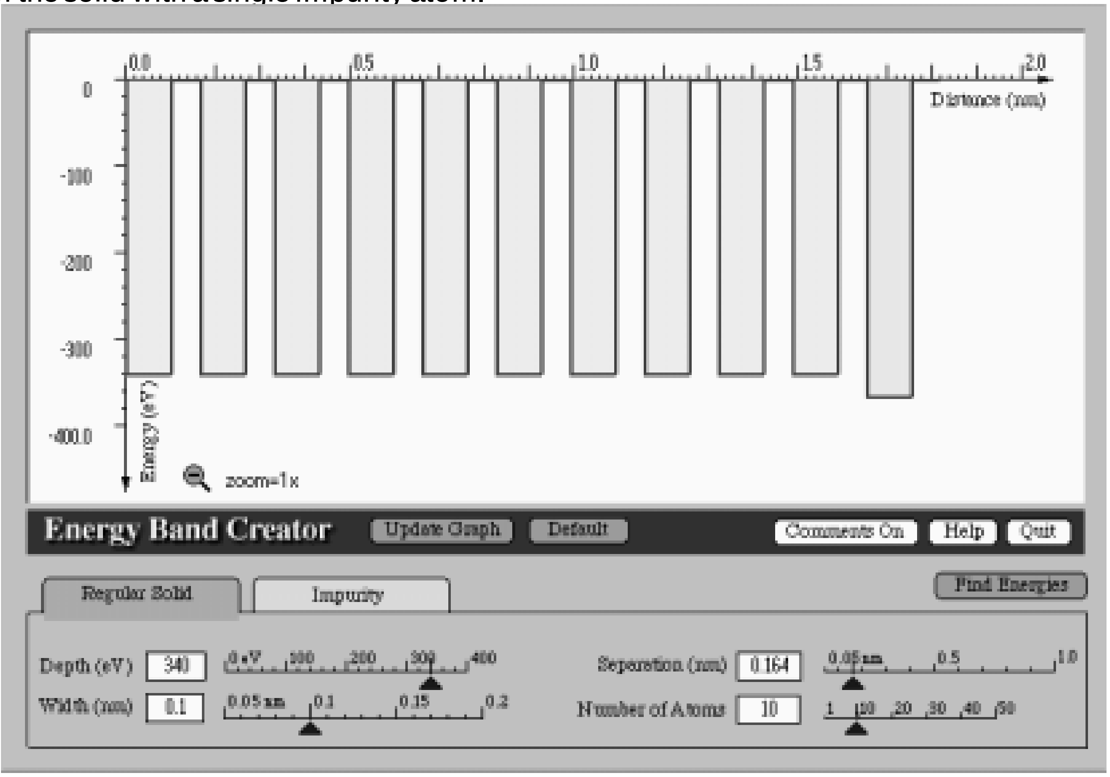
Sketch, in the space provided below, how the potential energy diagrams (the diagrams without the energy bands) would look for a very large number of atoms in which all atoms were identical except one which as a nucleus with a larger electrical charge than the other atoms.

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.



Depth (eV) 340

Width (nm) 0.1

Separation (nm) 0.164

Number of Atoms 10

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.

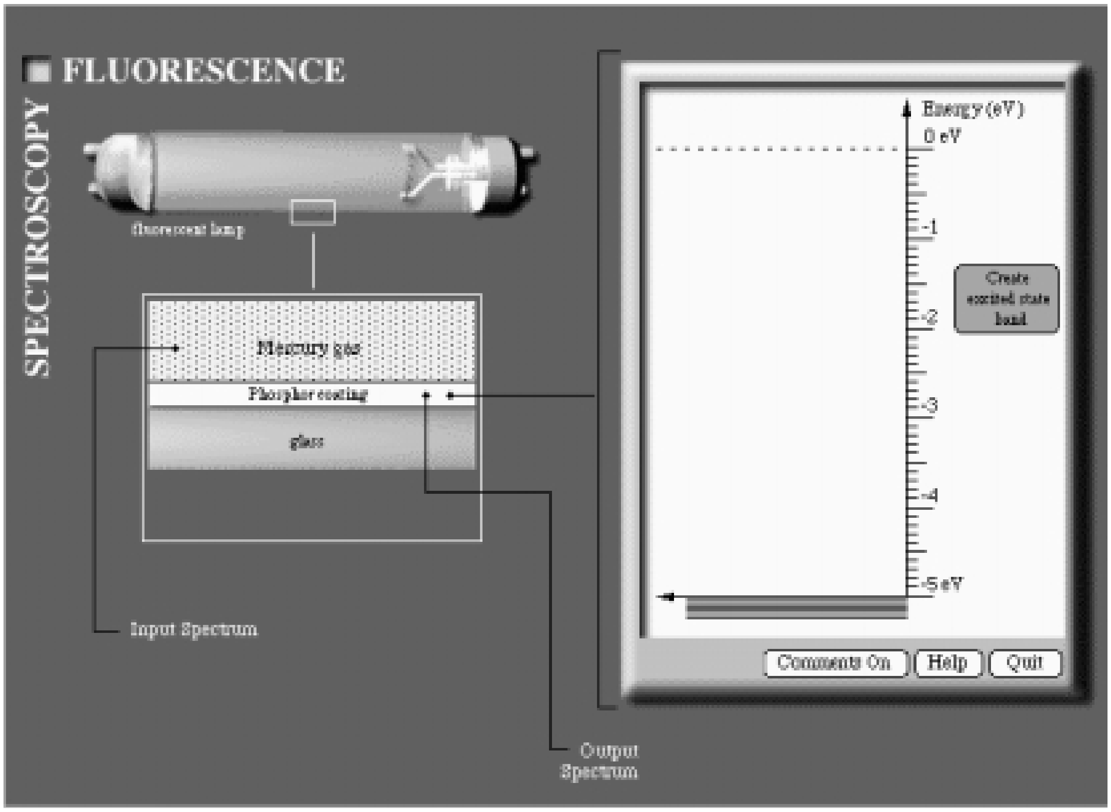


Figure 9-3: *Fluorescence Spectroscopy* Computer Program

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 clickTurn 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.

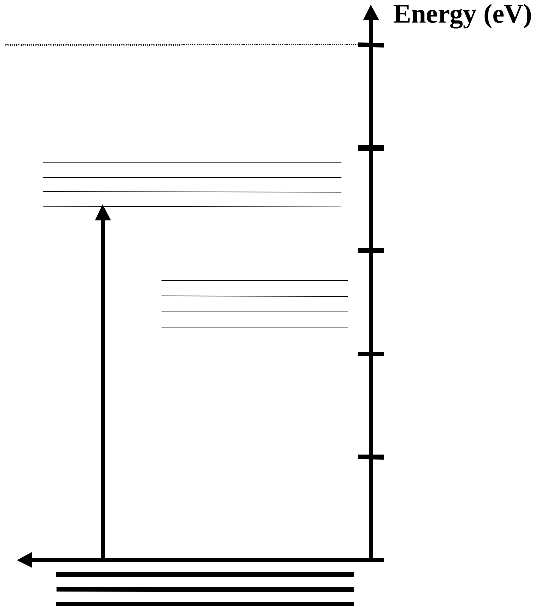


Figure 9-4: Electrons in solid phosphor coating make a transition to excited state band by absorbing ultraviolet light from the mercury gas.

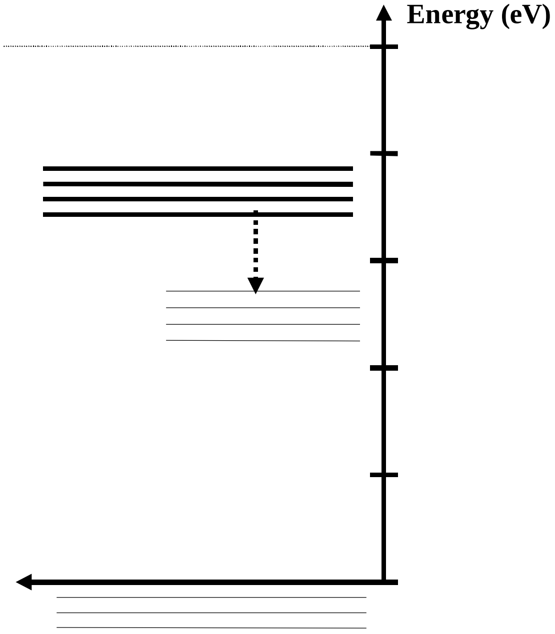


Figure 9-5: Electrons lose energy to neighboring atoms and make a transition to impurity state band. Light is not emitted.

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).

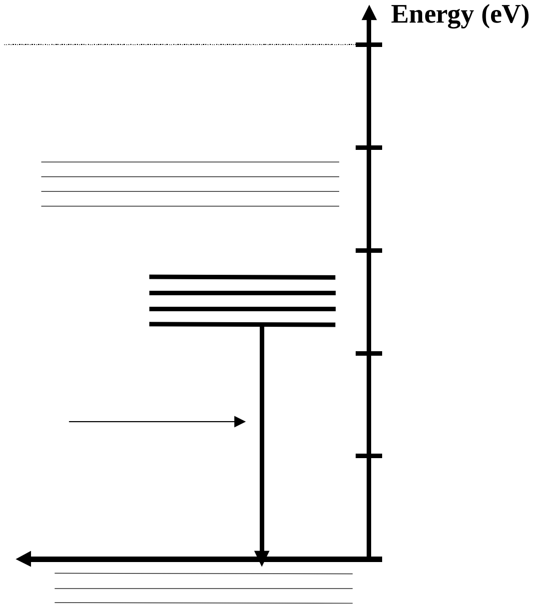


Figure 9-6: Electrons losing energy and making a transition to ground state band.

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?