
Student Explorations of Quantum Effects in LEDs and Luminescent Devices

Lawrence T. Escalada, University of Northern Iowa, Cedar Falls, IA

N. Sanjay Rebello and Dean A. Zollman, Kansas State University, Manhattan, KS

We developed activity-based instructional units to introduce basic quantum principles to students with limited physics and mathematics backgrounds. To emphasize the practical applications of contemporary physics, we introduced concepts using the contexts of light-emitting devices such as light-emitting diodes (LEDs), fluorescent lamps, and glow-in-the-dark toys. As our standard of living becomes more dependent on the latest developments in science and technology, our students' literacy must be at a level that enables them to make educated decisions on science- and technology-related issues and their everyday applications. Students need to have at least a basic understanding of 20th-century physics and its applications in order to make informed decisions about them. Unfortunately, many physics teachers either exclude or spend very little time on modern topics such as quantum mechanics in high school physics courses.^{1,2} The high degree of mathematical formalism and abstract nature of quantum mechanics is frequently given as a reason for not introducing quantum physics in high school physics courses.^{3,4}

Over the past few years we have been addressing these issues as part of the Visual Quantum Mechanics project. To enable a broad spectrum of students to learn quantum mechanics, we have developed a series of interactive instructional units that utilize hands-on activities and computer visualizations to introduce quantum principles. Two versions of the Visual Quantum Mechanics instructional materials have been developed — one called *Visual Quantum Me-*

*chanics – Original*⁵ for high school students and non-science undergraduates, and *Visual Quantum Mechanics – The Next Generation*⁶ for undergraduate physics majors, which is derived from the Original. Both versions focus on enabling students to make observations, develop mental models consistent with quantum principles, and then apply these models to other, related situations. This paper describes instructional strategies and computer tools that have been used and adapted from two instructional units in the *Visual Quantum Mechanics – Original*, and what introductory physics and physical science students can learn from exploring with everyday light sources. Materials for other audiences are under development.

The *Visual Quantum Mechanics – Original* instructional materials utilize a modified learning cycle in which student investigations of concrete phenomena precede and follow the introduction of abstract concepts.⁷ These materials are divided into four major, but relatively short, instructional units and two units for background review. The instructional units include the following:

- **“Solids & Light”** — Students observe the light emitted by solids and gases to understand energy quantization in atoms and its consequences in everyday devices such as the LED.
- **“Luminescence: It’s Cool Light!”** — Students observe light emitted by luminescent materials such as fluorescent lamps and glow-in-the-dark objects to build energy level models that explain a variety of light-emitting processes.

- **“Waves of Matter”** — Students develop a model to explain discrete energy states and to learn about the wave nature of matter by examining its applications to the electron microscope and Star Trek Transporter through visualization activities.
- **“Seeing the Very Small: Quantum Tunneling”** — Students learn about quantum tunneling and its applications to a scanning tunneling microscope using a computer program.
- **“Potential Energy Diagrams”** — Students review energy conservation through classical experiences involving Hot Wheels® cars or dynamics carts with magnets along the track. They explore how potential energy diagrams play an important role in understanding of the quantum ideas.
- **“Making Waves”** — A basic review on some properties of waves including interference.

“Solids & Light”

Students begin by investigating and comparing the electrical properties of LEDs and incandescent lamps. Students find that LEDs, unlike incandescent lamps, emit light of a single color that does not change when the applied voltage is increased. Students also find that LEDs, unlike incandescent lamps, will only emit light when connected in a certain polarity within the circuit and only above a threshold that depends upon

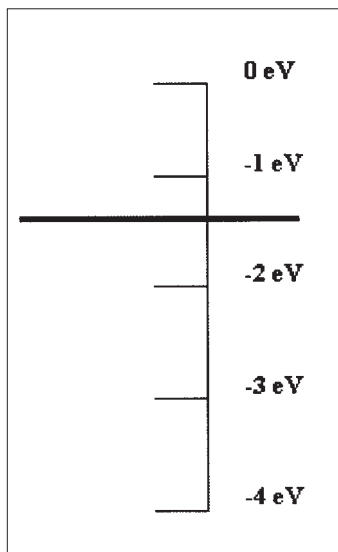


Fig. 1. An energy diagram for an electron with -1.3 eV of energy.

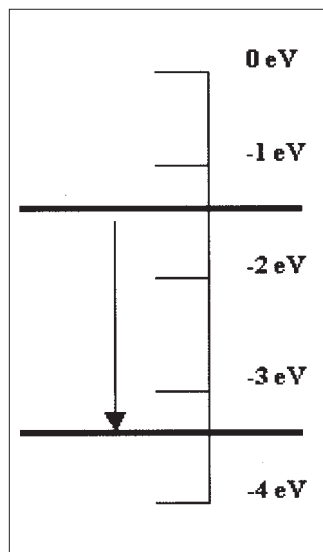


Fig. 2. An energy diagram of an electron resulting in the emission of a 2.0 -eV photon.

the color of light emitted. Students then can apply their observations to determine whether a Christmas light is an incandescent lamp or an LED.

Following the initial investigations of the electrical properties of LEDs and incandescent lamps, students compare the spectra of these devices with that of gas lamps using inexpensive hand-held spectrosopes. Students may overcome any difficulties in using the spectrosopes by first using rainbow glasses (paper glasses with diffraction gratings as “lenses”). They then use spectrosopes that have an eV scale⁸ to make measurements of the light energy directly. Thus, students do not need to learn the relationship between wavelength and energy of light at this time.

Students may recognize the spectral lines emitted by each gas lamp and the visible spectrum of the incandescent lamp from previous experiences. This investigation, however, may be their first experience with LEDs’ broad spectra.

Students realize that LEDs’ spectra is different from that of gas lamps and incandescent lamps. Students also recognize that an LED is made of a solid material, which is more complicated than a gas, because the atoms in a solid are more closely packed together and interact with each other. Therefore to understand the spectra of LEDs, one must first understand the spectra of gases.

Students have already observed that gases emit discrete spectral lines. Therefore, they must emit discrete energies of light. Thus students are introduced to an energy level model of an atom (Fig. 1) where the electron’s total energy or energy level is represented by a horizontal line.

Electrons undergo transitions, i.e., they change energy levels by emitting a photon of light. As per the law of energy conservation:

$$\text{Electron energy before} = \text{Electron energy after} + \text{Light (photon) energy. (1)}$$

Figure 2 illustrates what happens when a photon of 2.0 eV (red and orange light) of energy is emitted. Thus, by looking at the energy of emitted photons one can learn what is happening in an atom. This process provides students with the opportunity to build models of the atom.

The advantage of using the energy level model to represent the atom is that students would only require

a qualitative understanding of energy and energy conservation to understand how light sources consisting of either gases or solids emit light. The work of Fischler,⁹ Johnston et al.,³ and Petri and Niedderer¹⁰ have shown that students can understand the energy level model of the atom by utilizing concepts of energy and energy conservation in their reasoning. Thus, by using this model students could be introduced to a few basic quantum ideas and could reinforce their understanding of energy conservation.

In our initial development of *Visual Quantum Mechanics – Original*, when we asked students to construct an energy level diagram from the spectrum of gas, they often used to incorrectly associate the energies of the spectral lines with the energy levels, rather than the transitions between energy levels. To alleviate this misconception, we created a computer program. Students use the software Gas Lamp Emission Spectroscopy to aid in visualizing an energy level model.^{11,12} Students select one of the gas lamps on the computer screen and try to match its spectrum by placing energy levels and constructing transitions resulting in spectral lines (Fig. 3). When students drag the energy levels with attached transitions, they immediately see the corresponding changes in the spectral lines that they can match with the real spectrum. Thus, the program allows students to construct an energy level model that explains the spectrum that they observe.

The program confronts directly the aforementioned misconception that the energy of a spectral line is related to an energy level. In using the program, students quickly find that a spectrum cannot be produced by simply placing energy levels on the vertical energy scale, and that the energy of a spectral line is the energy difference associated with a transition.

An interesting aspect of this approach is that students often find that no two energy level models are identical! For example, one student may produce a model that looks like a ladder with transitions between each step. Another student's model may have a few energy levels close together at the top with each transition going to an energy level located on the bottom. Both of these models are correct since they each produce the desired spectrum. Following this activity, the instructor could introduce the limitations of this model in that it does not give us a unique description

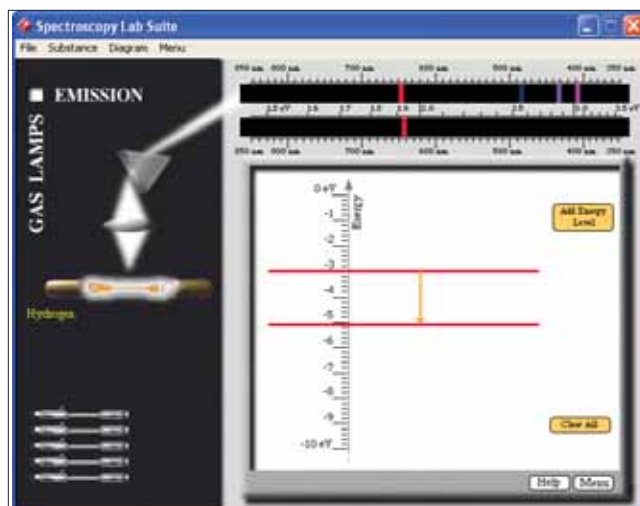


Fig. 3. Gas Lamp Emission Spectroscopy program.

of the energies of the atom. Thus, students can learn about the limitations of scientific models in general and how additional information can sometimes resolve the differences between models.

Students then use Gas Lamp Emission Spectroscopy to match the spectrum of an LED in which the spectral lines are grouped together very closely and appear like a spectral band. They find that their model has two sets of energy levels that are grouped closely together.⁶ Thus, students discover that atoms in an LED must have many energy levels that are extremely close together. Following this discovery, students are introduced to the idea that solids have many closely spaced, interacting atoms. These interactions create groups of very closely spaced energy levels called energy bands. LEDs have two energy bands — the conduction (or excited state) and valence band (or ground state), separated by a gap called the energy band gap. Students move to other programs, LED Spectroscopy and Incandescence Spectroscopy, to investigate how energy bands can explain the spectra of LEDs and incandescent lamps.¹¹

Depending on their physics background, students could then move to a computer program that simulates how two semiconductors are combined to construct an LED and how the LED operates in terms of energy bands. The program plays an important role because it illustrates how energy bands of solids can be used to explain student initial investigations of the electrical and spectral properties of LEDs.

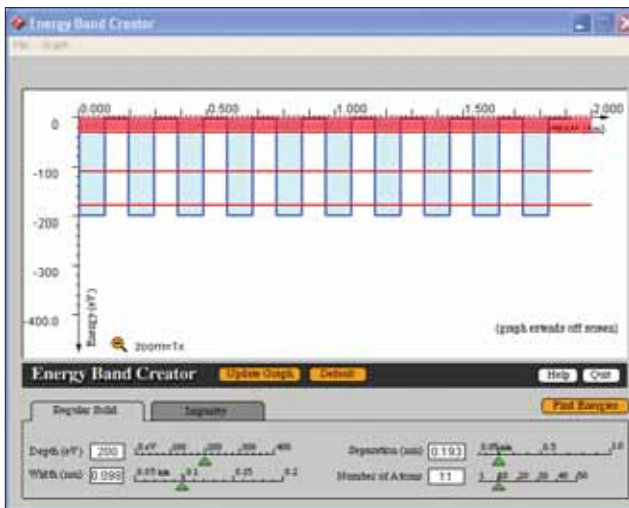


Fig. 4. Energy Band Creator program.

“Luminescence: It’s Cool Light!”

Students begin this unit by investigating the physical properties of different light sources, including an incandescent lamp, LEDs, a Lime Light[®] night-light, Wint-o-green[™] Lifesavers[®], light sticks, and phosphorescent and fluorescent objects. They find that, unlike the incandescent lamp, these other devices do not feel appreciably warm. These devices emit light, not through incandescence in which the primary mechanism used for light emission is thermal energy, but through various forms of luminescence in which some other process involving another type of energy is used. Students also observe the spectra of various light sources, including gas lamps, fluorescent lamps, LEDs, and phosphorescent and fluorescent objects.

Students are introduced to the energy level model in a manner similar to that used in “Solids & Light.” They are also introduced to a potential energy diagram — a visual graph of electrical potential energy versus distance to represent a model of an atom. Students also use the Energy Band Creator program. Energy Band Creator allows the students to visualize “atoms” of a gas (a few potential energy diagrams relatively far apart), a pure solid (a large number of potential energy diagrams relatively close together), and a solid with impurities (a large number of potential energy diagrams with a few of varying depth) and their effect on energy levels. The Energy Band Creator helps students investigate how the depth, width, and distance between potential energy diagrams affect en-

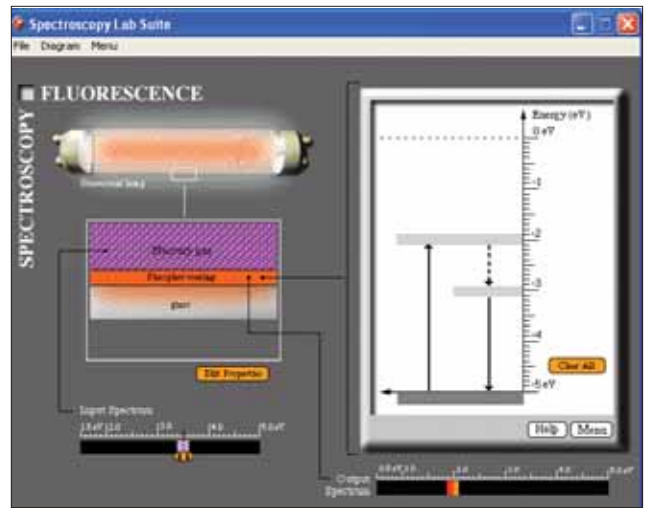


Fig. 5. Fluorescence Spectroscopy program.

ergy levels (Fig. 4).

Adding a large number of impurity atoms to a pure solid results in the formation of a third band of energies lying between the conduction and valence bands. This band of energies, called the impurity band or metastable-state band, is characteristic of luminescent solids. After the students are introduced to the concept of the impurity band, they use computer programs in Spectroscopy Lab Suite to create an energy level model to explain the working of a fluorescent lamp, a phosphorescent toothbrush, and an infrared detector card — a device used by repair people to determine whether remote controls for electronic devices function properly.¹¹

Students have observed the presence of both discrete spectral lines and a broad spectral band for a fluorescent lamp. From their previous observations of gas spectra, they are able to recognize the spectral lines as those from a mercury gas lamp. Students know that the fluorescent lamp is a mercury gas lamp with a material coating on the inner walls of the lamp. Students then use the Fluorescence Spectroscopy program to construct a model to explain the broad spectral band (Fig. 5). Students discover that electrons in the solid coating of a fluorescent glass tube make a transition from the ground-state band to the excited-state band by absorbing ultraviolet light emitted by a mercury gas found inside the tube. These electrons then lose a small amount of energy to neighboring atoms in the form of thermal energy and make a transition to the

impurity-state band. Electrons then lose energy in the form of visible light and make a transition to the ground-state band. The program allows the student to edit the properties of the fluorescent glass tube so that various white-light and black-light fluorescent lamps may be modeled.

In fluorescent materials, electrons have energies in the impurity-state band for a relatively short period of time. 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 shines on them. In phosphorescent objects, electrons remain in the impurity-state band. After a 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.

With the program Fluorescence Spectroscopy, students learn electrons of a glow-in-the-dark toothbrush make a transition from the ground-state band to the excited-state band by absorbing visible light from an external source. These excited electrons lose a small amount of energy in the form of thermal energy to nearby atoms to make the transition from the conduction band to the impurity band. These electrons then absorb thermal energy from the surroundings and make a transition back to the conduction band. The electrons lose energy by emitting the visible light characteristic of glow-in-the-dark objects and make a transition to the valence band. The program allows the student to edit the properties of the external light source and the phosphorescent toothbrush to investigate how these variables affect the resulting spectra.

After exploring the properties of an electronic remote-control device and an infrared detector card, students use the IR Detector Card Spectroscopy program to learn that electrons of an infrared detector card absorb energy from visible light and make a transition to the conduction band. Electrons then lose a small amount of energy to neighboring atoms in the form of thermal energy and make a transition to the impurity-state band. Electrons absorb energy from an infrared light source such as a remote control and then make a transition back to the excited-state band. These electrons then lose energy by emitting visible light and make a transition to the valence band.

After being introduced to these various energy band models to explain luminescent phenomena, students can make comparisons between models.

Results

The *Visual Quantum Mechanics – Original* materials have been used and adapted in a number of high school and introductory college physics and physical science classrooms. Results indicate that the use of hands-on activities, interactive computer programs, inexpensive materials, and the focus on conceptual understanding are very effective in these classes. Students have indicated that they liked the hands-on activities, computer programs, and the real-life science applications. When asked to report what they learned from these instructional units, some students mentioned the mechanism for emission and absorption of light, relating energy diagrams of atoms to spectra, different ways in which light can be emitted, and how potential energy diagrams can be used to represent all types of atoms from gases to solids.

Based on the results of our assessments, students are able to recognize the spectral and electrical features of various light sources. When presented with a diagram that has few energy levels, the majority of students are able to correctly sketch the electronic transitions and identify the resulting “colors” and energies of the resulting spectrum. Most students are able to understand the concept that the energy of the spectral line is related to the difference in energy between two levels and not the values of the levels themselves.

Students are able to correctly associate the energy diagram with a particular light-emitting device, but do experience some difficulty in identifying specific details about these models, especially those that are somewhat similar. Following the initial implementation of “Luminescence: It’s Cool Light” in different Iowa high school schools, 44% of 124 physics students were able to correctly identify the correct energy band diagram that explains the spectra of a white-light fluorescent lamp when presented with energy band diagrams for a phosphorescent toy, black-light fluorescent lamp, white-light fluorescent lamp, fluorescent object, and gas lamp. Fifty percent of the students were able to correctly identify the correct energy band diagram that explains the spectra of a black-light fluorescent lamp. In both cases, we found a number of

students who confused the energy band diagram that explains the spectra of a black-light fluorescent lamp with that of the diagram that explains the spectra of a white-light fluorescent lamp. This result is not surprising since both energy band diagrams are somewhat similar with the exception of the differences in energy requirements and the resulting energies of light emitted. Sixty-seven percent of the high school students were able, however, to identify the correct energy band diagram that explains the spectral properties of a phosphorescent toy.

Our assessments reveal some student confusion on the difference between absorption and emission of energy for electrons as they undergo a transition from one energy level to another. The confusion between absorption and emission could result from these students not fully understanding which energy level has the highest energy — the highest negative energy level, or the lowest negative energy level. These results suggest that students need additional practice in working problems involving energy diagrams and being able to identify electron transitions that result in the absorption and the emission of energy.

Adaptations

We have observed that in implementing “Solids & Light” and/or “Luminescence: It’s Cool Light!” in a high school physics classroom some instructors have focused on the concrete observational aspects of the materials and not on developing the energy model of the atom as a result of their lack of familiarity with this model. The *Potential Energy Diagrams* instructional unit was developed to provide both the students and instructor with experiences in reviewing energy conservation by using potential energy diagrams. We have found that when students are provided with opportunities to practice applying energy diagrams for various classical situations, they are likely to experience less difficulty when using these diagrams to explain the physical properties of light-emitting devices.

Since computer accessibility in many high school classrooms is a problem, an inexpensive alternative or supplement to the Gas Lamp Emission Spectroscopy program that has proven effective involves the use of “energy ladders” — wooden dowels or pencils placed on a piece of cardboard that contains an energy scale

similar to the one found in the program. The wooden dowels represent energy levels that may be placed horizontally on the scale. Electron transitions are represented as large bold arrows drawn to scale on separate pieces of paper. Students then can place these “transitions” pointing downward between two “energy levels” to represent electron transitions that result in the emission of energy. The energy difference between the two “energy levels” is equal to energy of a resulting spectral line. On the back of these “transitions,” a single vertical line of a specific color is used to identify the resulting spectral line. The energy ladder used in conjunction with the computer program provides students with a concrete, hands-on, and visual means to construct their energy level model. The use of the energy ladder could also be used to provide students with concrete experiences in constructing “electron transitions” that result in the absorption or emission of energy.

Investigations on the physical properties of luminescent devices themselves, without the introduction of energy level models of the atom, have also been adapted to provide students with a unique means to reinforce their understanding of the concepts of energy and light and to develop proficiency in scientific inquiry.¹³ For example, students can use light sticks to model how temperature affects the light emitted by a bioluminescent organism — the firefly. This investigation has been very effective and relevant in illustrating the general idea of a scientific model for audiences of all ages and cultures.

We have demonstrated that it is possible to introduce 20th-century physics ideas in an introductory university or high school physics and physical science course with the use of visual and interactive simulations, combined with interesting and relevant hands-on activities using accessible materials. *The Visual Quantum Mechanics – Original* materials are published by Ztek Inc., <http://www.ztek.com>. A sampler is available at <http://web.phys.ksu.edu/vqm/index.html>.

Acknowledgment

The research reported in this article was supported by NSF grant #ESI-9452782 and an Iowa Space Grant Consortium Phase I – “Seed Grant.”

References

1. A. Hobson, "Teaching quantum theory in the introductory course," *Phys. Teach.* **34**, 202–210 (April 1996).
2. M. Neuschatz and L. Alpert, *Overcoming Inertia: High School Physics in the 1990s* (American Institute of Physics, College Park, MD, 1996).
3. I.D. Johnston, K. Crawford, and P.R. Fletcher, "Student difficulties in learning quantum mechanics," *Int. J. Sci. Educ.* **20**, 427–446 (1998).
4. M.J. Morgan and G. Jakovidis, "Characteristic energy scales of quantum systems," *Phys. Teach.* **32**, 354–358 (Sept. 1994).
5. D.A. Zollman and KSU Physics Education Research Group, *Visual Quantum Mechanics – The Original CD-ROM*, Ztek, Lexington, KY (2001).
6. D.A. Zollman, N.S. Rebello, and K. Hogg, "Quantum mechanics for everyone: Hands-on activities integrated with technology," *Am. J. Phys.* **70**, 252–259 (2002).
7. R. Karplus, "Science teaching and development of reasoning," *J. Res. Sci. Teach.* **12**, 213–217 (1974).
8. Project STAR Spectroscope. Learning Technologies, Inc., Somerville, MA (<http://www.starlab.com/psgi.html>).
9. H. Fischler, "The atomic model in science teaching: Learning difficulties or teachers' problems?" Paper presented at the annual meeting of the National Association for Research in Science Teaching, St. Louis, MO (1996).
10. J. Petri and H. Niedderer, "A learning pathway in high school level quantum atomic physics," *Int. J. Sci. Educ.* **20**, 1075–1088 (1998).
11. N.S. Rebello, C. Cumarantunge, D.A. Zollman, and L.T. Escalada, "Simulating the spectra of light sources," *Comp. Phys.* **28**, 33 (1998).
12. D. Donnelly, "CIP's seventh annual educational software contest: The winners," *Comp. Phys.* **10**, 532–541 (1996).
13. L. Escalada, R. Unruh, T. Cooney, and J. Foltz, "Students see the light: Investigating luminescence and incandescence through a three-part learning cycle," *Sci. Teach.* **68**, 40–43 (2001).

PACS codes: 01.40Ga, 01.50H, 85.30

Lawrence Escalada is an associate professor in physics and science education at the University of Northern Iowa. He teaches introductory physics/physical science and secondary science methods courses, and works with high school physics teachers and students on a number of different projects and activities. He has taught high school physics and physical science and has been involved in

developing instructional materials including the Visual Quantum Mechanics—The Original and Physics Resources and Instructional Strategies for Motivating Students (PRISMS) PLUS.

**Department of Physics, 205 Physics Building,
University of Northern Iowa, Cedar Falls, IA 50614-0150; escalada@uni.edu**

Sanjay Rebello is an assistant professor in physics education at Kansas State University. He has been involved in physics education research for the past seven years. His interests include research on students' mental models of real-world applications, curriculum development in contemporary physics, and use of technology in the teaching and learning of physics.

**Department of Physics, Kansas State University,
Manhattan, KS 66506-2601; srebelo@phys.ksu.edu**

Dean Zollman is head of the Department of Physics and University Distinguished Professor at Kansas State University. He has been conducting research on student learning of physics and developing instructional materials for more than 30 years. AAPT awarded him its 1995 Robert A. Millikan Medal. In 1996 he was named the Doctoral University National Professor of the Year by the Carnegie Foundation for the Advancement of Teaching.

**Kansas State University, Manhattan, KS 66506-2601;
dzollman@phys.ksu.edu**
