# VISUALIZATION OF QUANTUM PHENOMENA

David J. Austen, Wytze Brouwer, Brian Martin

ABSTRACT
Many abstract phenomena are, by their nature, "unseeable". What then does it mean to visualize quantum phenomena such as Compton Scattering, Alpha and Beta Decay, or collisional de-excitation? Perhaps more importantly, how can one construct visualizations of such phenomena without introducing misconceptions or harmful distortions? In this paper we propose to navigate the troubled waters between the abstract presentation of ideas on one hand and visually enhanced representations of these same ideas on the other. We will illustrate this with a number of visualizations that we have produced as part of an ongoing project to visualize the unseen world of quantum phenomena. We will also present a summary of well known misconceptions about quantum phenomena held by students and suggest which of these are likely to be ameliorated through careful use of visualizations and which will likely be resistant to such treatments.

KEYWORDS
Collaborative Learning, Computer Aided Instruction, Conceptual Physics, Constructivism, html, Java, Pre-Conceptions, Laboratory, Applets, Simulations, Flash.

## INTRODUCTION

*"I am never content until I have constructed a mechanical model of the subject I am studying. If I succeed in making one, I understand; otherwise I do not."* Lord Kelvin - Notes of Lectures on Molecular Dynamics and the Wave Theory of Light.

The construction of models has always been at the centre of problem solving and of theory formation in physics. Lord Kelvin, in trying, and failing, to construct a mechanical model of electromagnetic phenomena and especially of the propagation of light through the ether, may have taken an extreme position on this issue, but there is little disagreement on the need for mental models in the physical sciences.

It seems reasonable to assume that textual material would offer little support to the development of internal visualization or model building, except for internally well-motivated learners. Diagrams in textbooks may well offer more support for the development of spatial visualization, and interactive computer simulations should provide excellent support for the development of internal visualization.

It is especially true in Modern Physics that students are confronted with the unseen, and where very few classroom experiments and demonstrations can be of much help in providing anchors for acceptable mental models or visualizations.

One of the objectives of the King's Center for Visualization in Science is to develop interactive simulations on various topics in Modern Physics and Chemistry and to test these applets in high school and university science classes. It is to be expected that the testing of such applets will lead to necessary revisions and improvements of the applets. Consequently, the research component of this project will involve the investigation of teacher and student use and attitude towards these applets.

One of the pedagogical objectives of the project is to use these applets in ways to develop mental models and thus to encourage the development of conceptual understanding in science. Many of the applets will be based on those experiments considered crucial to the development of Modern Physics in the 20th century.

A second objective relates to the development of student investigative skills. Many of the simulations require the students to make measurements, to analyze data, and to formulate reasonable conclusions. Because of the role these experiments being simulated played in the history of physics, the student conclusions will, in most cases, be triggers for further learning, similar to the way these experiments were historically triggers for further theoretical developments.

Such experiments include

- the Michelson-Morley experiment on the measurement of the speed of light with respect to the Earth.
- The Stern-Gerlach Experiment on the quantization of energy and the later hypothesis of a spin magnetic moment
- The Davisson-Germer Experiment on the wave properties of matter
- Alpha and Beta decay and the Conservation Laws
- Millikan's Oil Drop Experiment and the quantization of the charge of the electron
- Thomson's Experiment and the charge to mass ration for beta radiation

A number of applets familiarizing students with the motions of charged particles in magnetic fields, with particle accelerators and cyclotrons have also been produced and can be used to introduce students to the physics required to understand the above simulations.

In creating simulations of micro-physical phenomena one needs to remember that nature comes to us only though the lenses of our current theories and that the visualizations we create will, of necessity, share the limitations of our current theories. Therefore students and researchers need to be aware that in creating simulations of microphysical phenomena we might, perhaps will, help create misconceptions, or alternate conceptions, which may inhibit student further understandings. Despite the need for visualization in modern physics we need help students and teachers become aware of the possible limitations of such visualizations.

Russell and Kozma (1996 and later) have developed and tested a series of dynamic, interactive animations in introductory chemistry (called SMV:Chem) in order to develop student visualization skills, and conceptual understanding of basic chemistry. In order to test the effectiveness of the set of animations, Kozma and Russell (1997) found that test items requiring students to supply answers to questions were better at exposing student reasoning than choosing from a set of given alternatives. The SMV: Chem materials have been tested at high school and university levels (Russel and Kozma, 2005), and have demonstrated highly significant student growth in visualization skills and conceptual understanding of the chemistry topics studied. The authors noted (Gilbert, p. 326) that the SMV:Chem program was effective for all students, but especially effective for upper ability students. The authors make the following recommendations for visualization in chemical education:

1. Visualization animations are especially effective for developing students' conceptual understanding.
2. More carefully designed experiments should be designed to test the effectiveness of animations versus still pictures or physical models.
3. There is as yet a dearth of evidence of the effectiveness of visualization animations on 'the processes of investigation' in chemistry.

In previous papers (de Bruijn, Martin and Brouwer (2003); Martin, Austen, Brouwer (2001), Laue, Martin, Austen, and Brouwer(2003)), the authors have reported on JAVA applets developed under the Modular Approach to Physics project (MAP). This project has evolved into a similar project funded under the Natural Sciences and Engineering Research Council CRYSTAL program. One significant change in our work is the switch from JAVA to FLASH as a development medium. With the advent of Actionscript 2.0, FLASH has acquired sufficient power to enable the development of sophisticated learning objects. FLASH also is ubiquitous - installed on well over 90% of all Windows and Mac computers. As well, the FLASH platform is much more uniform in performance across OS's and has proven to be easier for teachers and students to work with than JAVA.

All applets are web deliverable and many are accompanied by example lessons that provide teachers and students with learning contexts in which to use the applets. We have found that this is an essential part of the design of such applets.

The following two sections are examples of the use of a "Cloud Chamber" applet to investigate alpha and beta decay. In the former, energy is conserved as expected while in the latter, and contrary to student expectation, energy does not appear to be conserved. The student carries out the measurements using the simulation and the instructions included as follows:

**ALPHA DECAY**

**Investigating the decay of Americium-243**

The alpha decay module is designed to show the emission of alpha particles from various sources, to measure the deflection of these alpha particles in a magnetic field, to calculate the energies of the alpha particles and to compare these results with the theoretical predictions of the energy expected for alpha decay. Students are encouraged to vary the strength of the magnetic field and the decay mode and nucleus being studied. Figure 1 shows a typical set-up with several option menus open. Since the principal tool of analysis will be the measurement of radius of curvature of the alpha particle in the magnetic field the student will be required to, in his or her judgment, select a magnetic field that provides an appropriately measurable path. Figure 2 illustrates the use of the curvature measurement tool in operation.

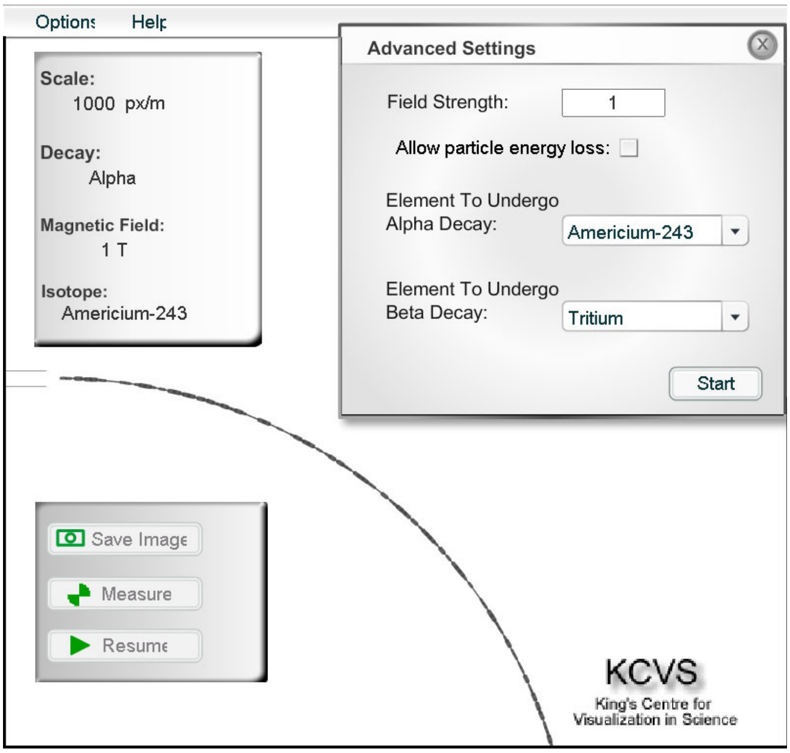


Figure 1. Americium-243 is undergoing decay in a magnetic field. The magnetic field strength can be changed and, as in figure 1, the radius of curvature for the path of the alpha particle measured. The elements Thorium, Uranium, Polonium and Radium are also available for measurement.

One of the goals of the Alpha decay simulation is to provide the student with sufficient data to make an assessment of the energy of a typical alpha decay process and to discover that, for the elements included in this simulation, alpha decay energies occur with a well defined and narrow range of values. In Appendix A we present examples of the kinds of questions used to guide students through an investigation of alpha decay.

**BETA DECAY**

**The beta decay of Tritium**

In the Beta Decay simulation students are asked to do a similar investigation as previously carried out in the Alpha Decay simulation, but find that the energies of the beta particles vary much more widely than the energies of the alpha particles in the previous simulation.

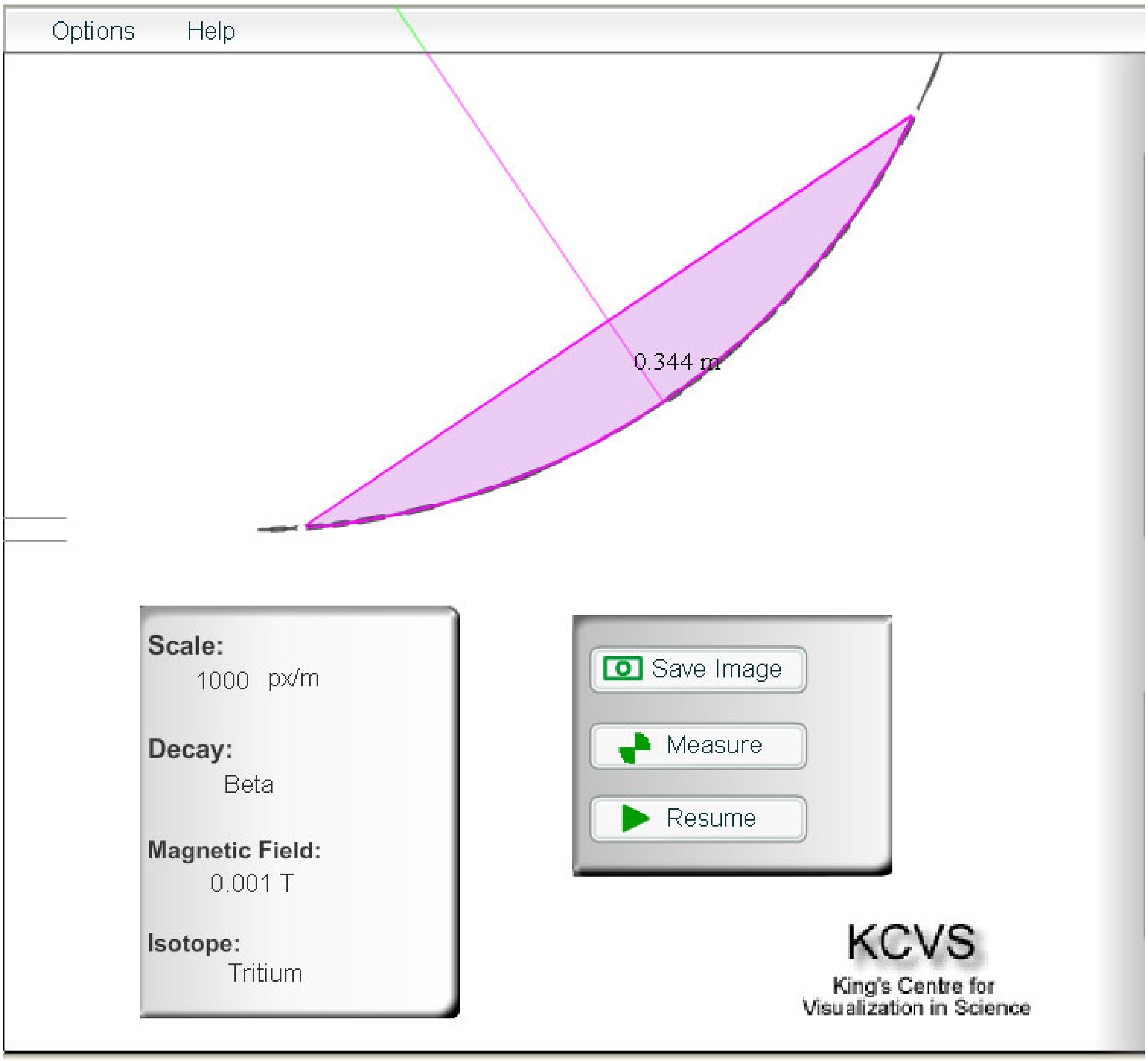


Figure 2. This simulation of a cloud chamber shows the decay of Tritium in a magnetic field. The animation makes it easy to measure the radius of curvature for the beta particle. The magnetic field strength is adjustable. The elements Sodium, Cobalt, Strontium, and Copper-64 are also available for measurement.

We now understand beta-minus decay to be the emission of electrons from some nuclei when they undergo radioactive decay. The student data shows an interesting problem - beta particles do not all have the similar energies. Instead a particular element will emit beta particles with a considerable range in energies. In fact, students can measure the energies of beta particles emitted by Tritium, Sodium, Cobalt and Strontium and note that similar ranges of beta particles energies occur for these different sources. In fact, these simulations also introduce students to positron decay processes.

**STUDENT QUESTIONS:**

1. Explain how your data provides evidence that there must be at least two different kinds of beta decay process?

2. Without performing any calculations rank the beta particle energies emitted by the different element from least energetic to most energetic. Explain how you determined this.
3. In all of these beta decay processes the law of conservation of energy appears to be violated. Physicists in the early parts of the twentieth century were divided on the issue of whether to give up the law of conservation of energy for microphysical processes. What would you decide in a situation of this sort?
4. Are there any alternatives to giving up the Law of Conservation of Energy?

Students should be given ample time for discussion of these questions before the accepted resolution of the beta decay dilemma is presented to them. Students should appreciate the nature and importance of the choice made by the majority of physicists in favour of the invention of a small nuclear particle, which carried off just the right amount of energy, momentum and angular momentum, while many physicists, Niels Bohr among them, were willing to consider giving up the Conservation Laws of Energy and Angular Momentum. Would the students be willing to believe in the existence of this little particle for thirty years before more direct evidence for its existence was found? (See Appendix A for the neutrino hypothesis).

**SUMMARY**

In the objectives for Science Education, of Alberta Education, student understanding of the nature of scientific discovery, and more broadly, an understanding of the nature of science, are emphasized. Few examples from the history of physics lend themselves as readily to the nature of scientific discovery, as many of the discoveries during the twentieth century do. The story of beta decay, and the subsequent questioning of the importance of conservation laws in physics teaches students that raw experimental results do not tell the whole story of scientific discovery. Physicists chose to adhere to the principle of the conservation of energy, momentum and angular momentum, even though the beta decay experiments ‘showed’ fairly conclusively that the conservation principles were violated.

The major objectives of our project is thus to develop a number of computer simulations of modern physics phenomena and to study:

a) the growth of conceptual understanding of modern physics
b) student understanding of the nature of scientific discovery
c) the role of observation and theory in the interpretation of experimental results.
d) The existence and persistence of student misconceptions in modern physics
e) The development of visualization techniques to aid in problem solving, especially in modern physics.

We are in the process of developing assessment materials similar to those developed by Russell and Geno (2000) and hope to test the simulations in Canadian high schools and in Canadian universities.

**APPENDIX A**

Questions to Guide Students Through the Simulation

1. Use the applet to determine whether alpha particles are positively or negatively charged. Explain in a well reasoned sentence how you determined this.

2. Adjust the magnetic field strength until you get strongly curved particle paths. Do this by selected the "Advanced Settings" choice from the options menu. What are "typical" magnetic field strengths that you will need to produce measurable radii for the alpha particle paths?

3. True or False: An alpha particle is a helium ion. Explain your answer.

4. In a previous unit you learned that a magnetic field of strength B exerts a force on a moving particle of charge q. If the particle is moving at rights angles to the field then the magnetic force is given by the expression $F = qvB$. Explain why this creates a circular arc and use your knowledge of circular motion to show that the momentum of the particle can be written as $p = Bqr$ where $p$ is the magnitude of the momentum and r is the radius of the path's arc.

5. Show that the kinetic energy of a particle can be related to the momentum by the equation $E_k = p^2/(2m)$ and that the kinetic energy of a particle can be related to the radius of its arc by the expression $E_k = (B\ p\ r)^2 / (2m)$.

6. Produce 5 different paths for the alpha decay of Americium-243 and record your results in a table. Measure the radius of each path as carefully as you can and use this to help determine the kinetic energy of alpha particles emitted by Americium-243. The mass of an alpha particle is $6.645 \times 10^{-27}$kg and the charge is +2e. In the last column of the table convert the energy to units of MeV or Million Electron Volts. Use the conversion 1 MeV = $1.602 \times 10^{-13}$ eV

Americium-243 (Am-243) is a very commonly used radioisotope - you probably have some in your home! This isotope is used in smoke detectors. Your measurements should have shown that the energy of alpha particles emitted during the alpha decay of Am-243 is approximately 5.4 MeV. Am-243 has a half-life of about 7370 years.

## Comparing alpha decay of various nuclei

1. Use the applet to compare the energies of alpha particles emitted by the Americium, Thorium, Uranium, Radium and Polonium. Run at least 3 different trials for each nucleus and average the results. Choose a convenient magnetic field strength to allow you to make an accurate measurement of the path radius. Express the energies in MeV.

2. Was there much variation in the energy of the alpha particles that you measured for any one element? To what would you attribute any variations in energy that you may have detected?

**REFERENCES**

DeBruyn, I., Martin, B., Brouwer, W. (2003). Simulations, Applets and Learning in Schools, CBLIS International Conference, Nicosia, Cyprus, July 7, 2003.

Kozma, R. and Russel, J. (1997). Multimedia and Understanding: Expert and Novice Responses to Different Representations of Chemical Phenomena, Journal of Research in Science Teaching, 43(9), 949-968.

Laue, H., Martin, B., Brouwer, W., Austen, D. J. (2003). A Constructivist Approach to Computer-Based Physics, Canadian Association of Physicists, Laval, Quebec.

Martin, B., Austen, D. J. & Brouwer, W. (1999). MAP - A Modular Approach to Physics, Proceedings of the 4th Biennial Conference for Computer-based Science Learning (G. Chapman, editor, University of Ostrava Press, Ostrava, Czech Republic).

Martin, B., Austen, D. J., and Brouwer, W. (2001). Using Computer-based Simulations to Enhance Conceptual Learning in Physics, Proceedings of the 5th Biennial Conference for Computer-based Science Learning (G. Chapman, editor, University of Ostrava Press, Ostrava, Czech Republic).

Russel, J. and Kozma, R. (1996). Multimedia Questions to Assess Students' Ability to Visualize Chemical phenomena, 14th Biennial Conference on Chemical Education, Clemson, SC.

Russel, J. & Kozma, R., in Gilbert, J.K. (ed), (2005). Visualization in Science Education, (Springer), 325-331.

David Austen
Department of Physics
University of Alberta
Edmonton, Alberta
Canada, T6G 2J1
Email: dausten@ualberta.ca