A Summary of *Particle Physics* for Teachers

Particles Prior to Accelerators

By the mid 1930s, the understanding of the fundamental structure of matter seemed almost complete. Decades before, Rutherford had shown that atoms have relatively tiny but massive *nuclei*. The *quantum theory* had made sense of atomic spectra and electron orbitals. The discovery of the *neutron* had explained nuclear isotopes. So *protons, neutrons*, and *electrons* provided the building blocks of all matter. Some puzzles remained, however:
What holds the protons and neutrons together to form the nucleus?
What are the forces involved in the radioactive decays of nuclei that make alpha, beta, and gamma rays?

Enter the Accelerator

To study the nucleus and the interactions of neutrons and protons that form it, physicists needed a tool that could probe within the tiny nucleus, as earlier scattering experiments had probed within the atom. The *accelerator* is a tool that allows physicists to resolve very small structures by producing particles with very high momentum and thus short wavelength. The wavelength (λ) of the associated wave is inversely proportional to the momentum (p) of the particle ($\lambda = h/p$), where h = Planck's constant.

Particle experiments study collisions of high energy particles produced at accelerators. In modern experiments, large multi-layered detectors surround the collision point. Each layer of the detector serves a separate function in tracking and identifying each of the many particles that may be produced in a single collision.

The Particle Explosion

To the surprise of the physicists, accelerator experiments revealed that the world of particles was very rich; many more particle types similar to protons and neutrons (called *baryons*) - and a whole new family of particles called *mesons* - were discovered. By the early 1960s a hundred or so types of particles had been identified, and physicists still had no complete understanding of the fundamental forces.

The Quark Proposal

In 1964, two physicists - Murray Gell-Mann and George Zweig - independently hit upon the idea that neutrons and protons and all those new particles could be explained by a few types of yet smaller objects; Gell-Mann called them *quarks*. They could explain all the

observed baryons and mesons with just three types of quarks (now called *up, down*, and *strange*) and their *antiquarks*. The revolutionary part of their idea was that they had to assign the quarks electric charges of 2/3 and -1/3 in units of the proton charge; such charges had never been observed!

Antiquarks are the antimatter partners of quarks; they have the same masses as, but the opposite charge from, the corresponding quarks. When a quark meets an antiquark, they may *annihilate*, disappearing to give some other form of energy.

The Standard Model

Nearly thirty years and many experiments later, the quark idea has been confirmed. It is now part of the *Standard Model of Fundamental Particles and Interactions*. New discoveries have shown that there are six types of quarks (given the odd names of *up, down, strange, charm, bottom*, and *top*, in order of increasing mass). Also, there are six types of particles including the electron, called *leptons*. The Standard Model accounts for the *strong, weak, and electromagnetic interactions* of the quarks and leptons, and thus explains the patterns of nuclear binding and decays.

The Particles Made from Quarks

The reason that fractional electric charges like those of quarks have not been seen is that the quarks are never found separately, but only inside composite particles called *hadrons*. There are two classes of hadrons: *baryons*, which contain three quarks, and *mesons*, which contain one quark and one antiquark. The sample hadron tables on the Standard Model chart give a few examples of the many known particles. Particles made from the first five quark types have been produced and studied at accelerators. The top quark is so massive it took many years and very high-energy accelerators to produce it. The top quark was finally discovered in April 1995 at Fermilab.

The Leptons

In contrast to the quarks, any of the six leptons may by found by itself. The *electron* is the best known lepton. Two other charged leptons, the *muon*, (discovered in 1936) and the *tau* (discovered in 1975) differ from the electron only in that

they are more massive than it.

The other three leptons are very elusive particles called *neutrinos*, which have no electric charge and very little, if any, mass. There is one type of neutrino corresponding to each type

of electrically charged lepton. For each of the six leptons there is an antilepton with equal mass and opposite charge.

Forces and Interactions

Now we know the building blocks of matter, but we must also ask: What holds it together? All forces are due to the underlying interactions of the particles. Interactions come in four types: *gravitational, electromagnetic, strong, and weak*. *Gravity* is perhaps the most familiar force to us, but it is not included in the Standard Model because its effects are tiny in particle processes and, furthermore, physicists have not yet figured out how to include it.

Electromagnetic forces are also familiar; they are responsible for binding the electrons to the nucleus to form electrically-neutral atoms. Atoms combine to form molecules or crystals because of electromagnetic effects due to their charged

substructure. Most everyday forces, such as the support of the floor or friction, are due to the electromagnetic forces in matter that resist displacement of atoms or electrons from their equilibrium positions in the material.

In particle processes the forces are described as due to the exchange of particles; for each type of force there is an associated carrier particle. The carrier particle of the electromagnetic force is the photon; gamma ray is the name given a photon from a nuclear transition.

For distances much larger than the size of an atomic nucleus, the remaining two forces have only tiny effects -- so we never notice them in everyday life. But we depend on them for the existence of all the stuff from which the world is made, and for the decay processes that make some types of matter unstable.

The *strong* force holds quarks together to form hadrons; its carrier particles are whimsically called *gluons* because they so successfully "glue" the quarks together. The binding of protons and neutrons to form nuclei is a residual strong interaction effect due to their strongly-interacting quark and gluon constituents. Leptons have no strong interactions.

Weak interactions are the only processes in which a quark can change to another type of quark, or a lepton to another lepton.

They are responsible for the fact that all the more massive quarks and leptons decay to produce lighter quarks and leptons. That is why stable matter around us contains only electrons and the lightest two quark types (*up* and *down*). The carrier particles of weak interactions are the W and Z *bosons*. Beta decay of nuclei was the first observed weak process: in a nucleus where there is sufficient energy a neutron becomes a proton and gives off an electron and an antielectron neutrino. This decay changes the atomic number of the nucleus. Beta ray is the name given to the emerging electron.

So now we have explained beta and gamma rays; what about the alpha? The *alpha particle* is a helium nucleus - one of the products of a nuclear fission. Fission is the breakup of a massive nucleus into smaller nuclei; this occurs when the sum of the masses of the smaller nuclei is less than the mass of the parent nucleus. This is a residual strong interaction effect.

What Questions Remain?

The Standard Model answers many of the questions of the structure and stability of matter with its six types of quarks, six of leptons, and the four force types.

But the Standard Model leaves many other questions unanswered: Why are there three types of quarks and leptons of each charge? Is there some pattern to their masses? Are there more types of particles and forces to be discovered at yet higher-energy accelerators? Are the quarks and leptons really fundamental, or do they, too, have substructure? How can the gravitational interactions be included? What particles form the dark matter in the universe?

Questions such as these drive particle physicists to build and operate new accelerators, so that higher-energy collisions can provide clues to their answers.

Activity One -- Fundamentally Speaking (Teacher Page)

Goal: To stimulate discussion about particles and curiosity to learn more.

This initial activity introduces students to the evolving field of high-energy particle physics and challenges their knowledge and conceptions of the fundamentals of physics. The agree/disagree quiz featured in the activity is designed to spark students' interest in learning more about this field, by revealing recently discovered facts that they may find surprising.

You could introduce this activity by initiating a class discussion of "fundamental" things, asking students to suggest how the term "fundamental" might apply to physics. This can lead into a discussion of fundamental particles and forces.

Distribute the activity sheets and allow time for students to complete them individually or in small groups. Spend a short time in class discussion of their conclusions, but do not give the answers. Suggest that students will learn them as the program progresses. Then encourage them to take the activity sheets home to test the scientific awareness of family members. Return later to review this sheet as a wrap-up activity.

Answers:

1. *There are subatomic particles that have no mass and no electric charge.*
Agree. Photons and gluons are all particles with no mass (or masses so small they have not yet been detected) and no electric charge.

2. *Some particles can travel through billions of miles of matter without being stopped (or interacting).*
Agree. Low-energy neutrinos have only very weak interactions with matter. They could travel a light year through matter with only a small probability of an interaction.

3. *Antimatter is science fiction and not science fact.*
Disagree. For every fundamental particle there is a corresponding antiparticle with opposite values for all charges. For bosons with all zero charges, however, there is no distinction between particle and antiparticle.

4. *Particle accelerators are used for cancer treatment.*
Agree. The advantage of particle beams over the more common x-ray therapy is that most of the radiation can be deposited in the tumor with less damage to surrounding healthy tissue.

5. *The smallest components of the nucleus of an atom are protons and electrons.*
Disagree. Protons and neutrons, not electrons, are the components of the nucleus. Protons and neutrons are themselves composite, made up of quarks and gluons.

6. *Particles and antiparticles can materialize out of energy.*
Agree. As long as the available energy $E = mc^2$, a particle of mass m and its corresponding antiparticle (also of mass m) can be produced. Since they have equal but opposite values for all charges, all conservation laws can be satisfied in such a process.

7. *Particle physicists need larger accelerators in order to investigate larger objects*
Disagree. A larger accelerator produces a higher-energy beam that has a shorter wavelength ($E = hc/\lambda$) and therefore can be used to probe structure on smaller scales than a lower-energy beam. It is, however, true that a higher-energy accelerator can be used to produce and study higher-mass fundamental particles.

8. *Magnets are used in circular accelerators to make the particles move faster.*
Disagree. The force on a moving charged particle due to a magnetic field is always perpendicular to the motion, and therefore does not change the speed but only the direction of the motion. Magnets are used to steer the particles.

9. *Work done by particle physicists at accelerators is helping us understand the very early development of the universe.*
Agree. At the beginning of its development, he universe was densely filled with energetic articles. Only by knowing about all types of fundamental particles and their interactions can we understand what could have occurred in that period.

10. *Gravity is the strongest of the fundamental forces of nature.*
Disagree. The strength of any force depends on the situation, but in most situations for fundamental particle processes, gravity is a tiny effect compared even to the weak interaction. In everyday life gravity is an obvious force because we live close to an extremely massive object, the Earth. Like people, most things around us carry little or no electric charge, so we experience only the residual effects of electromagnetism, such as forces due to the rigidity or elasticity of matter and friction forces. But even these are stronger than gravity in many situations; gravity does not make you fall through the floor, for example.

We are also dependent on strong forces to bind the nuclei of atoms, but we do not notice processes due to either strong or weak forces except in radioactive decays (for more details, see the table in the center of the Standard Model chart, under the heading "Properties of the Interactions").

11. *There are at least 100 different subatomic particles.*
Agree. There are over 100 types of particles that have been reliably observed and verified; many are now understood to be composites formed from quarks. Many more are postulated but very difficult to observe because they are extremely unstable.

(Subatomic is interpreted to mean "smaller in size than an atom"; most such particles do not exist inside ordinary atoms but can be produced in high-energy collisions.)

12. *All known matter is made of leptons and quarks.*
Agree. All observed matter is leptons or composites that contain quarks. The photon, the W and Z bosons and the gluons, although observed as particles, are the carriers of the force field and are not usually called "matter."

13. *The protons in the Large Hadron Collider (LHC) at the CERN lab in Geneva, Switzerland will cross the French-Swiss border 11,000 times each second (without a passport), when LHC is operational.*
Agree. Traveling at near the speed of light, the protons will circle the LHC accelerator 11,000 times a second. The LHC straddles the French-Swiss border, so the protons do cross the border 11,000 times each way.

14. *Friction is one of the fundamental forces of nature.*
Disagree. Friction is a secondary effect that results from electrical interactions between the atomic structure of one surface with that of a nearby surface.

15. *The world's largest magnet (which is at a particle physics lab) weighs half has much as the Eiffel Tower.*
Disagree. It weighs more than the Eiffel Tower (which weighs 9441 metric tons or 10,407 American tons). The magnet is contained within a large particle detector.

16. *Many of the physicists who will run the particle physics experiments now under construction are still students in high school.*
Agree. These experiments take about ten years to build and then run for about 15-20 years. To train a PhD scientist requires about 8 to 10 years after high school, so students now in high school will be the researchers in these experiments. The Large Hadron Collider at the CERN lab in Geneva, Switzerland will be the most powerful accelerator in the world when it begins running in 2007. There are also exciting neutrino experiments, astrophysical experiments, and others that are under construction. We expect they will make important discoveries throughout their lifetime.

Follow-up Activities

1. Suggest that students ask a parent or grandparent to explain what they were taught about the theory of atoms when they were in school. Have the students use this as the foundation for ongoing discussions with family members as each of the activities in this program is completed.

2. Encourage students to choose one statement from the quiz and do further research on that topic. Schedule a time when they can report back to the class with their findings.

Activity Two -- Psyching Out the System (Teacher Page)

Goal: To illustrate the universal method of analyzing a system in terms of its components and their interactions.

In this activity students assume the role of scientists as they interpret data while playing a "puzzle shape" game that challenges them to evaluate objects that are hypothetically "Observed" as well as those that are "Not Observed." This puzzle applies to all of science, not just particle physics. When scientists study any system, they must begin with the same two basic questions:

1) What are the components of this system?

2) How do these components interact?

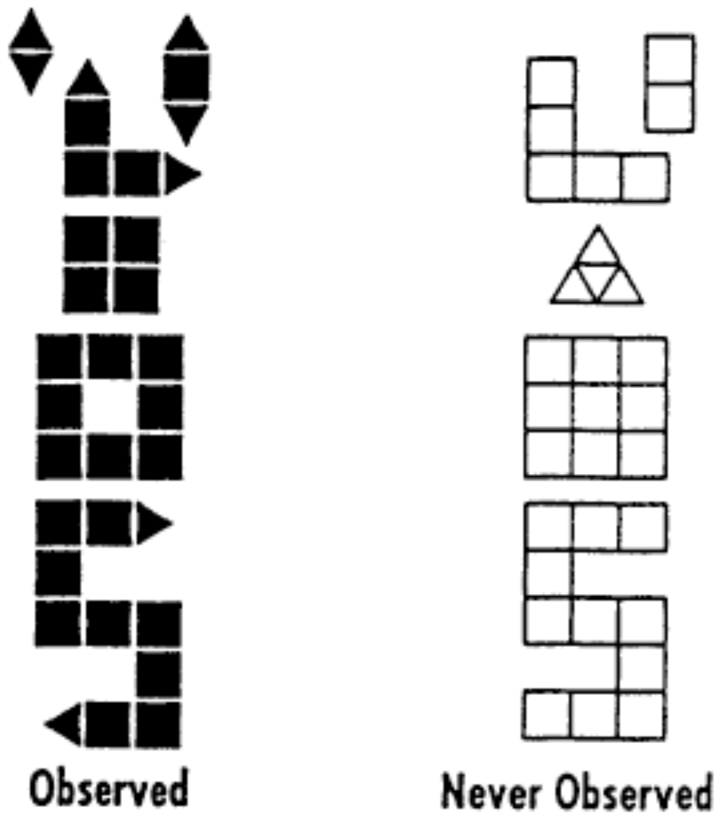
Through this exercise, students learn that the rules of interaction are as important as the "building blocks" in explaining data -- and that what does *not* occur is often as important a clue as what *does.*

As students begin working on this activity, give them a hint that the components they are looking for are two-dimensional shapes. After they find the shapes, point out that both the "Observed" and "Not Observed" shapes could be built from the same building blocks; the answer to the second question must explain why some shapes are not observed.

When they have completed the activity sheet, suggest that students draw additional objects using the building blocks and basic forces illustrated in the activity, indicating whether these new objects belong in the "Observed" or "Not Observed" lists. Note that these represent predictions for future experiments in the imaginary world of this game.

Answers:

The building blocks are small squares and small equilateral triangles, both with the same side length. The rules for constructing these figures are that every triangle must form a single bond and every square must form two bonds with other constituents.



Some students may suggest that the answer is triangles only; this is acceptable as long as they also see that there are two different types of triangles (the second of which is half of the square, or an isosceles right triangle). Then the rules of interaction are that the right triangles form two types of bonds: one that is a "pairing bond" with another right triangle, and one that can bind to any other constituent. As above, the equilateral triangles form a single bond.

Accept any equivalent answer. Students may identify the number of neighbors for each piece. This is a correct solution. It is valuable, however, to restate it in terms of bonds (as above) so that students see how the pattern that they have recognized can be interpreted as a consequence of a law of interactions.

Follow-up Activity:

Have students make a list of systems and their components and interactions encountered in other fields of science. For example: in chemistry, molecules and atoms are components, while chemical bonding represents their interactions; in ecology, animal and plant species are components, while the progression of the food chain represents their interactions, etc.

Activity Three -- Rutherford's Discovery (Teacher Page) ("Hands-on")

Goal: To apply the methodology of particle physics research in a simulation.

In this laboratory experiment students will gain practical experience in "observing" objects that cannot be seen. Employing the principles behind actual accelerator experiments, students will attempt to describe accurately the characteristics of these unseen objects in the same manner in which particle physicists approach the study of unknown particles. They are challenged to identity the shape of an object hidden underneath a wooden board by rolling "projectiles" (marbles) at this object and observing the deflected paths of the marbles. (To determine finer details, the activity can be repeated with smaller projectiles.)

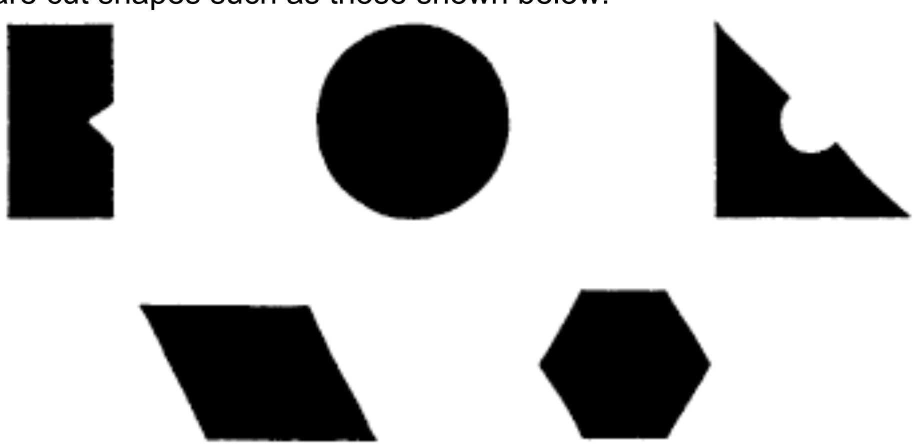
The activity is designed to help students:

- Understand that it is possible to study the characteristics of unseen objects.
- Use their knowledge of reflection from mirrors.
- Understand the analogy between this experiment and particle collision experiments.

This exercise employs principles explored by the work of pioneer physicist Ernest Rutherford (1871-1937), among others; it is analogous to accelerator experiments in that it uses the results of collisions to make inferences about unseen objects.

Materials required (for five teams of students):

- Five pieces of plastic foam or wood (approximately 20x20x2 cm), out of which are cut shapes such as those shown below:



- Five wooden boards (approximately 40x30 cm)
- Drawing paper (at least 20x20 cm)
- Pencils
- Marbles of various sizes

(Please note that a ready-made version of this activity is available from Science Kit.)
Place one shape under each wooden board on individual experiment tables so that they are not visible to the students.
Have the students divide into five teams to complete this experiment. Allow the teams five minutes to identify a shape. You could then have each team move on to another experiment table, to repeat the activity with a second shape.

Answers:

1. Yes. As students become proficient at using marbles to identify the shapes, they can also determine the approximate size of each object.

2. Smaller projectiles can be used to check for small details, such as notches.

3. The conclusions can be checked by performing repeated trials and comparing results with those of other groups; both steps are important in real experiments.

Follow-up Activities:

1. Have a group of students research and report on the history of the Geiger-Marsden-Rutherford experiments that led to the idea of the nucleus in the early 1900s.

2. A second group can research the 1990 Nobel Prize-winning work of Kendall-Friedman-Taylor that verified the quark structure of protons and neutrons.

3. Many particle physics experiments involve inelastic collisions where the outgoing objects are not the same as the initial colliding objects. To simulate inelastic collisions, repeat the experiment using a cluster of three or four magnetic marbles in place of the hidden shape. Use either ordinary or magnetic marbles as projectiles. Have students discuss what they can find out about the hidden target in this case.

Activity Four -- Tracking Unseen Particles (Teacher Page)
("Hands-on")

Goal: To illustrate the basics of a particle tracking detector through a simulation.

This "hands-on" activity focuses students' attention on the ***particle detector*** -- the "heart" of a particle experiment and a vital piece of equipment in particle physics research. Using iron filings and magnetic marbles, students will assemble their own "detectors" and use them to observe "tracks" similar to those left by particles in a tracking detector.

Materials required (for five teams of students):

- Ten box lids (from shoe or shirt boxes)
- Small objects (erasers, etc.) to prop up lids
- Magnetic marbles
- Ordinary marbles
- Fine iron filings

(Please note that a ready-made version of this activity is available from Science Kit.)
Working in teams, students follow the directions provided in the activity sheet to construct their own detectors. Each team will use an inverted shoe box lid to simulate a detector layer that registers particle tracks in two different ways. This simulation will work well as long as the tops of the marbles are within half a centimeter of the top surface of the cardboard as they roll beneath it. Iron filings should be thinly sprinkled to cover the inside of the box lid.

Have the student teams begin their experiments as instructed on the activity sheets. When they roll the magnetic marbles under their simulated detectors, iron filings will line up above the marble's path through the detector. This is roughly analogous to the various types of real detectors that register the paths of electrically charged particles. After each trial, "reset" the detector by gently shaking the box lid to redistribute the iron filings.

In the second part of the activity, the plain marbles will collide with one or more of the magnetic marbles, which will recoil and create a track that begins in the middle of the detector. (See answers to question 6 below.)

Here's an additional way of using this two-stage detector: Have one student roll a few marbles into the detector. Later, have another student (who didn't see which marbles were used by the first) analyze the patterns of tracks to determine how many magnetic and non-magnetic marbles went through the detector.

Suggested Observations & Answers (steps 3-6)

3. Iron filings line up above the marble's path through the detector.

4. A magnetic charge.

5. (a) The marble's path does not register.
(b) Neutral particles such as photons and neutrons.

6. (a) It suggests the existence of a non-magnetic marble that collided with one of the magnetic marbles in the middle of the detector.
(b) This is analogous to a real detector in which a neutral particle collides with a charged particle, or produces a pair of oppositely charged particles whose tracks can be observed.

Follow-up Activity

Have a group of students research each layer of the particle detector illustrated in cross section in the activity. Have them report back to the class on the role of this piece of equipment within the detector and its function in the study of particles.

Activity Five -- The Rules of the Game (Teacher Page)

Goal: Students learn that conservation laws are made up to explain what is and what is not observed, and are called laws only after many tests confirm their validity.

This activity is designed to introduce students to some fundamental concepts of particle physics that are the "rules of the game" played by nature -- the conservation laws and the nature of particle events. By completing the puzzle exercises on this activity sheet, students will learn that part of the theory and practice of particle physics is simple counting, and that an "event" in particle physics is comparable to a reaction in chemistry, in that one set of particles is formed from another. Further, they learn that this is how physicists discover the rules -- they are formulated to explain the data, not given *a priori;* to illustrate, refer to the rules of interactions that students encountered in Activity Two, Psyching Out the System!

You can introduce this activity by asking students to pretend that they are scientists -- who devise rules that explain observed phenomena and then use these rules to interpret new observations. Ask students to work in groups to find examples of "rules of nature" that explain the lists of processes seen and not seen.

Distribute the activity sheet and explain that the particle table can be used to identify the types of particles and charges in each event.

When the students understand how to read the particle charts, have them begin working on the activity in small groups, as do particle physicists.

You may want to explain that two types of "observed" events are represented on the list. Events 1, 5 and 6 are *particle decays*: a particle such as a neutron spontaneously decays to form two or more other particles. The other "observed" events (2, 3, 4, 7,8, 9 and 10) are *collisions:* the two particles to the left of the arrows come close enough together to interact and transform the incoming particles into two or more outgoing particles.

The following hints can also be given to simplify this activity. You may want to disclose them immediately, or give them one at a time as they seem to be needed, or you may choose to challenge the students to work without any hints at all.

Hints:

1. The conserved Quantities are not complicated combinations of things.

2. Students can check whether a quantity is conserved in an event by comparing the sum of that quantity on the left of the arrow to the sum of the same quantity on the right of the arrow.

3. In counting particle types, add the number of particles and subtract the number of antiparticles.

4. In addition to electrical charge, there are only two other conserved quantities shown by these examples.

5. If the counts match on the left and right of the arrows in all the "observed" events but not in all the "events never observed," this quantity is conserved.

6. Students should try counting numbers of particles of a given class (baryons, leptons, mesons) before and after a given event. It may be helpful to have students make a table to keep track of the counting for each quantity on the left and right sides of the equation in all 20 processes.

Answers:

1. When a quantity is "conserved ," it is the same after an event as it was before the event.

2. The following conserved quantities can be found: (a) electric charge; (b) number of baryons *minus* number of antibaryons, which is called "baryon number;" (C) number of leptons *minus* number of antileptons, which is called "lepton number."

3. An "event" is the basic type of observation in particle physics; it is a single *collision* of two particles (producing a transformation into two or more outgoing particles), or the *decay* of a single particle into two or more other particles. An event is similar to a chemical reaction in chemistry, in the sense that one set of particles is formed from another.

4. Events 1,5 and 6 are decays.

5. Events:

11. Electric charge
12. Baryon number
13. Baryon number and electric charge
14.-18. Baryon number

19.-20. Lepton number

Follow-up Activities:

1. After students have completed the activity sheet, discuss what the experience taught them about particle physics and how scientists conduct these experiments. Students should be able to recognize that part of the theory and practice of particle physics is simple counting, and that physicists *infer* the conservation laws from the data to explain what is and is not observed to occur.

2. Ask students to provide other examples of conservation laws in nature. Discuss how "conservation of mass" as taught in chemistry is an approximate result that is in fact a consequence of conservation of baryon number. (Mass is only approximately conserved in chemical reactions, since binding energies differ before and after the reaction.)

3. Discuss the difference between the term "conservation" as used in "conservation law" and the popular usage in reference to "conservation of resources." Since "energy conservation" is a law of physics, why do we need to worry about "conserving energy" in our daily lives? Where does "wasted energy" go?

Activity Six -- Observing Magnetic Effects (Teacher Page)
("Hands-on")

Goal: To illustrate the role of magnetism in the operation of a particle accelerator through a simulation.

In this "hands-on" activity, students use an ordinary oscilloscope and two small bar magnets to demonstrate two of the important ways in which particle beams are controlled in accelerators.

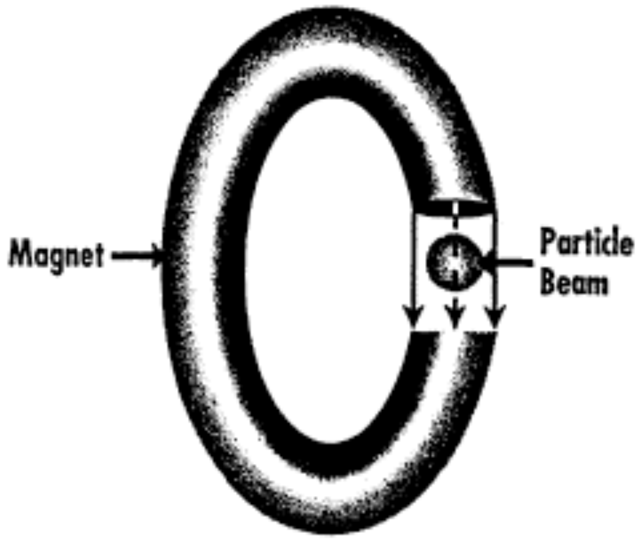
Required materials (repeat with each team of students):

- an oscilloscope or any apparatus with a visible electron beam (CRT)
- two bar magnets

Have each group set up the oscilloscope to produce a well-focused spot near the center of the screen. Then have students follow the directions on the activity sheet to show how a magnetic field can deflect a beam of charged particles (as shown in this diagram from the activity sheet:)

To explain deflection, use the rule for force on a moving charge in a magnetic field. (Remember that electrons are negative charges.)

Discuss the use of C-shaped "bending magnets" in a circulating accelerator:



Then have students show how a magnetic field can focus a beam of charged particles as described on the activity sheet.

Follow-up activity

After students have demonstrated how a magnetic field can focus a beam of charged particles, have them research how the electron beam in a television set is produced and steered.

Activity Seven -- Picturing Particles(Teacher Page)

Goal: To interpret some typical particle physics events.
This activity has students analyze and interpret a series of "event pictures" depicting the "tracks" of particle collisions produced by a detector. To introduce this activity, review with the class the physical characteristics of a particle detector, referring to the cross-section diagram of a detector in Activity Four.
Draw students' attention to the similar cross section of a detector here. Have them name the layers of the detector and describe their functions (referring to the Glossary if they need assistance). If any students studied detector components on their own, have them report their findings to the class now.
After discussing the layers and their functions, students will have a chance to evaluate particle events in a detector in the same way particle physicists do. Review the introductory material and the "rules of the game" as a class. Then have the students work independently or in pairs to analyze and interpret the four events pictured.

Answers:

1. Event 1:
   Particles are: an electron and a positron (i.e., antielectron) which emerge traveling back-to-back. Their paths are bent oppositely by the magnetic field.
   Event 2:
   Particles are: a muon and an antimuon.
   Event 3:
   Particles are: a muon and a positron, or an antimuon and an electron plus some unseen particles needed for momentum conservation.
   Event 4:
   Particles are: hadrons (more information is needed to identify them as specific hadrons).

2. Since the original particles were e- and e+, the total charge is zero. Thus, one of the final particles is positive and one is negative. You can tell which is which by using the curvature of the tracks.

3. Since the original particles had equal but opposite momenta, the total was zero. This means that there must be unseen particles (neutrinos) in this event that carried off some momentum, since the observed tracks cannot balance momenta.

Follow-up Activities

1. When students have completed this activity, open a class discussion regarding both fundamental particles and the equipment that is used to record their behavior. Discuss why detectors are constructed in many layers and why each type of particle has a characteristic pattern of tracks.

2. Suggest that students evaluate what they have learned by taking another look at the first activity sheet for this program and again indicating their responses to each statement.

Additional Things to Do:

1. Illustrate how much empty space exists within an atom and a proton by constructing rough "models" on a football field, using a marble and three to six golf balls. The entire field represents an atom; a bright marble placed near the center of the field represents the nucleus, which on this scale would be a bit smaller than the marble. Have students look for it from the sidelines.

Then have them imagine that a powerful microscope makes the nucleus expand until a single proton becomes as large as the football field; a vast space occupied only by three tiny objects -- the quarks -- represented by three golf balls randomly scattered on the field.

2. Encourage students to develop creative presentations about a specific table or illustration from the Standard Model of Fundamental Particles and Interactions chart. Possibilities include cartoons, stories told from a particle's point of view, dances representing particle characteristics and interactions and "daffy-nitions" that are humorous variations on the usual definitions. The Bibliography provided may be used as a starting point in their search for information.

3. Have students use a ripple tank to demonstrate that particles with long wavelengths (low energies) cannot detect small structures. Generate a straight wavefront and place an obstacle smaller than the wavelength in the water, then decrease the wavelength until it is about the same size as the obstacle. The resultant break in the waves illustrates that small structures are only visible to water waves of short wavelengths. In the same way, small particles are only visible with high-energy (extremely short wavelength) particle beams.

4. A simple cloud chamber -- one of the earliest types of particle detector -- can help you and your students experience particle tracks first hand! You can use a commercial chamber (such as a Wilson Cloud Chamber), or make your own. (Invert a wide-mouth glass jar so that the lid is on the bottom. Line the inside of the lid and the sides with

black construction paper; leave a hole for a light source.) Fill the bottom of the chamber with 1/2 cm of methyl alcohol; place the chamber on dry ice.

A commercial chamber will have its own radioactive source; if you build your own chamber, use a uranium rock or a radioactive smoke detector. Place the source in the chamber, and place a bright light about 10 cm from the chamber. Charged particles such as beta particles, protons and alpha particles will leave condensation trails as they ionize the air in the chamber; you may also see cosmic ray tracks.

Alpha particles will leave shorter tracks -- a few cm or less in length. The longer tracks are likely to be made by beta particles; these can be negative (electrons) or positive (positrons).