I. **Introduction**
   a) Activity 1 (1)
   b) http://microcosm.web.cern.ch/microcosm/P10/welcome.html
   Powers of 10. (Not on original web site page).

II. **History**
   a) Milliken Experiment (2)
   b) Activity 3 Rutherford (1)

III. **Define: Quarks and Leptons**
   a) CS Worksheet 1 (1)
   b) CS Worksheet 2 (1)
   c) Activity 2 Physicists are Charming (1)
   d) http://particleadventure.org
   e) http://perso.club-internet.fr/molaire1/e_index.html
   Humorous Tutorial, Applets on particles and forces. Chapter 4 is forces

IV. **Activity 13 Psyching Out the System (2)**

V. **What else: Hadrons**
   a) CS Worksheet 3 (2)
   b) CS Worksheet 4 (1)
   c) http://particleadventure.org

VI. **MS Worksheet 2 (2)**

VII. **Forces**
   a) MS Worksheet 1 (1)
   b) MS Worksheet 3 (1)
   c) Activity 17 Feynman Diagrams (3)
   d) CS Worksheet 5 (2)
   e) http://www.explorescience.com/coulomb.html
   Fun! Shows electronic force due to Coulomb's law.
   f) http://www.jlab.org/~cecire/Bedtime.html
   Very short. Carol has a worksheet on this.

VIII. **Conservation / Any Other Details**
   a) CS Worksheet 7 (1)
   b) CS Worksheet 8 (1)
   c) CS Worksheet 9 (1)
   d) Activity 18 Decay Processes (1)
   e) Activity 5 Rules of the Game (1)
   f) Activity 14 Particle Zoo (2)
   g) Activity 16 Unseen Particles (2)
   h) Activity 20 Lifetimes (3)
   i) www.hep.man.ac.uk/2wyatt/events/home.html
   Types of events

IX. **How Do We Know Any of This? Detector/Accelerator**
   a) Activity 7 Tracking Unseen Particles (1)
   b) Activity 9 Cloud Chamber (1)
   c) Activity 11 Picturing Particles (1)
   d) Activity 8 Cloudy Chamber (2)
   e) Activity 19 Bubble Chamber Tracks (3)
   f) Activity 4 Accelerator Physics (4)
   g) Activity 6 Beam Control (3)
   h) Activity 12 Student Accelerator and Detector (4)
   i) http://www2.slac.stanford.edu/vvc/accelerator.html
   Variety of activities and information with diagrams and photos
   j) http://education.jlab.org/
   Click on "Teacher Resources." A number of in-class activities at the "6th Grade" level.
   k) http://www.cern.ch/CERN/microcosm/rf_cavity/ex.html
   Flips batteries to accelerate a particle
   l) http://www.cern.ch/Physics/ParticleDetector/BriefBook
   Resource and glossary of terms
   m) http://outreach.cern.ch/public/gb/Page1.html
   Actual events from detectors

X. Why is it Important?
   a) Activity 21 – Determine the Top Quark Mass (1)
   b) www-ed.fnal/samplers/hsphys/activities/top_quark.html
   Find mass of Top Quark
   c) http://ast.leeds.ac.uk/haverah/aim.shtml
   Introduction to cosmic rays
   d) http://hepwww.ph.qmw.ac.uk/epp/higgs.html

QN 1

Activity One -- Fundamentally Speaking (Student Page)

"What is the world made of?
What holds it together"

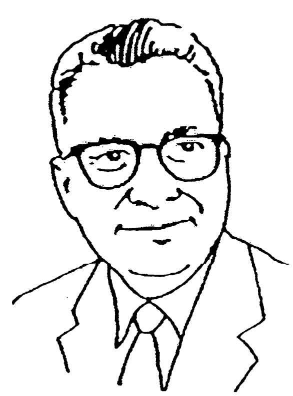
Democritus (460-370 B.C.)

People have asked these questions for thousands of years. But only recently has a clear picture of the "building blocks" of our universe been developed. The scientists who have developed this picture work in an exciting and challenging field called high-energy particle physics. Their discoveries are summarized in the chart, Standard Model of Fundamental Particles and Interactions.

How much do you know about the latest theories and research on these ancient questions? You can find out by reading each of the statements below and placing a check mark in the proper box to indicate whether you agree or disagree.

1. There are subatomic particles that have no mass an no electric charge. T F
2. Some particles can travel through billions of miles of matter without being stopped (interacting). T F
3. Antimatter is science fiction and not science fact. T F
4. Particle accelerators are used for cancer treatment. T F
5. The smallest components of the nucleus of an atom are protons and electrons. T F
6. Particles and antiparticles can materialize out of energy. T F
7. Particle physicists need larger accelerators in order to investigate larger objects. T F
8. Magnets are used in circular accelerators to make the particles move faster. T F
9. Work done by particle physicists at accelerators is helping us understand the very early development of the universe. T F
10. Gravity is the strongest of the fundamental forces in nature. T F
11. There are at least one hundred different subatomic particles. T F
12. All matter is made of leptons and quarks. T F
13. All of the particles needed to formulate a complete model of the universe have been discovered T F
14. Friction is one of the fundamental forces of nature. T F
15. Students who are in high school now will make major contributions to accelerators currently being built and planned. T F

"What is the world made of?
What holds it together"



Murray Gell-Mann (b. 1929)

Fundamentally Speaking

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.

1. There are subatomic particles that have no mass and no electric charge.
Agree. Neutrinos, 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.

QA-4

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/¬) 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, the universe was densely filled with energetic particles. 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 last of the fundamental particles was recently discovered.*

Disagree. Even though the top quark has been discovered, that is not the last of the fundamental particles. There is still the search for the Higgs boson. IF and when it is found, there will still be uncertainty about whether that level of particle is really the fundamental one.

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. *Most of the physicists who will run the particle experiments currently planned are still students in high school.*

Agree. It takes several years to plan and then to build accelerators and detectors. And, much of the experimentation is done by people in their twenties.

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.

Teacher Notes

FUNDAMENTAL UNITS

THE STANDARD MODEL OR THE MILLIKAN EXPERIMENT

Introduction: The Millikan Experiment and The Standard Model both require that students recognize that charge and matter are observed in discrete units. This activity can be used as an introduction to either of these topics.

Discussion: An understanding of the nature of fundamental particles helps students recognize both the complexity and simplicity of nature. Just as all the words in the English language are combinations of subsets of 26 letters, atomic physics showed that atoms of the many elements are combinations of three particles - the proton, neutron, and electron. As the number of "elementary particles" identified in cosmic ray showers and other high-energy interactions proliferated, some began to believe they were complex, composite particles created from a few, more fundamental particles. This activity will help students identify common elements of their "atoms" and also suggest that what is determined to be fundamental indeed has a substructure - an introduction to The Standard Model.

Activity: Using standard-size index cards place them in multiples of three into a number of standard-size envelopes. For example, for a class size of 25 students, prepare envelopes as follows.

# of envelopes	# of index cards per envelope
42	3
52	6
42	9
40	12
30	15
28	18
16	21
250	

Mix up the prepared envelopes and distribute 10 to each student. Each envelope may be used to represent a "particle" as identified in some high-energy reaction. Have the students mass their "particles" and share this information on a class data chart, or enter into a computer graphing program. (A student worksheet follows for use if you are not using a computer graphing program.) The use of top-loading analytical balances, with rounding to the nearest 0.1g, will greatly speed the data collection process. Examine the graph and note similarities in masses. Group and regraph the data, note that all differences occur in some "fundamental" unit, i.e., the mass of three index cards. After students have predicted the mass of the "fundamental particle," discuss how you might investigate if this fundamental particle itself might have an internal structure. Suggest that if greater energies were used to look inside the particle one might discover its structure. When an envelope is opened, students will notice that what they had assumed to be the "fundamental" unit was in fact itself made of three smaller particles just as the proton and neutron each have an internal structure made of three quarks.

Some helpful data and graphs follow.

QN-7

FUNDAMENTAL UNIT RAW DATA

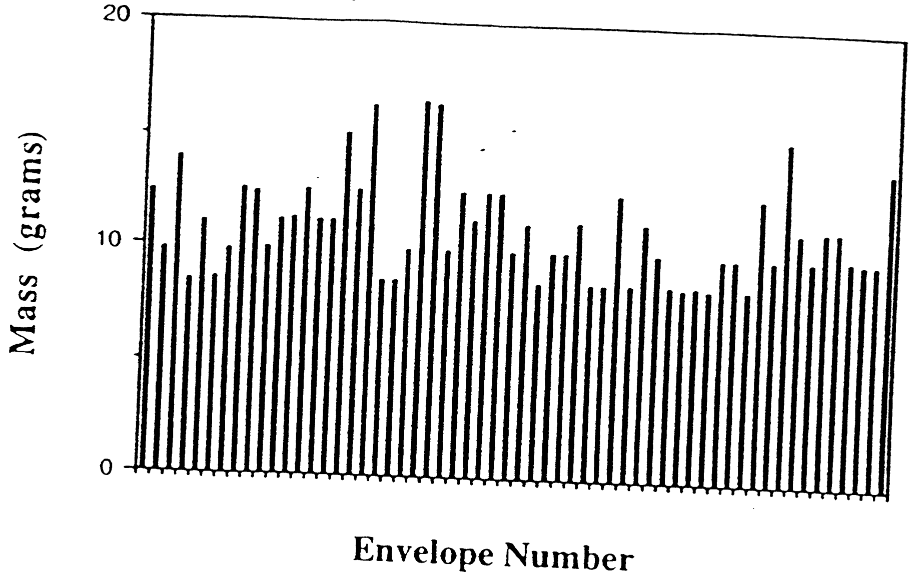
ENVELOPE	MASS (g)	ENVELOPE	MASS (g)
1	12.40	59	12.52
2	9.85	60	8.61
3	13.82	61	8.56
4	8.49	62	12.49
5	11.09	63	12.41
6	8.61	64	15.09
7	9.88	65	11.22
8	12.52	66	11.23
9	12.39	67	12.44
10	9.98	68	9.80
11	11.22	69	8.59
12	11.23	70	8.58
13	12.46	71	11.19
14	11.12	72	9.86
15	11.18	73	9.88
16	15.04	74	12.52
17	12.50	75	8.57
18	16.30	76	9.93
19	8.59	77	11.10
20	8.60	78	12.49
21	9.94	79	12.43
22	16.49	80	9.87
23	16.39	81	9.86
24	9.92	82	11.25
25	12.47	83	12.44
26	11.23	84	8.57
27	12.49	85	11.11
28	12.53	86	9.80
29	9.90	87	15.09
30	11.14	88	13.76
31	8.63	89	16.40
32	9.94	90	8.55
33	9.91	91	11.11
34	11.24	92	9.88
35	8.64	93	11.20
36	8.55	94	8.53
37	12.48	95	8.63
38	8.58	96	11.18
39	11.23	97	11.18
40	9.89	98	12.43
41	8.56	99	11.16
42	8.53	100	11.17
43	8.58	101	11.26
44	8.51	102	12.50
45	9.84	103	8.60
46	9.86	104	12.40
47	8.54	105	12.41
48	12.46	106	9.85
49	9.83	107	13.82
50	15.11	108	8.50
51	11.10	109	9.87
52	9.87	110	16.37
53	11.20	111	11.16
54	11.22	112	8.60
55	9.92	113	8.60
56	9.87	114	16.45
57	9.88	115	15.05
58	13.82	116	12.57

FUNDAMENTAL UNIT SORTED DATA

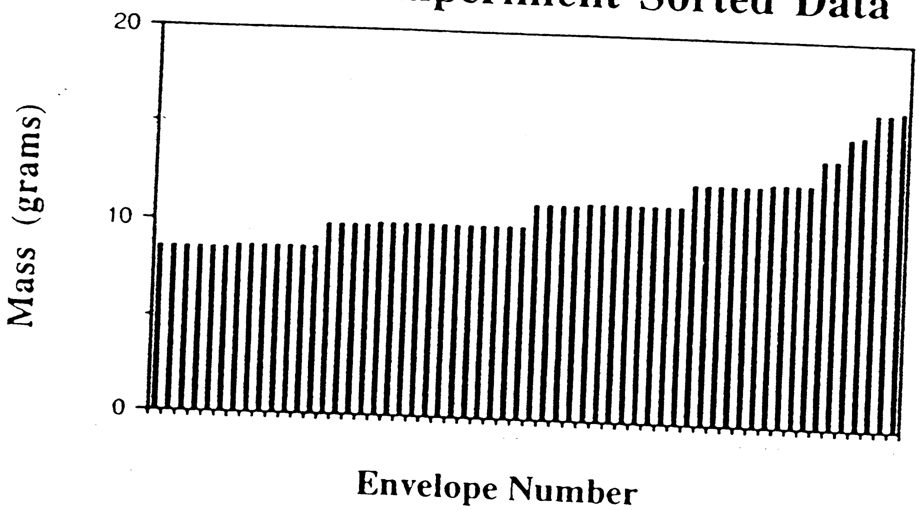
ENVELOPE	MASS (g)	ENVELOPE	MASS (g)
1	8.49	59	8.50
2	8.51	60	8.53
3	8.53	61	8.55
4	8.54	62	8.56
5	8.55	63	8.57
6	8.56	64	8.57
7	8.58	65	8.58
8	8.58	66	8.59
9	8.59	67	8.60
10	8.60	68	8.60
11	8.61	69	8.60
12	8.63	70	8.61
13	8.64	71	8.63
14	9.83	72	9.80
15	9.84	73	9.80
16	9.85	74	9.85
17	9.86	75	9.86
18	9.87	76	9.86
19	9.87	77	9.87
20	9.88	78	9.87
21	9.88	79	9.88
22	9.89	80	9.88
23	9.90	81	9.93
24	9.91	82	11.10
25	9.92	83	11.11
26	9.92	84	11.11
27	9.94	85	11.16
28	9.94	86	11.16
29	9.98	87	11.17
30	11.09	88	11.18
31	11.10	89	11.18
32	11.12	90	11.19
33	11.14	91	11.20
34	11.18	92	11.22
35	11.20	93	11.23
36	11.22	94	11.25
37	11.22	95	11.26
38	11.23	96	12.40
39	11.23	97	12.41
40	11.23	98	12.41
41	11.24	99	12.43
42	12.39	100	12.43
43	12.40	101	12.44
44	12.46	102	12.44
45	12.46	103	12.49
46	12.47	104	12.49
47	12.48	105	12.50
48	12.49	106	12.52
49	12.50	107	12.52
50	12.52	108	12.57
51	12.53	109	13.76
52	13.82	110	13.82
53	13.82	111	15.05
54	15.04	112	15.09
55	15.11	113	15.09
56	16.30	114	16.37
57	16.39	115	16.40
58	16.49	116	16.45

QN-8

Millikan Experiment Raw Data



Millikan Experiment Sorted Data



QN-9

Activity 3: Name ________________

Rutherford's Discovery

In this activity, you and your team members will use the methods pioneered by Ernest Rutherford in the early 1900s and still used by particle physicists in their accelerator experiments today. These methods enable scientists to identify the characteristics of particles that they cannot actually see. You will learn how precise your measurements must be when you can't see what you are studying.

On your team's experiemnt table there is a large wooden board, under which you teacher has placed a flat shape. Your team's job is to identify the shape without ever seeing it. You can only roll marbles against the hidden object and observe the deflected paths that the marbles take. Your team wilk have five minutes to "observe" a shape.

Place a piece of paper on top of the board for sketching the paths of the marbles. Then analyze ths information to determine the object's actual shape. Draw a small picture of each shape you studied in the boxes below, and answer the following questions.

Shape A

Shape B

QN-10

1. Can you tell the size of the object as well as its shape?

2. How could you find out whether the shape has features that are small compared to the size of your marbles?

3. Without looking, how can you be sure of your conclusions?

Shape C

Shape D

QN-11

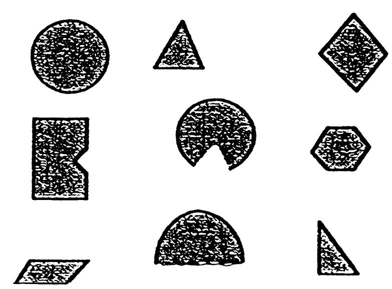
Rutherford's Discovery

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 identify 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 20 x 20 x 2 cm), out of which are cut shapes such as those shown here.

Five wooden boards (approximately 40x30 cm), drawing paper (at least 20 x 20 cm), pencils, and marbles of various sizes. (Please note that a ready-made version of this activity is available from ScienceKit.) Place one shape under each wooden board on individual experiment tables or on the floor, 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. Have students relate this to the Rutherford experiments and current experiments where you cannot see the particles directly.

QN-12

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.

Additional Activities

1. Models: 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 wave front 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. If you live near one of the **accelerator centers**, listed in the Resources, you and your students can tour it. All national labs are required to have educational programs.

5. Most large hospitals have a **medical linear accelerator** for the treatment of cancer. Call to set up a field trip. Usually there is a medical physicist on the staff who can talk about the physics of the machine as well as the medical aspects of the program.

PARTICLE PHYSICS WORKSHEET #1

NAME____________________________Go back to the **home page**. Click on the particle chart. Use the magnifying glass for the parts you want to enlarge.

QUARKS

Quark symbol and charge	Name of Quark	Quark pair symbol and charge	Name of Quark partners
$u^{+2/3}$			
$c^{+2/3}$			
$t^{+2/3}$			

LEPTONS

Lepton symbol and charge	Name of lepton	Lepton pair symbol and charge	Name of lepton partners
e^{-1}			
μ^{-1}			
τ^{-1}			

1)Which particles are quarks?

2) Which particles are leptons?

3) Which particles have no charge?

4) Which particles have charges?

5) Which particles have integer charges?

6) Which particles have fractional charges?

KEY

Go back to the home page. . Then click on the particle chart. Use the magnifying glass for the parts you want to enlarge.

PARTICLE PHYSICS WORKSHEET *1

NAME______________________________

QUARKS

Quark symbol and charge	Name of Quark	Quark pair symbol and charge	Name of Quark pair
"$u^{+2/3}$"	Up	$d^{-1/3}$	down
"$c^{+2/3}$"	Charm	$s^{-1/3}$	strange
"$t^{+2/3}$"	top	$b^{-1/3}$	bottom

LEPTONS

Lepton symbol and charge	Name of lepton	Lepton pair symbol and charge	Name of Lepton pair
e^{-1}	electron	ν_e	electron neutrino
μ^{-1}	muon	ν_μ	muon neutrino
τ^{-1}	Tau	ν_τ	tau neutrino

1. Which particles are quarks? up, down, charm, strange, top, bottom
2. Which particles are leptons? electron, electron neutrino, muon, muon neutrino, Tau, Tau neutrino
3. Which particles have charges? all quarks, electron, muon, Tau
4. Which particles have integer charges? electron, muon, Tau
5. Which particles have fractional charges? all quarks

QN-16

WORKSHEET #2 MATTER AND ANTIMATTER

NAME____

Go to any page in the Particle Adventure. On the left is a list titled "Home Glossary." The 2nd Topic below the words Home Glossary is "**What is the world made of?**" Click on "What is the world made of?" Then click on **Matter and Anti-matter.** Read it **ALL!** Some of the answers are within the paragraphs.

Symbol of particle and its charge	**Name of particle**	**Symbol and charge of antiparticle**	**Name of antiparticle**
$u^{+2/3}$			
$d^{-1/3}$			
$c^{+2/3}$			
$s^{-1/3}$			
$t^{+2/3}$			
$b^{-1/3}$			
e^{-1}			
ν_e^{0}			
μ^{-1}			
ν_μ^{0}			
τ^{-1}			
ν_τ^{0}			

7) Which particles are antimatter quarks?

8) Which particles are antimatter leptons?

Go to any page in the Particle Adventure. On the left is a list titled "Home Glossary." The 2nd topic below the words Home Glossary are What is the World made of? Click on What is the world made of? Click on Matter and Anti-matter. Read it ALL. Some of the answers are within the paragraphs.

MATTER AND ANTIMATTER WORKSHEET #2

NAME Key

Symbol of particle and its charge	Name of particle	Symbol of anti-particle and Charge	Name of antiparticle and its charge
"$u^{+2/3}$"	up quark	$\bar{u}^{-2/3}$	anti up antiquark
"$d^{-1/3}$"	down "	$\bar{d}^{+1/3}$	anti down
"$c^{+2/3}$"	Charm "	$\bar{c}^{-2/3}$	anti-
"$s^{-1/3}$"	strange "	$\bar{s}^{+1/3}$	anti-strange
"$t^{+2/3}$"	top "	$\bar{t}^{-2/3}$	anti-top
"$b^{-1/3}$"	bottom "	$\bar{b}^{+1/3}$	anti-bottom
"e^{-1}"	electron	e^{+}	positron
ν_e^0	electron neutrino	$\bar{\nu}_e$	electron anti neutrino
μ^{-1}	muon	$\bar{\mu}^{+1}$	anti-muon
ν_μ^0	muon neutrino	$\bar{\nu}_\mu$	muon anti-neutrino
τ^{-1}	Tau	$\bar{\tau}^{+1}$	anti-tau
ν_τ^0	Tau neutrino	$\bar{\nu}_\tau$	tau anti-neutrino

6. Which particles are anti-matter quarks? anti-up, anti-down, anti charm anti-strange, anti-top, anti bottom

7. Which particles are antimatter leptons?
positron, anti-electron neutrino, anti-muon, anti-muon neutrino anti-tau, anti-tau neutrino

8. Which particles do not have a charge?
neutrinos and anti-neutrinos

(9. has been removed)

All Physicists Have Charm!

Name ________________

Now that you have heard a little bit about Particles and Interactions, let's see if you can make sense of all the unusual names.

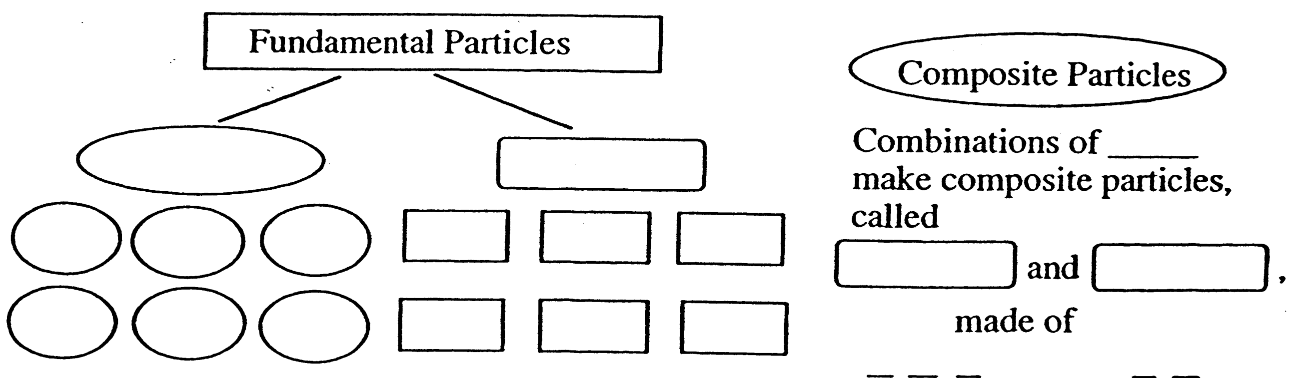
What are the two basic questions that people have always asked?

1.

2.

Draw and label all the parts of an atom that you can.

Fill in this chart the best that you can without looking at your notes or anything else. When your teacher tells you, consult with your neighbor and fill in more.



Forces or Interactions

1. ____________ 2. ____________ 3. ____________ 4. ____________

Draw lines from each force to the fundamental particles with which it interacts.

What questions do you have?

All Physicists Have Charm!

Don't "grade" this, but use it for the students to organize their thoughts and all the new words. This is a good activity for pairs of students. The answers may not be in the same order as below. Some students may be able to organize the quarks into "families", etc. Use the chart of the Standard Model to check different ideas. Students should be asking why the particles are grouped the way that they are. Leave some unanswered questions at this time. You might want to come back to this later in the unit.

Now that you have heard a little bit about Particles and Interactions, let's see if you can make sense of all the unusual names.

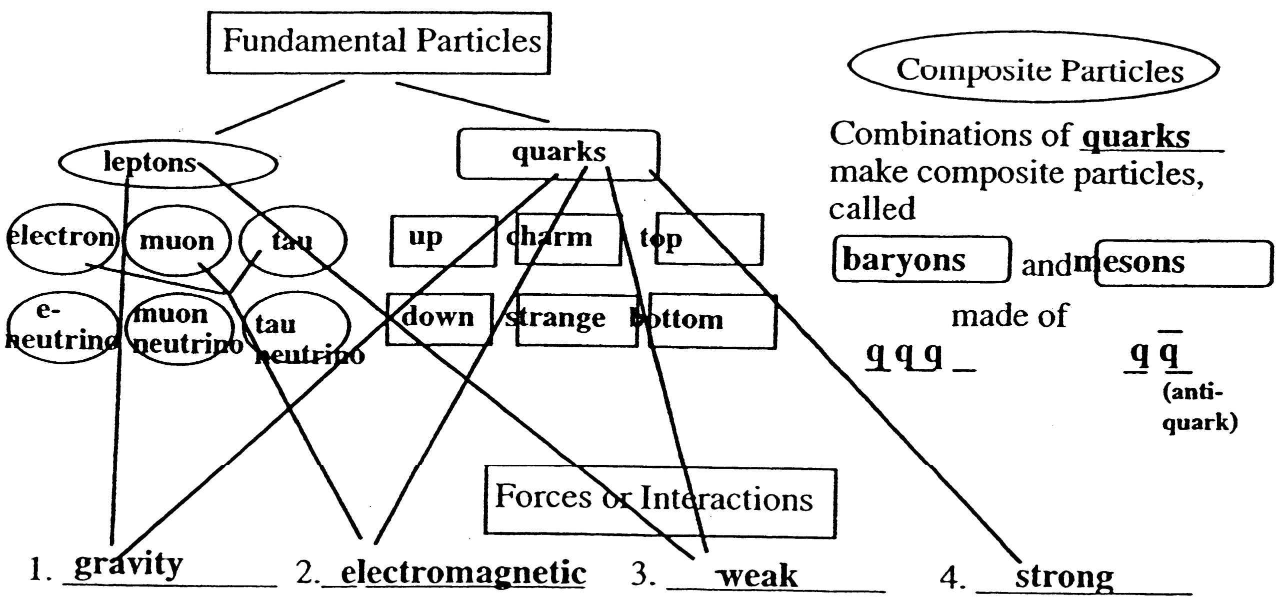
What are the two basic questions that people have always asked?

1. **Of what is the world made ?**
2. **What holds it together?**

Draw and label all the parts of an atom that you can.

Students should show the nucleus with protons and neutrons in it. They should show quarks in the protons and neutrons. Electrons should be outside the nucleus.

Fill in this chart the best that you can without looking at your notes or anything else. When your teacher tells you, consult with your neighbor and fill in more.



Draw lines from each force to the fundamental particles with which it interacts.

What questions do you have?

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

When scientists study any system they must ask two basic questions:

1) What are the basic objects, or "building blocks," from which this system is made?

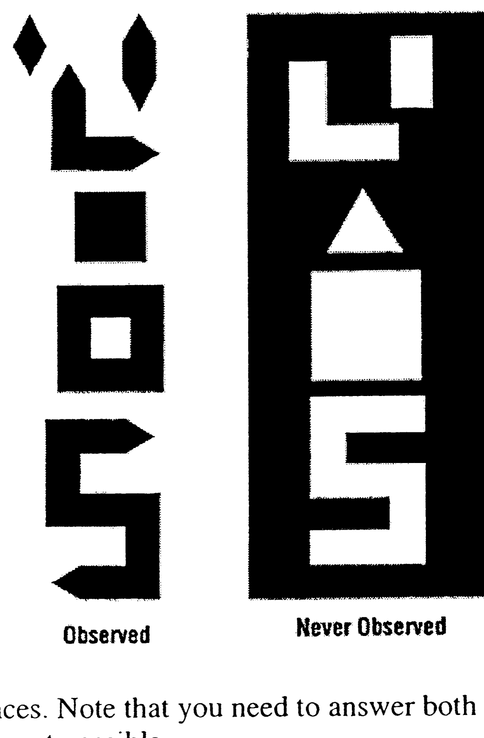
2) What are the interactions between these objects?

The answer to these questions depends on the scale at which you study the system. Particle physics plays this game on the smallest possible scales -- seeking to discover the basic building blocks of all matter and the fundamental interactions between them.

The connecting rules of these interactions, or basic forces, explain why some composite objects are observed and others are not observed. The basic forces are as important as the "building blocks" in explaining data, and what does not happen is as important a clue as what does.

This puzzle shows the challenge that particle physicists face. Imagine that the puzzle presents information that was obtained about particles from an accelerator. The black figures represent objects that were observed, while the objects shown in white have not been observed. In this puzzle, "objects" are all two-dimensional shapes, and "interactions" are ways in which they can combine.

The shapes that are not observed provide important clues to the answers.



Write your answers in these spaces. Note that you need to answer both questions to explain why the objects that are not observed are not possible.

The observed figures are constructed from:
1. ____

2. ______________________________________

The rules for connecting these shapes are:
1. ______________________________________

2. ______________________________________

[Puzzle adapted from Helen Quinn, "Of Quarks, Antiquarks, and Glue." The Stanford Magazine, Fall, 1983, p.29.]

Act 2

Psyching Out the System!

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.

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.

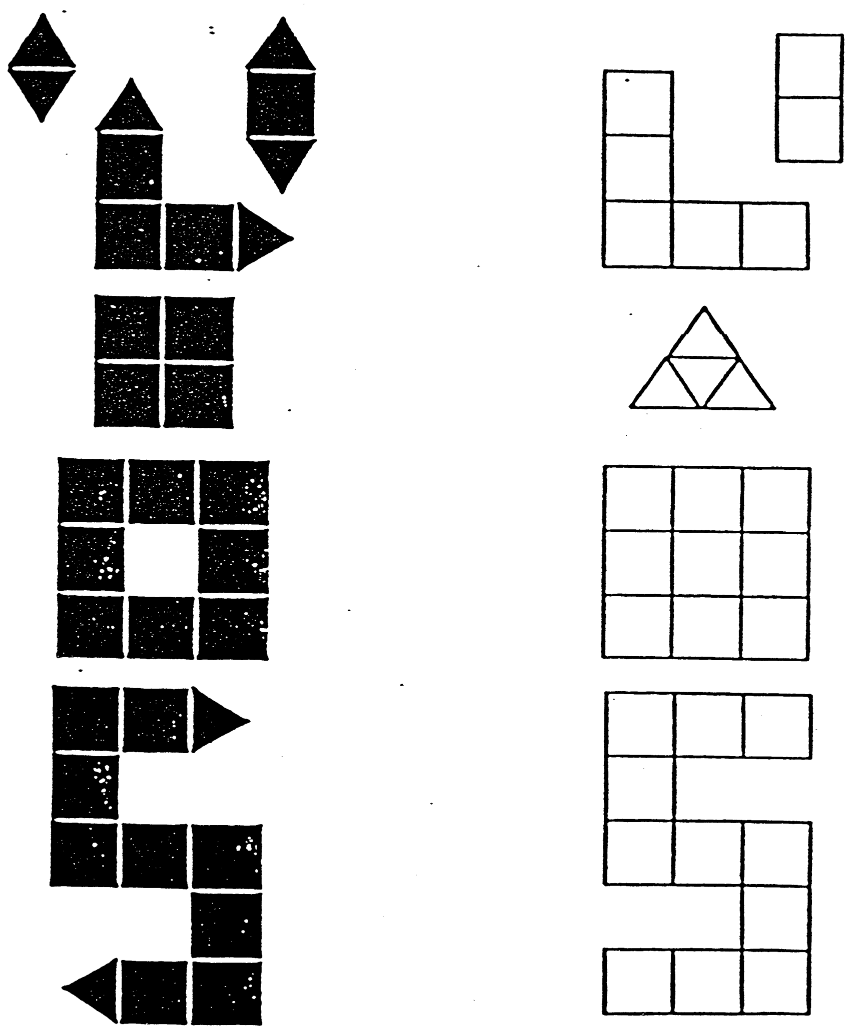
Some students may suggest that the answer is triangles only; this is acceptable as long as they also see that there are two different types of triangles (the second of which is half of the square, or an isosceles right triangle). Then the rules of interaction are that the right triangles form two types 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.

QN-23

Act 2

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.

OBSERVED NOT OBSERVED



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.

QN-24

WORKSHEET #3 MASS

NAME_______________________________

Because $E=mc^2$, mass can be measured in energy units: $m = \frac{E}{c^2}$

eV =**electron volt** is defined as the energy that an electron gains when accelerated through a potential difference of 1 volt.

GeV= Giga-electron volt=1 X 10^9 eV

$m = \frac{E}{c^2} = \frac{GeV}{c^2}$ where c^2 is the speed of light , squared.

Symbol of particle	**Name**	**Mass in** $\frac{GeV}{c^2}$	**Symbol of anti-particle**	**Mass in** $\frac{GeV}{c^2}$
u				
d				
c				
s				
t				
b				
e				
ν_e				
μ				
ν_μ				
τ				
ν_τ				
π				
K				
p				
n				
Λ				
Ω				

PN-25

KEY

WORKSHEET #3 MASS

NAME______________________________

Because $E=mc^2$, mass can be measured in energy units: $m = \frac{E}{c^2}$

eV =**electron volt** is defined as the energy that an electron gains when accelerated through a potential difference of 1 volt.
GeV= Giga-electron volt=1 X 10^9 eV

$m = \frac{E}{c^2} = \frac{GeV}{c^2}$ where c^2 is the speed of light , squared.

Symbol of particle	**Name**	**Mass in $\frac{GeV}{c^2}$**	**Symbol of anti-particle**	**Mass in $\frac{GeV}{c^2}$**
u	up	4×10^{-3}	$\bar{u}$	4×10^{-3}
d	down	7×10^{-3}	$\bar{d}$	7×10^{-3}
c	Charmed	1.5	$\bar{c}$	1.5
s	strange	0.15	$\bar{s}$	0.15
t	top	> 89 (not yet observed)	$\bar{t}$	> 89 (not yet observed)
b	bottom	4.7	$\bar{b}$	4.1
e	electron	5.1×10^{-4}	e^+	5.1×10^{-4}
ν_e	electron neutrino	$< 2 \times 10^{-8}$	$\bar{\nu}_e$	$< 2 \times 10^{-8}$
μ	muon	.106	$\bar{\mu}$	.106
ν_μ	muon neutrino	$< 3 \times 10^{-4}$	$\bar{\nu}_\mu$	$< 3 \times 10^{-4}$
τ	tau	1.784	$\bar{\tau}$	1.784
ν_τ	tau neutrino	$< 4 \times 10^{-2}$	$\bar{\nu}_\tau$	$< 4 \times 10^{-2}$
π	pion	0.140	$\bar{\pi}$	0.140
K	Kaon	0.494	$\bar{K}$	0.494
p	proton	0.938	$\bar{p}$	0.938
n	neutron	0.940	$\bar{n}$	0.940
Λ	lambda	1.116	$\bar{\Lambda}$	1.116
Ω	omega	1.672	$\bar{\Omega}$	1.672

WORKSHEET #4- PUTTING QUARKS TOGETHER
NAME____________________________

up quark = $u^{+2/3}$

down quark = $d^{-1/3}$

10)Write two up quarks and one down quark with their charges in these

blanks: ___ ___ ___

11)What is the total charge of the quarks in #10?__________

12)The total charge of # 10 means that it must be a (proton, neuton, electron)____________

13)Write two down quarks and one up quark with their charges in these

blanks: ___ ___ ___

14)What is the total charge of the quarks in #13?__________

15)The total charge of # 13 means that it must be a (proton, neuton, electron)____________

16)On the "family tree" of particles, the up and down quarks are on the same branch as the electron and electron neutrino. Can you think of a reason why these particles would be more closely related to each other than to the other quarks and leptons?

WORKSHEET #4- PUTTING QUARKS TOGETHER

NAME KEY

up quark = $u^{+2/3}$

down quark = $d^{-1/3}$

10)Write two up quarks and one down quark with their charges in these blanks: $U^{+2/3}$ $U^{+2/3}$ $d^{-1/3}$ $= +\frac{4}{3} - \frac{1}{3} = +\frac{3}{3} = +1$

11)What is the total charge of the quarks in #10? +1

12)The total charge of # 10 means that it must be a (proton, neuton, electron) proton

13)Write two down quarks and one up quark with their charges in these blanks: $d^{-1/3}$ $d^{-1/3}$ $u^{+2/3}$ $= -\frac{2}{3} + \frac{2}{3} = 0$

14)What is the total charge of the quarks in #13? 0

15)The total charge of # 13 means that it must be a (proton, neuton, electron) neutron

16)On the "family tree" of particles, the up and down quarks are on the same branch as the electron and electron neutrino. Can you think of a reason why these particles would be more closely related to each other than to the other quarks and leptons?

These particles make up ordinary matter.

MS-2

Name That Charge

In the 1960's, there were already names for electric charges and magnetic "charges." Can you fill in the blanks?

Electric Charge: ______________________ attracts __________________________

Magnetic Charge: _______________________ attracts ________________________

Why do you think, I used the word "charge" when dealing with magnetism? What name do we usually use instead of charge?

Whereas, electric and magnetic charges have only one line for each, we found that the strong nuclear charge needed three lines. (You can make up any names you want for these. Be creative and consistent).

Strong Charge (type 1): _____________________ attracts ______________________

Strong Charge (type 2): _____________________ attracts ______________________

Strong Charge (type 3): _____________________ attracts ______________________

Are these "charges" for the strong nuclear force the same as the "charge" for electricity or the "charge" for magnetism? Why do we use the word "charge" here?

MS #2

Name That Charge

In the 1960's, there were already names for electric charges and magnetic "charges." Can you fill in the blanks?

Electric Charge: ______+______ attracts ______−______

Magnetic Charge: ______N______ attracts ______S______

GRAVITATIONAL CHARGE ___MASS___

Why do you think, I used the word "charge" when dealing with magnetism? What name do we usually use instead of charge? – POLE

– SAME CARRIER

Whereas, electric and magnetic charges have only one line for each, we found that the strong nuclear charge needed three lines. (You can make up any names you want for these. Be creative and consistent).

' COLOR

Strong Charge (type 1): BITRONS ___ RED u ___ attracts ___ ANTI RED d ___

Strong Charge (type 2): downTONS ___ BLUE d ___ attracts ___ ANTI BLUE d ___

Strong Charge (type 3): UPTONS ___ GREEN u ___ attracts ___ ANTI GREEN u ___

Are these "charges" for the strong nuclear force the same as the "charge" for electricity or the "charge" for magnetism? Why do we use the word "charge" here?

COLOR GENERATE STRONG NUCLEAR FORCE

MASS GENERATES GRAVITATIONAL FORCE

CHARGE

QN - 30

ms-1

The Fundamental Forces
(From: The Particle Adventure - with additions)

Which fundamental interaction is responsible for

Friction?

Nuclear bonding?

Planetary orbits?

The chemistry of life?

Other Questions

Which interactions act on neutrinos?

Which interactions act on the protons in you?

Which force carriers cannot be isolated? Why?

Which force carriers have not been observed?

MS #1

The Fundamental Forces
(From: The Particle Adventure - with additions)

Which fundamental interaction is responsible for

Friction? EM PHOTONS

Nuclear bonding? STRONG

Planetary orbits? GRAVITY

The chemistry of life? EM

Other Questions

Which interactions act on neutrinos? WEAK

Which interactions act on the protons in you? STRONG , ALL

Which force carriers cannot be isolated? Why? ~~W± SHORT TIME THAT IT EXISTS~~
ALWAYS 3 COLORS GLUONS CARRY COLOR

Which force carriers have not been observed? GRAVITY
GRAVITON

GLUBALL

MS-3

The Electromagnetic Force

1. What property must an object possess if it is to interact by the electromagnetic force?

2. What particle is the force carrier for the electromagnetic force?

3. How do electrically neutral particles interact by the electromagnetic force?

4. What property must an electrically neutral particle possess if it is to interact by the electromagnetic force?

5. What is the maximum distance that the electromagnetic force can propagate?

Further Exploration

1. Draw a picture of how the electric charge is distributed when two water molecules bind together. (The oxygen atom attracts electrons more than the hydrogen atom).

2. How does a the electromagnetic force allow a symmetric molecule, like H_2, to bind with another molecule of the same type.

MS #3

The Electromagnetic Force

1. What property must an object possess if it is to interact by the electromagnetic force?

   CHARGE

2. What particle is the force carrier for the electromagnetic force?

   PHOTON

3. How do electrically neutral particles interact by the electromagnetic force?

   RESIDUAL e m FORCE

4. What property must an electrically neutral particle possess if it is to interact by the electromagnetic force? ? ELECTRIC CHARGES

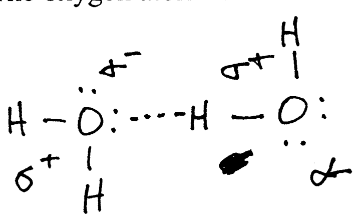
   NEUTRINOS HAVE NONE

5. What is the maximum distance that the electromagnetic force can propagate?

   ∞

Further Exploration

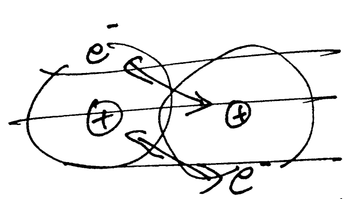
1. Draw a picture of how the electric charge is distributed when two water molecules bind together. (The oxygen atom attracts electrons more than the hydrogen atom).



2. How does a the electromagnetic force allow a symmetric molecule, like H_2, to bind with another molecule of the same type.

   ~~RESIDUAL em FORCE~~

   LONDON DISPERSION FORCES



TWO MOLECULES NOT ONE

Feynman Diagrams

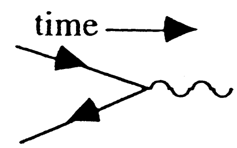
Name ________________

Introduction: Feynman Diagrams are used by particle physicists to show possible processes and as shorthand to derive a calculation of the expected rate for the processes. However, we will use them just as sketches to show possible processes. You will find that there is more than one possible diagram for many processes.

The Rules of the Game:

A. • Time goes from left to right. The left side shows the situation before the process begins. The right shows the end of the process.

B. • The diagrams are made of combinations of 2 fermions (quarks and leptons) shown by straight lines and a force carrier (gluons, W^+, W^-, Z^o, photon) shown by wavy lines.



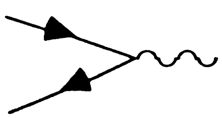
• All 3 lines are joined at a vertex and may be rotated about that vertex point.

• An arrow pointing right (positive time direction) is a particle; one pointing to the left is an antiparticle.

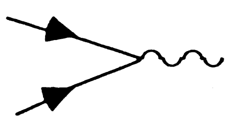
• At each vertex there is one arrow in , one arrow out, and one carrier.

(There are other processes with 3 carriers, but we won't discuss them.)

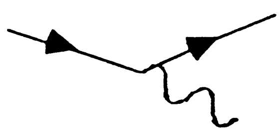
Problem 1. Three of these pictures are wrong. Write OK, or tell why it's wrong.



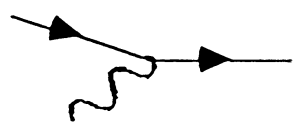
a. ________



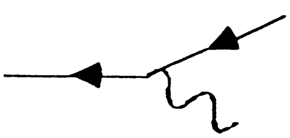
b. ________



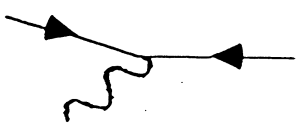
c. ________



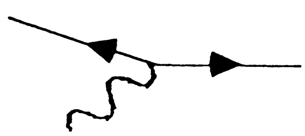
d. ________



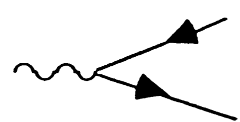
e. ________



f. ________



g. ________

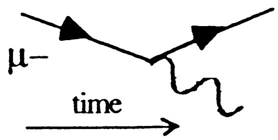


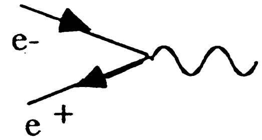
h. ________

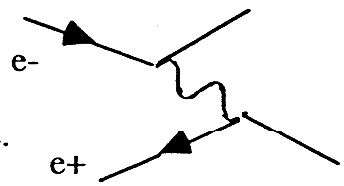
Problem 2. On the diagrams above label the particles **p**, the antiparticles $\overrightarrow{\mathbf{p}}$, and the force carrier **F**.

QN-35

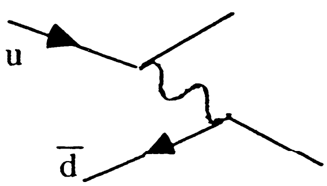
Problem 4. In each of the following vertex diagrams, identify all the unlabeled quarks, leptons, antiparticle, or carrier particles. There may be more than one possible correct answer. Find as many as you can.

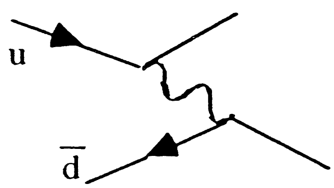
a.


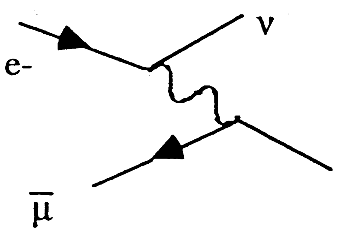
b.


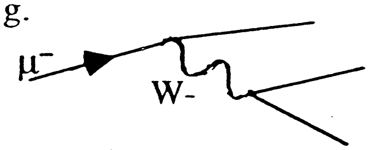
c.


How else can this reaction take place?
(Consider different timings.)

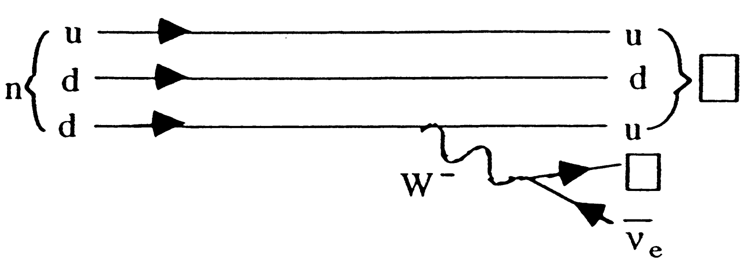
d.


e.


f.


g.


muon decay



h. This is a neutron (beta) decay.
Fill in the empty boxes.

QN - 36

Problem 3. Match each of the six possible orientations for a Feynman vertex (below) with one of these descriptions.

a. A particle emits a force carrer

b. A particle absorbs a force carrier

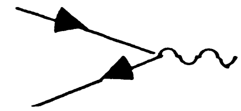
c. A force carrier produces a particle and an antiparticle.

d. An antiparticle emits a force carrier

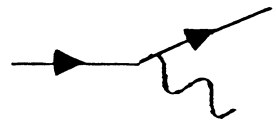
e. An antiparticle absorbs a force carrier .

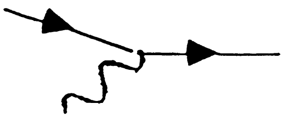
f. A particle and an antiparticle annihilate to produce a force carrrier.

3.1 _____

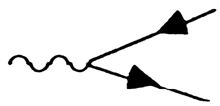


3.2_____

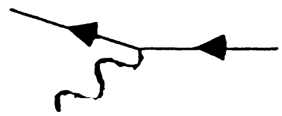




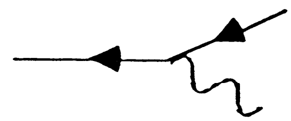
3.3 _____



3.4 _____



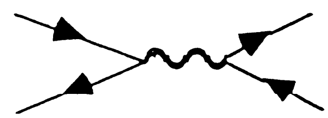
3.5 _____



3.6 _____

Rules, continued:

C. There must be a least 2 vertices for a complete process:



D. Even though isolated quarks cannot exist in initial or final states, we will sometimes dissect out the quarks for the hadronic interaction.

Rules of the Interactions:

E. Electromagnetic interaction: Electric charge is conserved. Photons couple with quarks and leptons, but only if they are charged particles.

F. Weak interactions involve W^+, W^-, or Z^0. In a Z process the fermion type does not change. In a W process the fermion type changes with the following rules: Any lepton is only connected to the other lepton of its own type (electron to electron neutrino, etc.). Any quark can be connected to any quark with the other electric charge (2/3 to -1/3); processes with quarks of the same family (u & d, c & s, or t & b) proceed fastest.

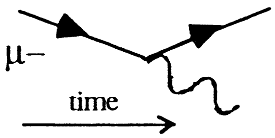
G. Strong interaction: Gluons are exchanged. They connect to only quarks, antiquarks, and gluons. Isolated quarks or gluons cannot exist in initial or final states. Real particles containing quarks must be baryons (3 quarks) or mesons (a quark and an antiquark).

H. The sum of the mass/energy and momenta of the products must be equal to the sum of the mass/energy and momenta of the originals. In a decay the mass of the products must be less than the mass of the original. A single real particle cannot decay into another single real particle.

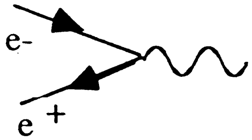
QN-37

Problem 4. In each of the following vertex diagrams, identify all the unlabeled quarks, leptons, antiparticle, or carrier particles. There may be more than one possible correct answer. Find as many as you can.

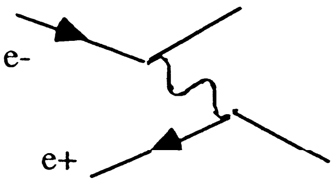
a.



b.

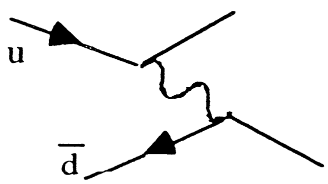


c.

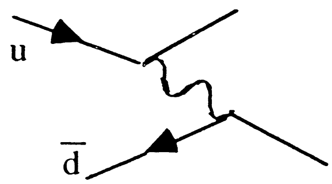


How else can this reaction take place?
(Consider different timings.)

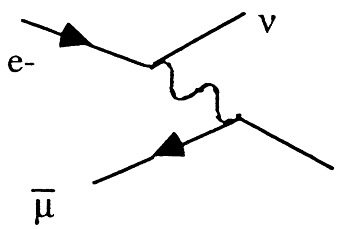
d.



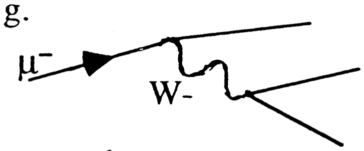
e.



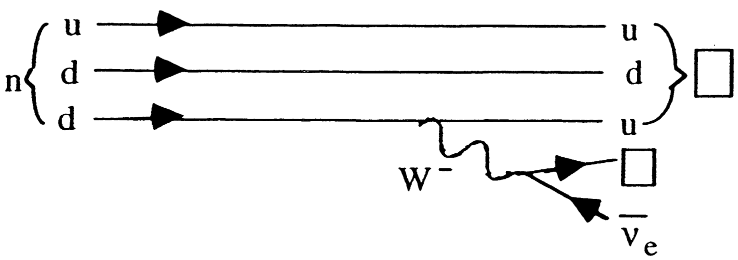
f.



g.



muon decay



h. This is a neutron (beta) decay.
Fill in the empty boxes.

QN-38

Draw Feynman Diagrams for these decays. The quark constituents are shown below each process.

Electromagnetic or weak:

5a. J/Ψ ($c\bar{c}$) → e^+ e^-

5b. J/Ψ ($c\bar{c}$) → μ^+ μ^-

5c. Φ ($s\bar{s}$) → e^+ e^-

5d. ω ($u\bar{u}$, $d\bar{d}$) → e^+ e^-

Weak:

5e. n (udd) → p (uud) e^- $\bar{\nu}_e$

5f. Σ^+ → Λ^o e^+ ν_e

uus uds

5g. Σ^- → Λ^o e^- ν_e

dds uds

5h. μ^- → ν_μ e^- ν_e

Strong:

5i. Σ^- → n π^-

dds udd $d\bar{u}$

5j. Δ^{++} → p π^+

uuu uud $u\bar{d}$

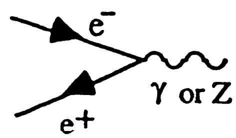
Feynman Diagrams

Introduction: Feynman Diagrams are used by particle physicists to show possible processes and as shorthand to derive a calculation of the expected rate for the processes. However, we will use them as sketches to show possible processes. You will find that there is more than one possible diagram for many processes.

The Rules of the Game:

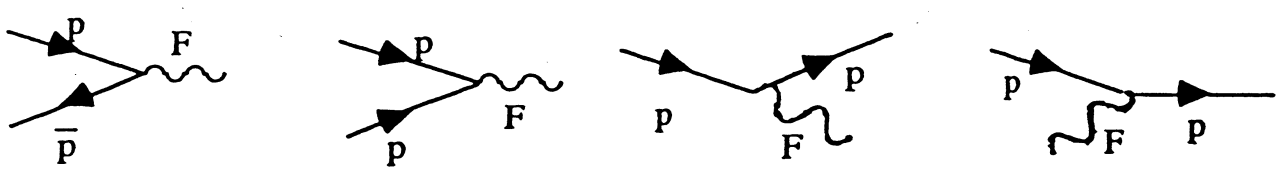
A. Time goes from left to right. The left side shows the situation before the process begins. The right shows the end of the process.

B. The diagrams are made of combinations of 2 fermions (quarks and leptons) shown by straight lines and a force carrier (gluons, W^+, W^-, Z^o, photon) shown by wavy lines.
All 3 lines are joined at a vertex and may be rotated about that vertex point.
An arrow pointing right (positive time direction) is a particle; one pointing to the left is an antiparticle.
At each vertex there is one arrow in, one arrow out, and one carrier.
(There are other processes with 3 carriers, but we won't consider them here.)

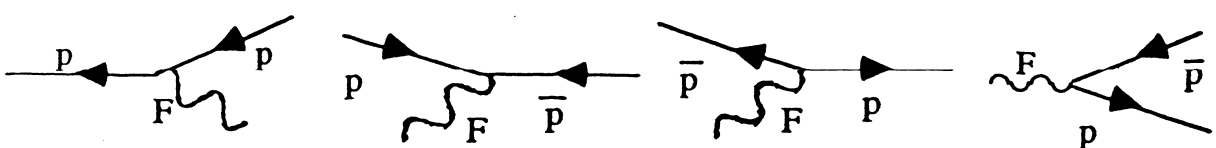


** *(You might have the students connect 2 straws and a curled pipe cleaner together with a brad fastener. Attach paper arrows to the straws - one toward and one away from the fastener. Any way that the straws and pipe cleanser can be rotated is correct.)*

Problem 1. Three of these pictures are wrong. Write OK, or tell why it's wrong.



OK — **No. Both particles "going in"** — **OK** — **OK**



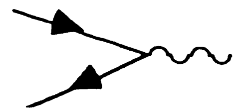
OK — **No. Both going in.** — **No. Both going out.** — **OK**

Problem 2. On the diagrams above label the particles **p**, the antiparticles **p**, and the force carrier **F**.

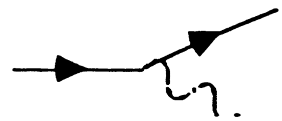
Problem 3. Match each of the six possible orientations for a Feynman vertex (below) with one of these descriptions. Remember that time goes to the right.

a. a particle emits a force carrier
b. a particle absorbs a force carrier
c. a force carrier produces a particle and an antiparticle

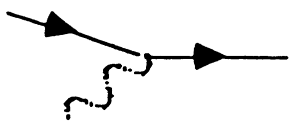
d. an antiparticle emits a force carrier
e. an antiparticle absorbs a force carrier
f. a particle and an antiparticle annihilate to produce a force carrier.



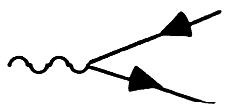
3.1 f



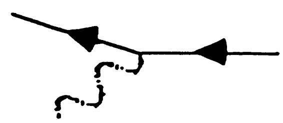
3.2 a



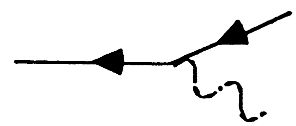
3.3 b



3.4 c



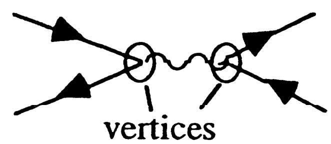
3.5 e



3.6 d

Rules, continued:

C. There must be a least 2 vertices for a complete process:



D. Even though isolated quarks cannot exist in initial or final states, we will sometimes dissect out the quarks for the hadronic interaction.

The Rules of the interactions:

E. Electromagnetic interaction is by photons. Electric charge is conserved. Photons couple with quarks and leptons, but only if charged particles.

F. Weak interactions involve W^+, W^-, or Z^o. In a Z process the fermion type does not change. In a W process the fermion type changes with the following rules: Any lepton is only connected to the other lepton of its own type (electron to electron neutrino, etc.). Any quark can be connected to any quark with the other electric charge (2/3 to -1/3); processes with quarks of the same family (u & d, c & s, or t & b) proceed fastest.

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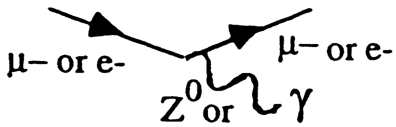
H. The sum of the mass/energy and momenta of the products must be equal to the sum of the mass/energy and momenta of the originals. In a decay the mass of the products must be less than the mass of the original. A single real particle cannot decay into another single real particle.

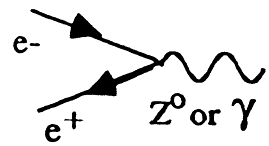
Problem 4 In each of the following vertex diagrams, identify all the unlabeled quarks, leptons, antiparticle, or carrier particles. There may be more than one possible correct answer. Find as many as you can.

a.



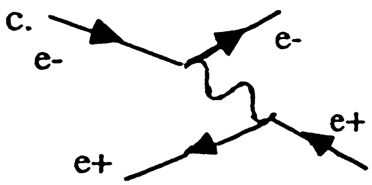
(only partial process)

b.



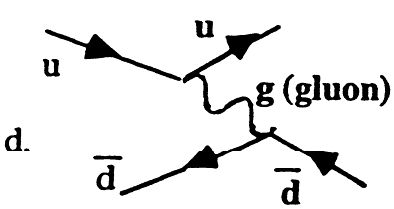
(only partial process.)

c.

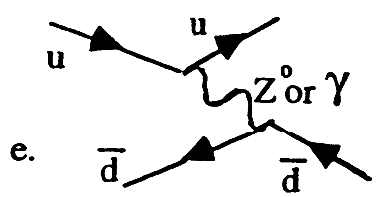


How else can this reaction take place? Consider different timings.
The diagram may be turned so the timing is different. See # 3.

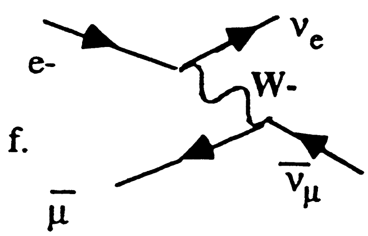
d.



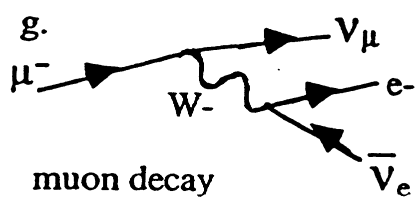
e.



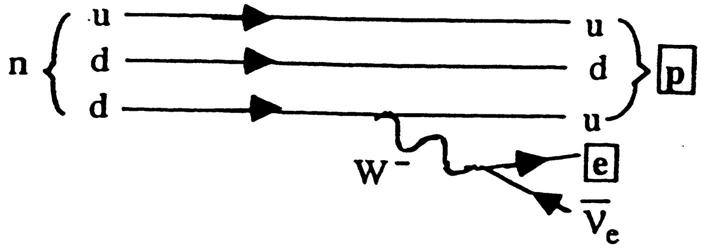
f.



g.



h. This is a neutron (beta) decay. Fill in the empty boxes.



QN-43

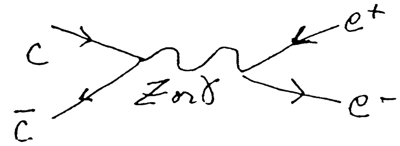
TEACHER

Draw Feynman Diagrams for these decays. The quark constituents are shown below each process.

Electromagnetic or weak:

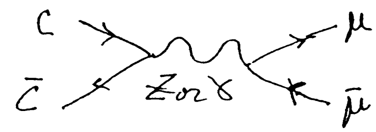
5a. J/Ψ → e^+ e^-

$c\bar{c}$



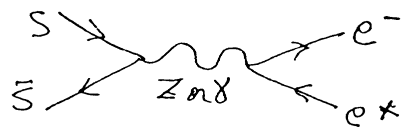
5b. J/Ψ → μ^+ μ^-

$c\bar{c}$



5c. Φ → e^+ e^-

$s\bar{s}$



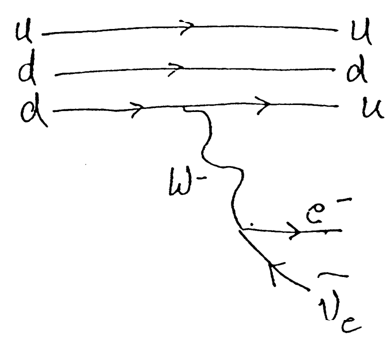
5d. ω → e^+ e^-

$u\bar{u}d\bar{d}$

Weak:

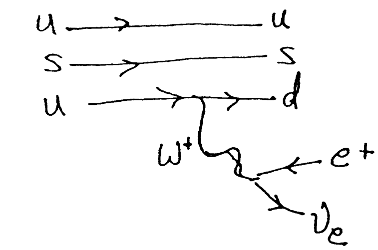
5e. n → p e^- $\bar{\nu}_e$

udd → uud

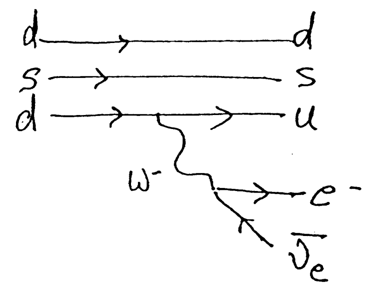


QN-44

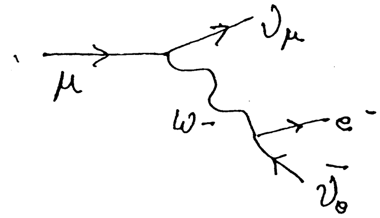
5f. Σ^+ uus	→	Λ^0 uds	e^+	ν_e



5g. Σ^- dds	→	Λ^0 uds	e^-	$\bar{\nu}_e$

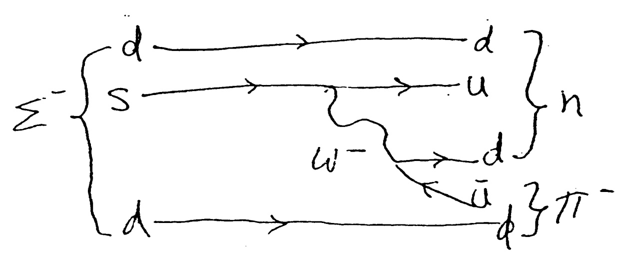


5h. μ^-	→	ν_μ	e^-	$\bar{\nu}_e$

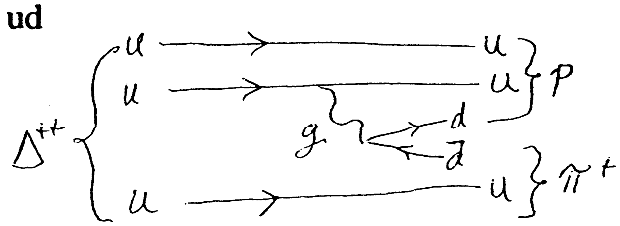


Strong:

5i. Σ^- dds	→	n udd	π^- $d\bar{u}$



5j. Δ^{++} uuu	→	p uud	π^+ $u\bar{d}$



CS 5

Go to : http://www.jlab.org/~cecire/Bedtime.html

1) Once upon a time, there were 3 particles in the atom, the ____________________, the ____________________, and the ____________________.

2) What does an accelerator do?

3) What did Gell-mann call the somethings that protons and neutrons were made of?____________________

4) What kinds of quarks make up a proton? _______quark, _______quark, _______quark.

5) What kinds of quarks make up a neutron ? ? _______quark, _______quark, _______quark.

6) Are electrons quarks?_____ If not, what are they?____________

7) What are hadrons ?

8) What holds hadrons together?__________________

9) What carries the force that holds hadrons together?________________

10) What carries the weak nuclear force?________________

11) What carries the electromagnetic force? ________________

QN-46

KEY

1) Once upon a time, there were 3 particles in the atom, the ____________________, the____________________, and the ______________________.proton, neutron, electron
2) What does an accelerator do?accelerates particles to high speeds, but more importantly, high ENERGY
3) What did Gell-mann call the somethings that protons and neutrons were made of?_____________________quarks
4) What kinds of quarks make up a proton? _______quark, _______quark, _______quark. 2ups,1 down, = up, up, down
5) What kinds of quarks make up a neutron ? ? _______quark, _______quark, _______quark. 2 down, 1 up = down, down, up
6) Are electrons quarks?_____ If not, what are they?____________ no, leptons
7) What are hadrons ? protons, neutrons, and their "kin"
8) What holds hadrons together?___________strong nuclear force
9) What carries the force that holds hadrons together?_________________gluons
10) What carries the weak nuclear force?_________________bosons
11) What carries the electromagnetic force? ___________________photons

QN-47

CS 7

ELECTRON LEPTON NUMBER WORKSHEET

NAME____

Symbol of particle	**Electron Lepton Number**	**Symbol of anti-particle**	**Electron Lepton Number**
u			
d			
c			
s			
t			
b			
e			
ν_e			
μ			
ν_μ			
τ^-			
ν_τ			
π^+			
K^-			
p			
n			
Λ			
Ω^-			

QN-48

ELECTRON LEPTON NUMBER WORKSHEET

NAME____

Symbol of particle	Electron Lepton Number	Symbol of anti-particle	Electron Lepton Number
u	0	$\bar{u}$	0
d	0	$\bar{d}$	0
c	0	$\bar{c}$	0
s	0	$\bar{s}$	0
t	0	$\bar{t}$	0
b	0	$\bar{b}$	0
e	+1	e^+	−1
ν_e	+1	$\bar{\nu}_{e^+}$	−1
μ	0	$\bar{\mu}$	0
ν_μ	0	$\bar{\nu}_\mu$	0
τ^-	0	$\bar{\tau}$	0
ν_τ	0	$\bar{\nu}_\tau$	0
π^+	0	π^-	0
K^-	0	K^+	0
p	0	$\bar{p}$ (p^{-1})	0
n	0	$\bar{n}$	0
Λ	0	$\bar{\Lambda}$	0
Ω^-	0	Ω^+	0

CS 8

MUON LEPTON NUMBER WORKSHEET

NAME____

Symbol of particle	Muon Lepton Number	Symbol of anti-particle	Muon Lepton Number
u			
d			
c			
s			
t			
b			
e			
ν_e			
μ			
ν_μ			
τ^-			
ν_τ			
π^+			
K^-			
p			
n			
Λ			
Ω^-			

QN-50

CS #8

MUON LEPTON NUMBER WORKSHEET

NAME______________________________

Symbol of particle	Muon Lepton Number	Symbol of anti-particle	Muon Lepton Number
u	0	$\bar{u}$	0
d	0	$\bar{d}$	0
c	0	$\bar{c}$	0
s	0	$\bar{s}$	0
t	0	$\bar{t}$	0
b	0	$\bar{b}$	0
e	0	e^+	0
ν_e	0	$\bar{\nu}_{e^+}$	0
μ	+1	$\bar{\mu}$	-1
ν_μ	+1	$\bar{\nu}_\mu$	-1
τ^-	0	$\bar{\tau}$	0
ν_τ	0	$\bar{\nu}_\tau$	0
π^+	0	π^-	0
K^-	0	K^+	0
p	0	$\bar{p}$ or p^{-1}	0
n	0	$\bar{n}$	0
Λ	0	$\bar{\Lambda}$	0
Ω^-	0	Ω^+	0

CS 9

BARYON NUMBER WORKSHEET

NAME____

Symbol of particle	Baryon Number	Symbol of anti-particle	Baryon Number
u			
d			
c			
s			
t			
b			
e			
ν_e			
μ			
ν_μ			
τ^-			
ν_τ			
π^+			
K^-			
p			
n			
Λ			
Ω^-			

1

CS #9

BARYON NUMBER WORKSHEET

NAME____

Symbol of particle	Baryon Number	Symbol of anti-particle	Baryon Number
u	+ 1/3	$\bar{u}$	− 1/3
d	+ 1/3	$\bar{d}$	− 1/3
c	+ 1/3	$\bar{c}$	− 1/3
s	+ 1/3	$\bar{s}$	− 1/3
t	+ 1/3	$\bar{t}$	− 1/3
b	+ 1/3	$\bar{b}$	- 1/3
e	0	e^+	0
ν_e	0	$\bar{\nu}_e$	0
μ	0	$\bar{\mu}$	0
ν_μ	0	$\bar{\nu}_\mu$	0
τ^-	0	$\bar{\tau}$	0
ν_τ	0	$\bar{\nu}_\tau$	0
π^+	0	π^-	0
K^-	0	K^+	0
p	+1	$\bar{p}$ or p^{-1}	−1
n	+1	$\bar{n}$	−1
Λ	+1	$\bar{\Lambda}$	−1
Ω^-	+1	Ω^+	−1

QN-53

Decay Processes

Name ______________

Use conservation laws to check the validity of each of the following decay processses. For any reactions which are not valid, state a reason and show the sums. For a particle give it +1 for its flavor (e, μ, or τ no.), and for an antiparticle give it -1 for its flavor.

Valid or not?

Ex. $K^- \rightarrow \mu^- + \bar{\nu}_\mu$

el. charge: -1 = -1 + 0✓ = ok
electron no. 0 = 0 + 0✓
muon no. 0 = 1 + -1✓
baryon no. 0 = 0 + 0✓

yes

1. $\pi^+ \rightarrow \bar{\mu} + \nu_\mu$

2. $\Lambda^o \rightarrow p + \pi^-$

3. $\pi^- \rightarrow \bar{\mu} + \nu_e$

4. $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

5. $n \rightarrow p + \pi^-$

6. $\Sigma^+ \rightarrow n + \pi^o$

7. $n \rightarrow p + e^-$

8. $K^+ \rightarrow \bar{\mu} + \pi^o$

9. $\pi^o \rightarrow e^+ + e^- + \nu_e$

10. $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

QN-54

Decay Processes

Not all the conservation laws are shown each time; others not shown may be invalid also. The list of some particles, 2.8.1, would be useful.______

Decay	Conservation	Valid or not?
Ex. $K^- \rightarrow \mu + \bar{\nu}_\mu$	el. charge: -1 = -1 + 0 electron no. 0 = 0 + 0 muon no. 0 = 1 + -1 baryon no. 0 = 0 + 0 mass/E: 494 106 + 0 MeV	yes
		ANSWERS
1. $\pi^+ \rightarrow \bar{\mu} + \nu_\mu$	±: 1 = 1+0 μ#: 0 = -1 + 1	yes
2. $\Lambda^o \rightarrow p + \pi^-$	±: 0 = 1 + -1 B#: 1 = 1+0	yes
3. $\pi^- \rightarrow \bar{\mu} + \nu_e$	±: -1 = 1 + 0 e#: 0 = 0 + 1 μ#: 0 = -1 + 0	no
4. $\pi^- \rightarrow \mu + \bar{\nu}_\mu$	±: -1 = -1 + 0 μ#: 0 = 1 + -1	yes
5. $n \rightarrow p + \pi^-$	±: 0 = 1 + -1 B#: 1 = 1 + 0 mass/energy:940 < 938 + 140 MeV	no
6. $\Sigma^+ \rightarrow n + \pi^o$	±: 1 = 0 + 0	no
7. $n \rightarrow p + \nu e^-$	±: 0 = 1 + -1 B#: 1 = 1 + 0 e#: 0 = 0 + 1	no
8. $K^+ \rightarrow \bar{\mu} + \pi^o$	±: 1 = 1 + 0 μ#: 0 = -1 + 0	no
9. $\pi^o \rightarrow e^+ + e^- + \nu_e$	±: 0 = 1 + -1 + 0 e#: 0 = -1 + 1 + 1	no
10. $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$	±: -1 = -1 + 0 + 0 e#: 0 = 1 + -1 + 0 μ#: 1 = 0 + 0 + 1	yes

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The Rules of the Game

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 Act. 13, 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 in small groups, as particle physicists do.

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.

Hints:

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.

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 in 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," that 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 the 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."
   (Note - number of mesons is NOT conserved!)

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?

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

Scientists in every field devise rules that explain what they have observed. They then use these rules to interpret new observations. This activity will give you the chance to discover rules, called *conservation laws*, that play a crucial role in the study of particle physics.

The most common type of observation in particle physics is called an *event*. An event is similar to a chemical reaction in chemistry, in the sense that one set of particles is formed from another.

The following particle charts can help you identify the types and charges of particles in a number of events given below. As indicated, each particle can have an electrical charge of +1, -1, or 0.

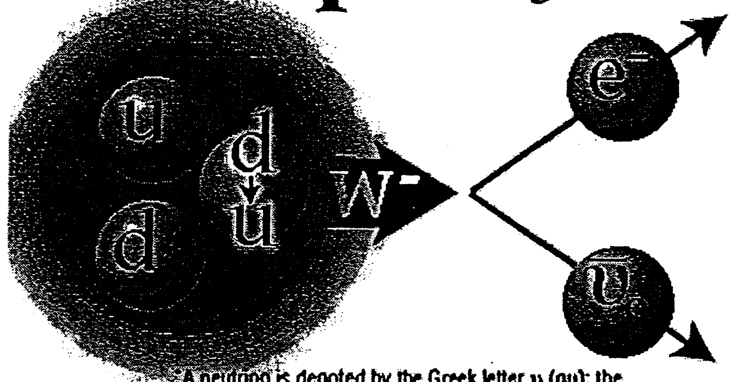
Note that antiparticles are denoted by a bar over the name of the particle (e.g., p-bar = antiproton, nu-bar sub-e = antielectron -- neutrino); or simply by the charges (e^- = electron, e^+ = positron = antielectron); pi^+ and pi^- are particle and antiparticle, and similarly K^+ and K^-. An antiparticle has the same mass as its corresponding particle, but the opposite value for all charges.

BARYONS		MESONS		LEPTONS		PHOTON	
Symbol	Charge	Symbol	Charge	Symbol	Charge	Symbol	Charge
p	+1	π^+	+1	e^-	−1	γ	0
$\bar{p}$	−1	π^-	−1	e^+	+1		
n	0	π^0	0	ν_e	0		
Δ	0	K^+	+1	$\bar{\nu}_e$	0		
		K^-	−1				
		K^0	0				

Two sets of particle events are shown in the table at right. The set in the left column consists only of events that are known to take place, and the set in the right column consists only of events that are believed not to take place (they've never been observed). By examining the two sets, along with the preceding chart of particles, we must determine what quantities are or are not conserved in these particle physics events. These are the "rules of the game" played by nature.

All of the quantities whose conservation can be deduced from the following events can be found by counting. All such quantities are conserved in every "observed" event, but at least one of these quantities is not conserved in each "unobserved" event. Assume that the incoming particles have sufficient energy to generate the outgoing particles.

$$n \rightarrow p\, e^- \bar{\nu}_e$$



A neutrino is denoted by the Greek letter ν (nu); the symbol ν_e denotes an electron-type neutrino.

OBSERVED EVENTS	UNOBSERVED EVENTS
1. $n \longrightarrow p + e^- + \bar{\nu}_e$	11. $n + p \longrightarrow p + p$
2. $\pi^+ + n \longrightarrow p + \pi^0$	12. $p \longrightarrow \pi^+ + \pi^0$
3. $\pi^- + p \longrightarrow n + \pi^- + \pi^+$	13. $p \longrightarrow \pi^+ + \pi^-$
4. $\pi^- + p \longrightarrow p + \pi^0 + \pi^-$	14. $\pi^+ + n \longrightarrow K^+ + K^0$
5. $\Delta \longrightarrow p + \pi^-$	15. $\Delta \longrightarrow \pi^+ + \pi^- + \pi^0$
6. $\Delta \longrightarrow n + \pi^0$	16. $\Delta \longrightarrow K^+ + K^-$
7. $n + p \longrightarrow p + p + \pi^-$	17. $\pi^0 + n \longrightarrow \pi^+ + \pi^-$
8. $p + p \longrightarrow p + n + \pi^+$	18. $\pi^0 + n \longrightarrow p + \bar{p}$
9. $e^+ + e^- \longrightarrow p + \bar{p}$	19. $\Delta \longrightarrow n + \pi^0 + \nu_e$
10. $e^+ + e^- \longrightarrow \gamma + \gamma$	20. $\pi^- \longrightarrow e^- + \gamma$

1. What is meant when we say that a quantity is "conserved?"

____

____

____

2. What quantities or numbers of object types are conserved?

a) ____________________

b) ____________________

c) ____________________

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3. What is an "event" in particle physics?

____
____
____

4. Which of the above events are decays?

____
____

5. For each of the unobserved events, indicate what is not conserved (there may be more than one answer).
Event #:

11: ________________	16: ________________
12: ________________	17: ________________
13: ________________	18: ________________
14: ________________	19: ________________
15: ________________	20: ________________

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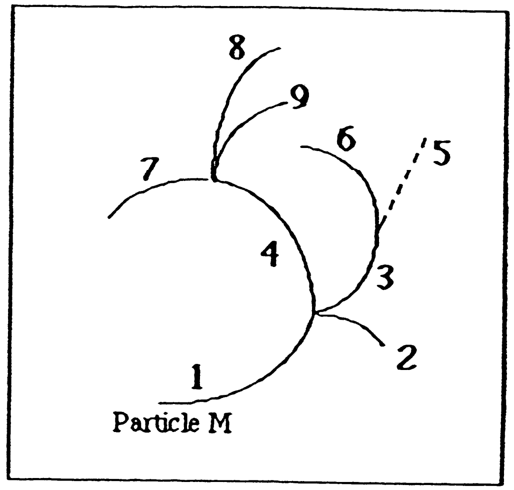
A Particle Zoo

Name ________________



This is a sketch of a cloud chamber in which an initial particle called M decayed into three particles. Each track is labeled. The particle that created track 3 decayed into two particles, but only one of them left a track because the other one was neutral. (An uncharged particle does not leave a trail in a cloud chamber.) The particle that created track 4 later decayed into three other particles. A magnetic field curved the tracks. Although the direction of curvature for each track is represented correctly, the radius of curvature is not.

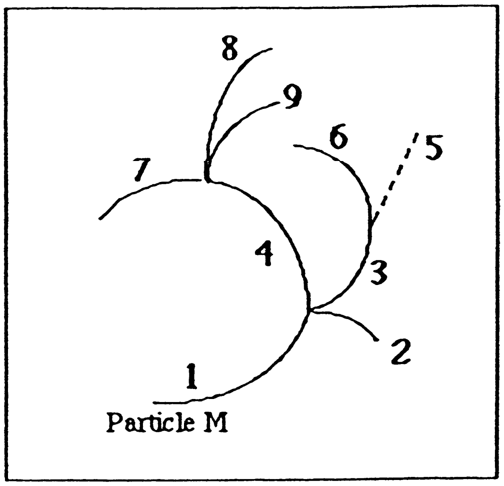
Some fictional quantum numbers associated with fictional particles are listed below. At each decay point in the sketch the quantum numbers must be conserved. For example, when particle M decays, the three products must have a total charge of +1, because that is the charge of M. Those three products must also have a total whimsy of +1, a total seriousness of -2, and a total cuteness of -2, because those were the quantum numbers of M.

Match the particles to the tracks by following the conservation rules, using a particle only once in the identification. There is only one complete solution. Here is a clue: Track 8 is known to be created by a particle with a seriousness of zero.

Particle	Charge	Whimsy	Seriousness	Cuteness	Track No.
M (initial)	1	1	-2	-2	
N	0	4	3	0	
O	1	2	-3	-1	
P	-1	-1	0	1	
Q	-1	0	-4	-2	
R	1	0	0	0	
S	-1	-1	1	-1	
T	3	3	1	0	
U	0	6	4	6	
V	1	-6	-4	-6	

From Jearl Walker's "The Lonesome Trolley" and Other Physics Games, " The Physics Teacher, December, 1987, p.574.

A Particle Zoo



Particle	Charge	Whimsy	Seriousness	Cuteness	ANSWERS Track No.
M (initial)	1	1	-2	-2	**1**
N	0	4	3	0	**--**
O	1	2	-3	-1	**4**
P	-1	-1	0	1	**8**
Q	-1	0	-4	-2	**9**
R	1	0	0	0	**3**
S	-1	-1	1	-1	**2**
T	3	3	1	0	**7**
U	0	6	4	6	**5**
V	1	-6	-4	-6	**6**

HINT: Particle 8 has S = 0, so it must be track P.

Particle M (track 1) has Ch = 1, W = 1, S = -2, C = -2. So try different combinations of particles. Ch = 1 could be 1 + 1+ -1 or particles O and R or V and P,Q, or S. Which of those could give you W = 1? Continue on.

From Jearl Walker's "The Lonesome Trolley" and Other Physics Games, " The Physics Teacher, December, 1987, p.574

Unseen Particles

Name _______________

The less a particle interacts with other matter the harder it is to detect. Of all the known particles neutrinos (symbol, ν) are the only ones that do not interact through either the strong or the electromagnetic force. They only interact through the weak force. This force is literally weak, but it is also very short in range ($<10^{-16}$ m). Consequently, neutrinos are extremely hard to detect and never leave direct evidence of their passage in a detector.

The following exercise is designed to help you understand how particle physicists use a subset of the conservation laws available to them in tracking (pun intended) down the unseen. The conservation laws used most will be those for which a simple integer can be assigned to each particle. (See Activity 15: The Rules of the Game.) The rule will then be that the sum of all of the integers assigned to the incoming particles by each conservation law must equal the sum of all of the integers assigned to the outgoing particles. For example, electrical charge is conserved. If an electron (-1) collides with a positron (+1), the total initial charge is zero and the result could be a set of neutral particles or a particle with charge +1 along with another of charge -1 or any other combination with total charge of zero. In this example the particular outcome will be further limited by other conservation laws.

In order to complete this exercise you will need to know the particular conservation laws to be used and the integers assigned to each particle by the conservation law.

I. Conservation of electrical charge: Neutrinos have zero charge. The charges of all other particles will be indicated as superscripts. For example, the electron has charge -1 and is symbolized as e^- while the positron, being the anti-electron, has charge of +1 and is symbolized as e^+.

II. Conservation of Baryon Number: While baryons can be transformed, it seems that the total number of them always stays the same - if in the counting, each baryon is assigned a baryon number of one and each anti-baryon is assigned a baryon number of -1. Baryons are particles composed of three quarks. Protons and neutrons are the only baryons we will be dealing with in this exercise. Leptons and Mesons have baryon numbers of zero.

III. Electron, Muon and Tau Number: For some reason nature seems to keep separate account of the numbers of particles in each of three "generations" of leptons. The electron generation consists of electrons plus electron neutrinos (ν_e), the muon generation consists of muons plus muon neutrinos (ν_μ) and the tau generation consists of taus plus tau neutrinos (ν_τ). The three kinds of neutrinos seem to be

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nearly identical except that each is found to be associated with only the charged lepton with the similar name. In other words, an muon cannot turn into an electron neutrino or a tau neutrino.

To be more precise, if each electron and each electron neutrino is assigned an electron number of +1, positrons and anti-electron neutrinos are assigned -1, and all other particles have electron number of 0, the total electron number for incoming particles will equal the total electron number for outgoing particles in any process. Corresponding conservation laws hold for the muon and tau numbers, similarly defined.

Part of the process by which particle physicists determine the existence of unseen particles is started by writing down the known incoming particles, followed by an arrow to the right, followed by the known outgoing particles. Then under each particle, they write the charge, baryon number and the number for each lepton generation. Finally, they look for one particle or more (usually a neutrino or two) that makes all of the numbers on the left give the sum of all of the numbers on the right.

As an example of the use of conservation laws in particle identification, consider the decay of the muon (μ^-). The muon is an observed particle that spontaneously decays. The only decay product that is observed is the electron. Are any other particles involved? We will use the following conservation table to organize the given information.

$\mu^- \rightarrow e^- + ??$

a.	Incoming	Outgoing
Conserved Quantity	μ^-	e^- + ??
Electric Charge		
Baryon #		
Electron Flavor #		
Muon Flavor #		
Tau Flavor #		

Note that energy conservation appears to be violated; we will assume that the energies are such that it is conserved. The use of a table such as the one above shows that everything balances with just an outgoing electron - except for the electron and the muon flavor. If we include an outgoing particle with electron flavor of -1 and no other conserved quantum numbers, we would solve part of the problem. If we include another outgoing particle with muon flavor of +1 and no other conserved quantum numbers, we would solve the rest of our problem. It just happens that two such particles exist. They are the anti-electron neutrino and the muon neutrino. The final table is seen below.

b.	Incoming	Outgoing		
Conserved Quantity	μ^-	e^- +	$\overline{\nu_e}$ +	ν_μ
Electric Charge	- 1	-1	0	0
Baryon #	0	0	0	0
Electron Flavor #	0	+1	-1	0
Muon Flavor #	+1	0	0	+1
Tau Flavor #	0	0	0	0

Determine any unseen particles in the following scattering events:

1. A positive pion (π^+) is observed to decay. The only observed outgoing particle is a positive muon (μ^+).

1.	Incoming	Outgoing
Conserved Quantity	π^+	μ^+ +
Electric Charge		
Baryon #		
Electron Flavor #		
Muon Flavor #		
Tau Flavor #		

2. A neutron (n) decays, and a proton (p) and an electron (e^-) are the only outgoing particles observed.

2.	Incoming	Outgoing
Conserved Quantity	n	p^+ + e^- + ??
Electric Charge		
Baryon #		
Electron Flavor #		
Muon Flavor #		
Tau Flavor #		

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The third and last exercise involves an historic discovery. There is a straightforward outcome using the same procedures that worked above, but it is only partly correct. Go ahead and try for this result, but be prepared to go one step farther. Additional hints will be given once you have produced the "partly correct" result. Please do not look ahead to the answer.

3. An electron (e^-) and a positron (e^+) come together in a collider with a total energy of about 3.6 GeV. (Note that at energies below 3.6 GeV no such events had been observed.) The observable outgoing particles were an electron (e^-) and an anti-muon (μ^+). What else came out of the collision?

3a.	**Incoming**		**Outgoing**		
Conserved Quantity	e^- +	e^+	e^- +	μ^+ +	
Electric Charge	-1	+1	-1	+1	
Baryon #	0	0	0	0	
Electron Flavor #	+1	-1	+1	0	
Muon Flavor #	0	0	0	-1	
Tau Flavor #	0	0	0	0	

Stop here! Do the above problem before going on.

Activity 16: Unseen Particles

The electron and the muon numbers are the only ones that are not the same for incoming and seen outgoing particles. Both of these should total zero on the outgoing side. We need an unseen particle with electron number of -1 and another with muon number of +1. These would be an anti-electron neutrino and a muon neutrino as shown in the chart below.

3b.	**Incoming**		**Outgoing**			
Conserved Quantity	e^-	e^+	e^-	μ^+	$\overline{\nu}_e$	ν_μ
Electric Charge	-1	+1	-1	+1	0	0
Baryon #	0	0	0	0	0	0
Electron Flavor #	+1	-1	+1	0	-1	0
Muon Flavor #	0	0	0	-1	0	+1
Tau Flavor #	0	0	0	0	0	0

The problem with this result is that it has a low probability of occurring. It can happen if two unseen intermediate particles are produced from the annihilation of the electron and the positron. One would have to be positively charged and the other negatively charged. Each would have electron and muon numbers of zero. There are two particles that meet these requirements. They are the W^+ and the W^-. These are two of the three particles that mediate the weak interaction. However, at the time that electron-muon events like that of this problem were discovered experimentally, the rate at which they could be produced through the W^+ and the W^- was know to be much lower than the observed rate for these events at the energy of the collisions, so something else had to be involved.

All of this evidence pointed to the production of a pair of *previously undetected particles* consisting of a particle and its anti-particle. This follows from the fact that the incoming particles are anti-particles of one another and give a total of zero for all of the conserved quantities used in our tables. The simplest way of continuing this total of zero is not with electrons, muons and their neutrinos, but with another charged particle - antiparticle pair.

Arguments such as these led particle physicists to conclude that they had evidence for another kind of lepton. In particular they said that a negative particle (tau or τ^-) and its positive anti-particle (τ^+) were formed from the initial interaction. They would have to be charged in order to decay into charged electrons and muons. They would have to have a mass of about of 1.8 GeV each to be pair-produced only at 3.6 GeV or above, not at lower energies. Otherwise, they have no characteristics different from electrons or muons. They are just another version of charged leptons that happens to be very massive. Presumably they would also be associated with their own neutrinos. This means that the original table of outgoing particles usually isn't quite correct, even as outcomes of a second set of particles.

The table below describe the unseen intermediate tau particles:

3c.	**Intermediate**	
Conserved Quantity	τ^-	τ^+
Electric Charge	-1	+1
Baryon #	0	0
Electron Flavor #	+1	-1
Muon Flavor #	0	0
Tau Flavor #	+1	-1

But we must now compare these to the observed outgoing particles to finish the analysis. Try this before looking ahead.

3d.	**Incoming**		**Outgoing**		
Conserved Quantity	τ^-	τ^+	e^-	μ^+	+ ??
Electric Charge	-1	+1	-1	+1	
Baryon #	0	0	0	0	
Electron Flavor #	+1	-1	+1	0	
Muon Flavor #	0	0	0	-1	
Tau Flavor #	+1	-1	0	0	

Activity 16: Unseen Particles

It looks as if we still need only two additional neutrinos to balance the books. But that is not correct, because the above table is misleading. We don't have a tau and an anti-tau combining to form new particles. We have a tau moving a very short distance in one direction before decaying and an anti-tau moving a very short distance in the opposite direction before decaying. Therefore, for each decay, an anti-tau neutrino or a tau neutrino must be produced as summarized below.

3e.	**Incoming**		**Outgoing**					
Conserved Quantity	τ^-	τ^+	e^-	μ^+	$\overline{\nu_e}$	ν_μ	ν_τ	$\overline{\nu_\tau}$
Electric Charge	-1	+1						
Baryon #	0	0						
Elcctron Flavor #	+1	-1						
Muon Flavor #	0	0						
Tau Flavor #	0	0						

The events could be explained by this hypothesis. Further checks were made by calculating the rate of such events as a function of collision energy on the basis of this hypothesis and comparing the prediction to the observations. The results confirmed the interpretation in terms of the τ^-, τ^+ production.

The total event is e^- and e^+ colliding and forming τ^- and τ^+.
The τ^- decays into e^-, $\overline{\nu_e}$, ν_τ and the τ^+ decays into e^+, ν_e, and $\overline{\nu_\tau}$.

Unseen Particles — TEACHER

Objective: to have students understand how scientists hypothesize unknown, or known but undetected, particles from conservation laws.

This activity is designed to lead them through several problems of greater and greater complexity. Many of the answers are given in the students's pages, after they have had a chance to work them out. Encourage students to try each problem before looking ahead for the answers.

Answers:

The answer for **a.** is given in **b.** on the next page.

1. A positive pion (p^+) is observed to decay. The only observed outgoing particle is a positive muon (μ^+).

A muon neutrino is needed to conserve muon number.

1.	**Incoming**	**Outgoing**
Conserved Quantity	p^+	μ^+ + ν_μ
Electric Charge	+1	+1 0
Baryon #	0	0 0
Electron Flavor #	0	0 0
Muon Flavor #	0	-1 +1
Tau Flavor #	0	0 0

2. A neutron (n) decays, and a proton (p) and an electron (e^-) are the only outgoing particles observed.

An anti-electron neutrino is needed to conserve electronb number.

2.	**Incoming**	**Outgoing**
Conserved Quantity	n	p^+ + e^- + $\bar{\nu}_e$??
Electric Charge	0	+1 + -1 + 0
Baryon #	0	0 + 0 + 0
Electron Flavor #	0	0 + +1 + 0
Muon Flavor #	0	0 + 0 + -1
Tau Flavor #	0	0 + 0 + 0

3. Each chart is filed out on the next page of students sheets, except the one on page 3.16.6. You should expect students to realize that they need two neutrino to conserve the electron and muon numbers. But there are more particles as they will soon see.

3d.	Incoming		Outgoing			
Conserved Quantity	τ^-	τ^+	e^-	μ^+	+ ?? $\bar{\nu}_e$	+ ν_μ
Electric Charge	-1	+1	-1	+1	0	0
Baryon #	0	0	0	0	0	0
Electron Flavor #	+1	-1	+1	0	-1	0
Muon Flavor #	0	0	0	-1	0	+1
Tau Flavor #	+1	-1	0	0	0	0

The last step is worked out for them. The whole process is summarized here.

3e.	Incoming		Outgoing					
Conserved Quantity	τ^-	τ^+	e^-	μ^+	$\bar{\nu}_e$	ν_μ	ν_τ	$\bar{\nu}_\tau$
Electric Charge	-1	+1	-1	+1	0	0	0	0
Baryon #	0	0	0	0	0	0	0	0
Electron Flavor #	+1	-1	+1	0	-1	0	0	0
Muon Flavor #	0	0	0	-1	0	+1	0	0
Tau Flavor #	0	0	0	0	0	0	+1	-1

The events could be explained by this hypothesis. Further checks were made by calculating the rate of such events as a function of collision energy on the basis of this hypothesis and comparing the prediction to the observations. The results confirmed the interpretation in terms of the τ^-, τ^+ production.

The total event is e^- and e^+ colliding and forming τ^- and τ^+.
The τ^- decays into e^-, $\bar{\nu}_e$, ν_τ and the τ^+ decays into e^+, ν_e, and $\bar{\nu}_\tau$.

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Activity 2D

Lifetimes

Name ____________________

You can learn some interesting information about the way particles are classified by comparing their lifetimes. Information is given here for a few particles; you will be more convinced if you use more data from the Particle Data Book. It will give either the lifetime of the particle, ˋ, or what is called the width, Γ. You can convert Γ to lifetime by this relationship: ˋ = h/(2 Γ), where h = 4.13 x 10^{-21} MeV· sec.

To simplify the comparisons use only the decays that go into two particles. Classify the decays as ones that go to:

- **a. quarks only**
- **b. one photon plus other particles**
- **c. two photons plus other particles**
- **d. ones with a neutrino**
- **e. charged lepton pair**
- **f. flavor-changing (either leptons or quarks)**
- **g. flavor-changing with photon**

There will be a large range of lifetimes, so use semi-log paper and graph the lifetime on the vertical and the decay number (grouped by a-g and in the order in which you did your list - for identification purposes) on the horizontal.

a. Quarks only

a1.	Δ^{++}	→	p	π^+	Γ = 220 MeV
	u u u		u u d	u $\bar{d}$	
a2.	K^{*+}	→	K^o	π^+	Γ = 176 MeV
	u s		d $\bar{s}$	u $\bar{d}$	

b. One photon

b1.	Δ^+	→	p	γ	Γ = 230 MeV
	u u d		u u d	γ	
b2.	η'	→	ρ	γ	Γ = 0.2 MeV
	u $\bar{u}$		u $\bar{u}$	γ	

c. Two photons

c1.	π^o	→	γ	γ	τ = 8.4 x 10^{-17} sec
	u $\bar{u}$		γ	γ	

d. ones with a neutrino

d1.	K^+	→	μ^+	ν_μ	$\tau = 1.2 \times 10^{-8}$ s
	$u\bar{s}$		μ^+	ν_μ	
d2.	π^+	→	e^+	ν_e	$\tau = 2.6 \times 10^{-8}$ s
	$u\bar{d}$		e^+	ν_e	

e. charged lepton pair

e1.	π^o	→	e^+	e^-	$\tau = 8.4 \times 10^{-17}$s
	$u\bar{u}, d\bar{d}$				

f. flavor-changing (either leptons or quarks)

f1.	Σ^-	→	n	π^-	$\tau = 1.5 \times 10^{-10}$ s
	dds		udd	$d\bar{u}$	
f2.	Λ^o	→	p	π^-	$\tau = 2.6 \times 10^{-10}$s
	uds		uud	$d\bar{u}$	
f3.	B^o	→	D^-	π^+	$\tau = 12.9 \times 10^{-13}$s
	$d\bar{b}$		$d\bar{c}$	$u\bar{d}$	

1. Is there pattern to the lifetimes and the type of decay process?

____

2a. Which decays were strong ones? ____________ (Check the the Interaction Chart.)
b. Which decays were electromagnetic ones? ____________
c. Which decays were weak ones? ____________

Label them by type of interaction on your graph.

3a. Which interaction was the fastest? ____________

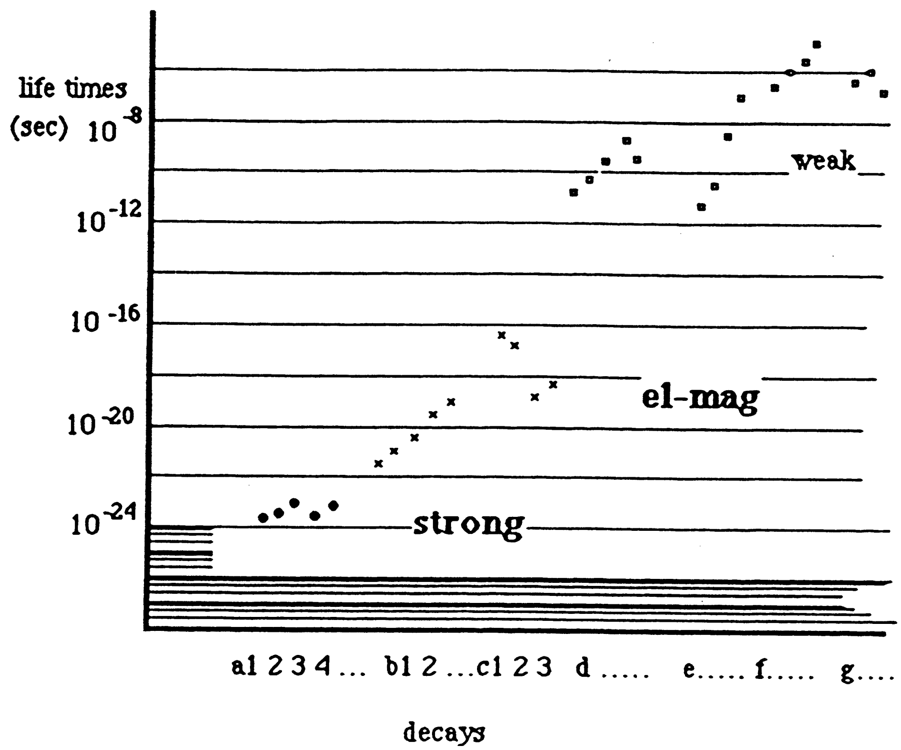
b. Which was the slowest? ____________

4. What is your conclusion about the decay rates and the type of interaction?

____

____

Lifetimes



This is semi-log paper. Remember that the horizontal axis is just the order that the student chose the processes. Be sure that the student marks the data points differently to indicate which processes were which.

Answers:

1. Is there a pattern to the lifetime and the type of decay process?
Yes, the quarks only were very short-lived, the photons were middle range, and the others were longest-lived.

2a. Which decays were strong ones?
a, the quarks only

b. Which decays were electromagnetic ones?
b and c, the photon ones

c. Which decays were weak ones?
d-g, those with leptons or where the flavor changed.

Label them as such on your graph.

3. Which type of decay was the fastest?
strong

Which was the slowest?
weak

4. What is your conclusion about the decay rate and the type of interaction?
The interactions can be classified by their decay times.
The strong interactions are fastest .

Activity suggested by Tom Humphreys, Exploratorium and 1993 SLAC Workshop.

QN - 75

Accelerator Physics

Name ____________________

In this activity you will be exploring some of the surprising physics associated with particle accelerators. A bit at a time you will be given some information about the physics along with questions and/or problems that will help you to use or think about this information.

To start with imagine a very unusual outcome of a common event. You are watching two football players run straight toward each other. They collide and both stop. The unusual outcome is that, as they stop, two other people suddenly materialize and slowly move away from the collision region in opposite directions.

At this point you are probably wondering what this has to do with particle accelerators or with anything at all. Oddly, something very similar to the above scene happens routinely in the collisions that occur in particle accelerators throughout the world. Instead of people colliding and new people suddenly appearing, subatomic particles collide (and usually vanish), and new subatomic particles suddenly appear. This is a consequence of a fundamental relationship which Einstein expressed in the equation

$$E = mc^2. \qquad [1]$$

To the particle physicist this means that sometimes energy, E, can be converted to mass, m, in the form of new particles as long as there is enough energy. The reverse can also occur. Mass can be converted to energy. Part of the key to making sense of this is the constant c^2 that connects mass and energy.

Now lets get back to the football players. Imagine that each is of mass 100 Kg and each is moving at 5.0 m/s just before the collision. Also imagine the c = 10. m/s (It isn't! This is just to contrast the everyday world to the world of particle physics).

<u>Problem 1:</u> Calculate how much kinetic energy the football players lose in the collision, and use $E = mc^2$ and c = 10. m/s to determine how much mass could be produced from the original amount of kinetic energy.

If you are on the right track, there should be enough energy to produce two toddlers who have very little kinetic energy.

Of course this doesn't happen. It's not because Einstein's $E = mc^2$ is wrong. We just used the wrong number for c. It turns out the c is a very important quantity in physics. It is the speed of light, and it roughly equals 3×10^8 m/s. c^2 is then roughly 9×10^{16} m^2/s^2. The next problem will help you see how this affects our football player collision.

QN - 76

Problem 2: Calculate how much kinetic energy the football players lose in the collision, and use $E = mc^2$ and $c = 3 \times 10^8$ m/s to determine how much mass could be produced from the original amount of kinetic energy.

Your answer should show that the collision does not involve enough kinetic energy to result in the production of people of any size. Oddly, it does involve enough kinetic energy to result in the production of many subatomic particles, except that this energy is too spread out to turn into localized things like particles. Instead the bulk kinetic energy of the football players is converted by the collision into molecular kinetic energies, sound energy, etc. But what would happen if the original kinetic energy could be efficiently converted into subatomic particles?

Your last calculation should have been a mass of about 3×10^{-14} Kg. This doesn't look like much, but its a lot in particle physics where the Kg is much too large a unit. Particle physicists use an energy unit called the electron volt (eV) rather than the joule, and they use this along with $E = mc^2$ to define a mass unit of eV/c^2. This may seem odd at first, but consider that the original particle accelerators literally used a potential difference (measured in volts) to give particles such as protons (same amount of electrical charge as the electron) a lot of energy. Since the energy gained by a particle of electrical charge e in going through a potential difference V is e times V or eV, the electron-volt was the energy unit easiest to work with. The only problem with this is that sometimes it is necessary to convert between joules and eVs and between Kg s and eVs/c^2. For this it is useful to know that one eV equals 1.6×10^{-19} J (If you have studied electrical potential, derive this conversion by using the facts that the magnitude of the charge of an electron or a proton is 1.6×10^{-19} C, and one volt is one J/C).

Problem 3: Use the conversion factor between eV and joules to calculate how many eVs of kinetic energy the two football players had just before their collision. Why can you just divide the result by c^2 to get the mass equivalent of this amount of energy in the units commonly used in particle physics?

Problem 4: The proton has a mass of 938 MeV (1 MeV = 1,000,000 eV or one Million eV). If all of the original kinetic energy of the football players could be converted into protons, how many protons could be produced by this collision? The most massive subatomic particle believed to be produced in a particle accelerator is the top quark. Its mass is estimated to be about 170 GeV (1 GeV = 1,000,000,000 eV or one Billion eV). If all of the original kinetic energy of the football players could be converted into top quarks how many top quarks could be produced by this collision?

The answers to the last two problems might suggest that football players could be useful in producing the various particles that physicists would like to study. The problem is that it just doesn't work this way. As mentioned above the energy involved is over too large a volume to often result in the production of particles, and in the rare case that it did happen, it would be nearly impossible to study the particles. After careful consideration we decide that we can't pursue particle physics by colliding football players together (unless the players agree to contribute part of their salaries to support this study!).

In order to take advantage of the implications of $E = mc^2$ to produce subatomic particles, it is necessary to concentrate the energy that is to be converted into new particle masses into a very small volume in a short time. We can't do this by colliding football players who are moving a few meters per second, but we can succeed by colliding particles that are moving much faster. The collision region is necessarily of very small volume, the high speed implies a lot of kinetic energy and a collision of very short duration.

The outcome can be further enhanced if the colliding particles are antiparticles of one another. Since a particle and its antiparticle will partially or totally annihilate one another in a collision, some or all of their mass, as well as their initial kinetic energies, is available for the creation of new particles. Imagine that in an accelerator an electron and its antiparticle, the positron, are coming toward each other, and the two have the same amount of kinetic energy but opposite momenta

Question 1: If an electron and its antiparticle, the positron (same mass as the electron but oppositely charged), annihilate one another what is left as they cease to exist?

The answer to the above question is not as simple as it might appear at first. At first it seems that we could just say that all of the mass of the electron and the positron has been converted into energy. This is a good start, but then we should ask about what it is that has this energy. Can we have pure energy in the absence of anything else? This seems unlikely, and, as may be expected, a particle physicist will talk about this energy as being that of another particle. This makes sense because all of the energy is concentrated into a very tiny volume. But what would this particle be? Since the original electron and positron electrical charges add to zero, the new particle cannot be electrically charged. We can think of the immediate consequence of the collision of an electron and a positron of high kinetic energies as some sort of neutral particle (something that has a very tiny volume) with a lot of energy. The problem is that a creature with all of this energy can't just stay in one place, and, it can't go anywhere without violating the law of conservation of momentum! One of two things must happen in a very very short time. The first possibility is that all of the mystery particle's energy turns into mass. This could happen if there just happens to be a neutral particle with a mass exactly equal to the total energy resulting from the collision. None of the original energy would be left over as kinetic energy, and the particle could just sit there until it decays into something else, and the law of conservation of momentum would not be violated. Since particles have definite masses, this is unlikely, unless the original energies are chosen with this outcome in mind, but it has happened a few times by accident.

<u>Question 2:</u> What is the other possible outcome that could conserve momentum? Hint - remember that we are thinking of an experiment where the two original momenta are opposites.

Don't read on if you want to answer the above question yourself, because the answer is too important to delay. The other outcome is simply the creation of two or more subatomic particles with total momentum of zero. Usually this would be the production of two particles created with opposite momenta. In other words the two particles would be moving in opposite directions. Oddly if there is a lot of energy available from the collision, there is more than one pair of particles that could be formed - no matter how carefully controlled the collision is.

<u>Question 3:</u> Why is this odd? Hint - if you had two football players of identical masses and opposite momenta colliding head-on, how many distinctly different outcomes would you expect?

The branch of physics known as Classical Mechanics is often referred to as an exact science. The reason for this is that predictions made on the basis of this science are often (but not always!) surprisingly accurate. This accuracy whether applied to the motion of a projectile, a billiard ball collision or the motion of a planet suggests that any well defined physical situation has only one possible outcome. This is simply not the case in the quantum world which is the background for particle physics. The energy produced by the collision of an electron and a positron can be exactly the same and still result in many different outcomes. The only restriction that nature seems to provide is that any particular outcome can not violate any conservation laws such as conservation of energy, momentum and electrical charge. When these and other conservation laws are taken into account, the only allowed two-particle outcomes of our electron-positron collision are those for which the two particles are antiparticles of one another with combined mass less than or equal to the energy resulting from the collision divided by the speed of light squared. Note that what is meant by the energy resulting from the collision is the sum of the kinetic energies of the electron and the positron plus the energy equivalents of their masses (for an electron and a positron the total energy equivalent of their masses is 0.511 MeV + 0.511 MeV = 1.022 MeV)

<u>Problem 5:</u> If the electrons and positrons in head-on collisions each have kinetic energy of 800 MeV, how many of the "Sample Bosonic Hadrons" form the Chart of the "Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS" could be produced? Hint - each of the particles shown has an antiparticle that is not shown. The antiparticles have the same mass as the corresponding particles and opposite charge.

We have considered football players moving at a few meters per second, and we have used the speed of light in calculations. It has also been mentioned that particles such as electron used in particle accelerators are accelerated to high speeds. by this time you may have wondered how fast these particles are moving before the collisions. If you assume that their kinetic energies can be calculated from $\frac{1}{2}mv^2$ you may be surprised.

<u>Problem 6:</u> The electrons of the previous problem had kinetic energies of 800 MeV each. Convert this energy into joules, and use the mass of the electron (9.11 x 10^{-31} Kg) in K = $mc^2\sqrt{1-(v/c)^2}$ $\frac{1}{2}mv^2$ to calculate the electron speed, v. What's wrong with your answer?

If the formula $\frac{1}{2}mv^2$ worked for high energy electrons, it would be routine to accelerate electrons past the speed of light in particle accelerators. However, this has never been observed to happen. Is there something wrong with the concept of kinetic energy? It turns out that kinetic energy is still a very useful thing in particle physics. It's the formula that's the problem. $\frac{1}{2}mv^2$ is not a definition of kinetic energy. Its just a formula that works very well at speeds mush less than the speed of light, and becomes useless for speeds approaching the speed of light. This gets us back to Einstein's relativity.

The formula $E = mc^2$ expresses the amount of energy that a mass, m, is equivalent to even if the object with this mass is just at rest in a particular frame of reference. In this sense the mass can be considered as a form of potential energy. Einstein also derived a similar formula for the **total energy** of an object in a frame of reference in which the object is moving with speed v. The total energy, E_t, is equal to $\frac{mc^2}{\sqrt{1-(\frac{v}{c})^2}}$ $\frac{K}{mc^2}$. As in the case of classical mechanics the kinetic energy is equal to the total energy minus the potential energy, or $K = \frac{mc^2}{\sqrt{1-(\frac{v}{c})^2}} - mc^2$. This simplifies a little to:

$$K = mc^2\left[\frac{1}{\sqrt{1-(\frac{v}{c})^2}} - 1\right]. \qquad [2]$$

If the total energy is large compared to the mass equivalent, mc^2, the kinetic energy can be calculated from the formula for total energy with little error. i.e.,

$$K \sim \frac{mc^2}{\sqrt{1-(\frac{v}{c})^2}}. \qquad [3]$$

Notice that for either formula [2] or [3], as v gets close to c, $\frac{1}{\sqrt{1-(\frac{v}{c})^2}}$, gets very large, and a small change in v corresponds to a large change in the particle's kinetic energy. This accounts for the fact that the particles accelerated at all modern particle accelerators end up going at over 99% of the speed of light. In fact the word accelerator might be less appropriate than the word energizer. As the particle energy gets larger and larger, the speed grows very little, but the particles become more and more energetic.

<u>Problem 7:</u> Calculate the total energy and the kinetic energy of an electron that is moving at 80% of the speed of light. Use 0.51 MeV for mc^2 (why is this OK) and express your answer in MeV

You've probably noticed that we still haven't solved for the speed of the 800 MeV electrons. We should be able to do this with either formula [2] or formula [3], but this turns out to involve some difficult arithmetic. Formula [2] is particularly difficult to solve for v, and fortunately, we usually don't have to. An exact solution of formula [3] (remember that [3] is already an approximate formula) results in $v = c\sqrt{1-(\frac{mc^2}{K})^2}$. [4]

Alternately, [4] can be simplified a little by keeping just the first two terms of the binomial expansion of the square root to give the approximate solution of

$$v = c[1 - \frac{1}{2}(\frac{mc^2}{K})^2]. \qquad [5]$$

Now it's time to find out how fast our electron is moving.

<u>Problem 8:</u> Use both formulas ([4] and [5]) to calculate the speed of an electron with kinetic energy, K, of 800 MeV. Express you answer as a % of the speed of light, c. If your calculator doesn't carry a lot of figures, you may not be able to use it to solve [4]. How close are the two answers?

After our particles have collided to form new particles, the goal is to identify as many of the new particles as possible. Some of the other activities in this book deal with typical detector characteristics that make this possible for many of the particles. Here we will consider only the problem of detecting particles which very quickly decay into other particles

Most subatomic particles have very short average lifetimes. In some cases they are so short that there is no hope of the particle lasting long enough to leave a track, and its existence can only be inferred from the characteristics of the particles it decays into. There are other particles with lifetimes so short that it seems unlikely that they would leave a track in a detector, and yet they do. This brings up another aspect of relativity. It turns out that the duration of events depends on the frame of reference in which they are observed. This was predicted by Einstein in his Special Theory of Relativity, and it is routinely verified in particle physics experiments. Specifically, time intervals measured in the particle's frame of reference differ from those measured in a frame of reference in which the particle is moving. The lifetime of a particle moving at speed v relative to our detector will be larger in the detector frame than in the particle's own frame by a factor of $\frac{1}{\sqrt{1-(\frac{v}{c})^2}}$, that is,

$$\text{Lifetime in detector frame} = \text{lifetime in particle frame}\left[\frac{1}{\sqrt{1-(\frac{v}{c})^2}}\right]. \qquad [6]$$

Notice that the term $\frac{1}{\sqrt{1-(\frac{v}{c})^2}}$ also appears in formula's [2] and [3]. This gives us a handy way to simplify [6] when we know the particle's mass and its energy. In cases where the kinetic energy is large compared to the mass times the speed of light squared, and [3] can be used, $\frac{1}{\sqrt{1-(\frac{v}{c})^2}} \sim \frac{K}{mc^2}$.

With this we can convert [6] to

$$\text{Lifetime in detector frame} = (\text{lifetime in particle frame})\left(\frac{K}{mc^2}\right) \qquad [7]$$

__Problem 9:__ A meson called a D+ is produced with a kinetic energy of 120 GeV, and it has a mass of 1.86 GeV/c^2. It's lifetime in its own frame is only 1.1 x 10^{-12}s. How far could this particle travel after being produced before it decays? Answer this question first pretending that its lifetime doesn't depend on frame of reference, then use formula [7] to get the answer. Could the particle leave a track of more than a centimeter in the detector in either case? Hint - roughly how fast do particles travel when their kinetic energies are much larger than their mass times the speed of light squared?

__Question 4:__ It has been found that people who do a lot of jogging and running throughout their lives tend to live a few years longer than average. Is this because of the relativistic implications of formula [6] How small would the speed of light have to be before [6] would have an impact on a person's lifetime in the earth frame of reference?

At this point it is hoped that you know why particle physicists do not look for new particles around the collisions that occur in a game of football. You may also have a better idea of the kinds of things that happen in nature when particles are moving near the speed of light. As odd as the relativistic effects are, they have all been verified many times. The physics of the very small and of the very fast is much different than the appearances of our everyday world.

Accelerator Physics

Answer Key

Problem 1: **Calculate how much kinetic energy the football players lose in the collision, and use $E = mc^2$ and $c = 10.$ m/s to determine how much mass could be produced from the original amount of kinetic energy.**

A: $2(1/2\ mv^2) = (100\ Kg)(5.0\ m/s)^2 = \underline{2500\ J}$.

$m = K/c^2 = 2500J/(10\ m/s)^2 = \underline{25\ Kg}$.

Problem 2: **Calculate how much kinetic energy the football players lose in the collision, and use $E = mc^2$ and $c = 3 \times 10^8$ m/s to determine how much mass could be produced from the original amount of kinetic energy.**

A: $2(1/2\ mv^2) = (100\ Kg)(5.0\ m/s)^2 = \underline{2500\ J}$.

$m = K/c^2 = 2500J/(3.0 \times 10^8\ m/s)^2 = \underline{2.8 \times 10^{-14}\ Kg}$.

Problem 3: **Use the conversion factor between eV and joules to calculate how many eVs of kinetic energy the two football players had just before their collision. Why can you just divide the result by c^2 to get the mass equivalent of this amount of energy in the units commonly used in particle physics?**

A: $K = (2500\ J)/(1.6 \times 10^{-19}\ J/eV) = \underline{1.6 \times 10^{22}\ eV}$.

Problem 4: **The proton has a mass of 938 MeV (1 MeV = 1,000,000 eV or one Million eV). If all of the original kinetic energy of the football players could be converted into protons, how many protons could be produced by this collision? The most massive subatomic particle believed to be produced in a particle accelerator is the top quark. Its mass is estimated to be about 170 GeV (1 GeV = 1,000,000,000 eV or one Billion eV). If all of the original kinetic energy of the football players could be converted into top quarks how many top quarks could be produced by this collision?**

A: # protons = $(1.6 \times 10^{16}$ MeV)/ (938 MeV/proton) = $\underline{1.7 \times 10^{13}\ \text{protons}}$.

taus = $(1.6 \times 10^{16}$ MeV)/ (170,000 MeV/tau) = $\underline{9.2 \times 10^{10}\ \text{taus}}$.

Question 1: **If an electron and its antiparticle, the positron (same mass as the electron but oppositely charged), annihilate one another what is left as they cease to exist?**
A: Energy in the form of a very short lived particle.

Question 2: **What is the other possible outcome that could conserve momentum? Hint - remember that we are thinking of an experiment where the two original momenta are opposites.**
A: Two (or more) particles are produced with total momentum of zero. If two particles are produced, and the initial momentum was zero, the two particles must be formed moving in opposite directions.

Question 3: **Why is this odd? Hint - if you had two football players of identical masses and opposite momenta colliding head-on, how many distinctly different outcomes would you expect?**
A: Most collisions in classical physics with definite initial conditions have a single predictable outcome.

Problem 5: **If the electrons and positrons in head-on collisions each have kinetic energy of 800 MeV, how many of the "Sample Bosonic Hadrons" form the Chart of the "Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS" could be produced? Hint - each of the particles shown has an antiparticle that is not shown. The antiparticles have the same mass as the corresponding particles and opposite charge.**
A: Three. The π^+, the K^- and the ρ^+, along with their respective antiparticles. There is not enough energy available to become masses of the rest.

Problem 6: **The electrons of the previous problem had kinetic energies of 800 MeV each. Convert this energy into joules, and use the mass of the electron (9.11 x 10^{-31} Kg) in $K = \frac{1}{2}mv^2$ to calculate the electron speed, v. What's wrong with your answer?**
A: $\frac{1}{2}mv^2$ = (800 MeV)(1.6 x 10^{-13} J/MeV)

v2 = (1.3 x 10-10 J)/(9.11 x 10^{-31} Kg)

v = 1.2 x 10^{10} m/s. This is greater than the speed of light! No physical object has ever been observed to go this fast.

Problem 7: Calculate the total energy and the kinetic energy of an electron that is moving at 80% of the speed of light. Use 0.51 MeV for mc^2 (why is this OK) and express your answer in MeV

A: $E_t = \frac{mc^2}{\sqrt{1-(\frac{v}{c})^2}}$ = (0.51 MeV)/(0.60) = 0.85 MeV.

$K = E_t - mc^2$ = 0.34 MeV.

Problem 8: Use both formulas ([4] and [5]) to calculate the speed of an electron with kinetic energy, K, of 800 MeV. Express you answer as a % of the speed of light, c. If your calculator doesn't carry a lot of figures, you may not be able to use it to solve [4]. How close are the two answers?

A: Using [4]: $v = c[1-(\frac{mc^2}{K})^2]^{\frac{1}{2}}$ = $c[1 - (.51/800)^2]^{1/2}$

v = 0.999999796c.

Using [5]: $v = c[1 - \frac{1}{2}(\frac{mc^2}{K})^2]$ = $c[1 - 1/2(.51/800)^2]$

v = 0.999999796c. The same. The approximation works very well.

Problem 9: A meson called a D+ is produced with a kinetic energy of 120 GeV, and it has a mass of 1.86 GeV/c^2. It's lifetime in its own frame is only 1.1 x 10^{-12}s. How far could this particle travel after being produced before it decays? Answer this question first pretending that its lifetime doesn't depend on frame of reference, then use formula [7] to get the answer. Could the particle leave a track of more than a centimeter in the detector in either case? Hint - roughly how fast do particles travel when their kinetic energies are much larger than their mass times the speed of light squared?

A: distance = (3.0 x 10^8 m/s)(1.1 x 10^{-12} s) = 3.3 x 10^{-4} m.

With formula [7]: distance = (3.3 x 10^{-4} m)$(\frac{K}{mc^2})$

distance = $(3.3 \times 10^{-4}$ m)(120/1.86) = 0.021 m or 2.1 cm.

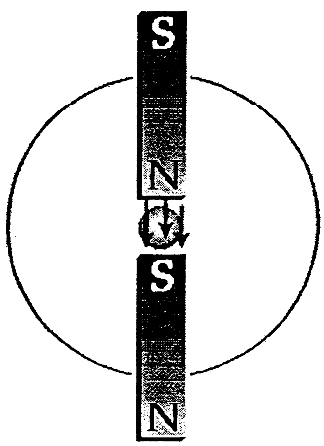
Question 4: It has been found that people who do a lot of jogging and running throughout their lives tend to live a few years longer than average. Is this because of the relativistic implications of formula [6] ? How small would the speed of light have to be before [6] would have an impact on a person's lifetime in the earth frame of reference?

A: No the relativistic correction is not significant. Probably no more than 10 times the speed of commercial aircraft.

Activity Six -- Observing Magnetic Effects on Particle Beams (Student Page)

An ordinary oscilloscope and two small bar magnets can enable you to see two of the important ways in which particle beams are controlled in accelerators.

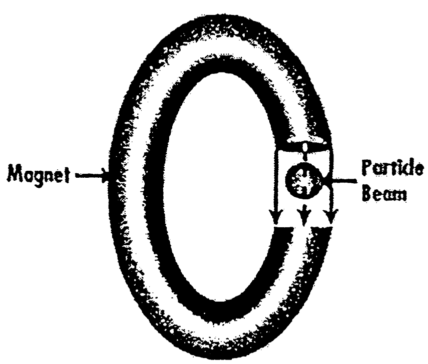
There is an electron beam in the oscilloscope that moves in a nearly straight line from back to front, as a result of a potential difference of tens of thousands of volts. To show how a magnetic field can deflect a beam of charged particles, set an oscilloscope to produce a well-focused spot near the center of the screen. Position the north pole of one bar magnet directly above the beam of the oscilloscope, and position the south pole of another magnet directly below the beam as shown here. (Be careful to avoid bumping or scratching the screen with the magnets.)



Magnetic field produced at oscilloscope screen by students using two bar magnets:

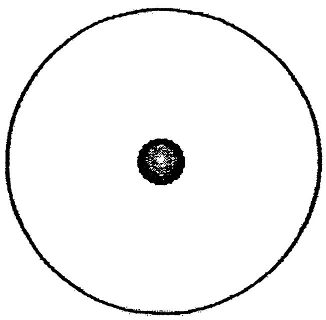
Explain the direction in which the beam is deflected.

By using C-shaped magnets (as shown below) placed regularly around the beam pipe of a circular accelerator, physicists are able to continuously bend a particle beam through a near-circular path.



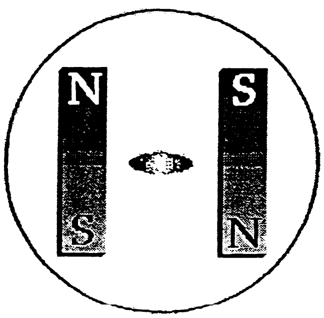
Particle beam within the magnetic field of a C-shape magnet

Next, you can demonstrate how a magnetic field can focus a beam of charged particles by setting an oscilloscope to produce an unfocused beam (turn the focus knob until the spot on the screen is as large as possible). An unfocused beam results in a large spot on the screen, as shown at top right. In particle accelerators, unfocused beams are undesirable because they result in low rates of collisions between beam particles.



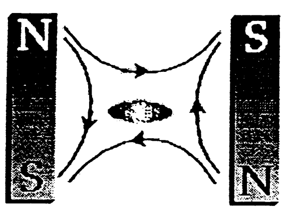
Unfocused oscilloscope without magnets

Place a bar magnet (with the north pole up) against the oscilloscope screen and to the left of the beam (as shown below). Then place another bar magnet with the north pole down against the oscilloscope screen and to the right of the beam. The spot on the screen should now be vertically compressed and horizontally expanded.



Unfocused oscilloscope with magnets

Try to visualize the situation you've just set up by looking at the next diagram and using the "left-hand rule" (the beam is negative).



The arrangement of magnets you've just used is called a *quadrupole*. As you've seen, one quadrupole arrangement will improve the focus of a particle beam in one direction, and worsen it in the perpendicular direction. By using two quadrupole arrangements with the right spacing along the beam path -- and one set rotated 90 relative to the other -- it is possible to improve the overall focus of a particle beam. This is how physicists improve the focus of beams in particle accelerators.

QN-89

Additional Notes to the Teacher

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.

Objectives - Students should be able to:
1. manipulate an oscilloscope beam with magnetic fields.
2. recognize that magnetic fields produce forces that are perpendicular to the fields.
3. describe arrangements of magnets that will produce "dipole fields" and "quadruple fields."
4. explain how dipole magnets can force particle beams along circular paths.
5. describe the effects of quadruple fields on unfocused particle beams.
6. understand the basic principles of particle beam control.

Required materials (repeat with each team of students):
• an oscilloscope or any apparatus with a visible electron beam (CRT)
• two or more bar magnets

In this activity your students will be using an oscilloscope as a particle accelerator. This means that you will not want the beam to be sweeping across the screen. To keep the spot produced by the electron beam in one place, rotate the sweep control dial counterclockwise as far as it will go.

If you have an oscilloscope which can not be unfocused, a similar effect can be produced in two other ways. The first is to turn the sweep control until a horizontal line is formed, turn the horizontal gain down until this line is about half a centimeter long and use any a.c. signal generator as input to the oscilloscope. Finally, adjust the vertical gain until the height of the oscillating signal is about half a centimeter.

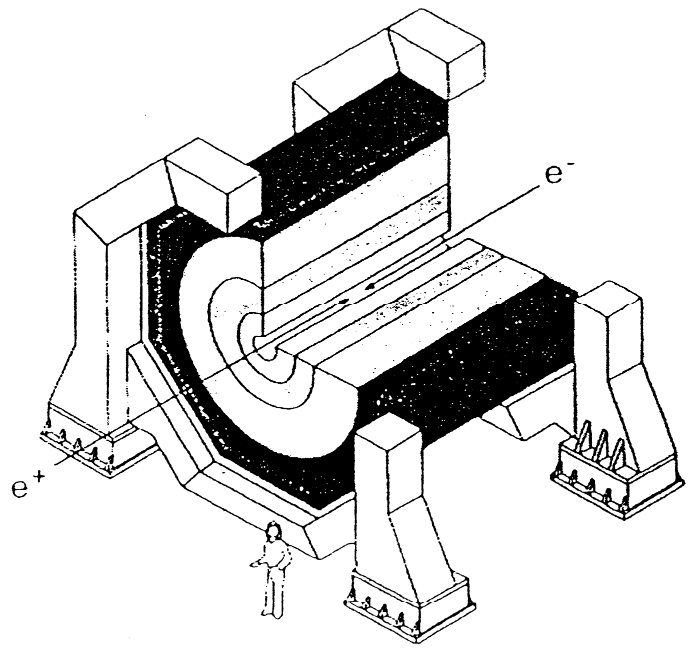
The second method is to control the vertical beam deflection with an a.c. signal generator at the usual input and the horizontal beam deflection with a similar generator at the other input which is usually labeled with an x. You can get some complex and interesting figures (Lissajous Figures) in this way, but all that is needed is any rough figure that is about half a centimeter in diameter.

If you only have one oscilloscope, do this activity as a demonstration. Ask your students what will happen when two bar magnets are used in the dipole configuration shown in the first diagram, and tell them to test their hypotheses in small groups. Use the same approach for magnets in the quadruple configuration of the second diagram. Whether this activity is done as a demonstration or a short investigation, it will typically take between ten minutes and half an hour.

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 Four -- Tracking Unseen Particles (Student Page)

This experiment demonstrates how particle detectors work and why they are multi-layered, as shown in the cutaway and schematic illustrations on this page. Using a few simple materials you will be able to track the paths of magnetic marbles in the same manner that particle physicists track the movements of fundamental particles.



You will need these materials:

- Two shoe or shirt box lids, turned upside down
- Small objects to prop up the lids
- Magnetic marbles
- Ordinary marbles
- Fine iron filings

Follow these directions:

1. Place one lid upside down on the table and insert props at each corner to raise it just enough so that any of your marbles can roll under it.

2. Sprinkle iron filings in the lid so as to cover all of it. This is your simulated detector.

3. Roll a magnetic marble rapidly under this simulated detector. Write your observations here.

____

____

____

____

____

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4. What property of the marble would you say your detector is recording?

____

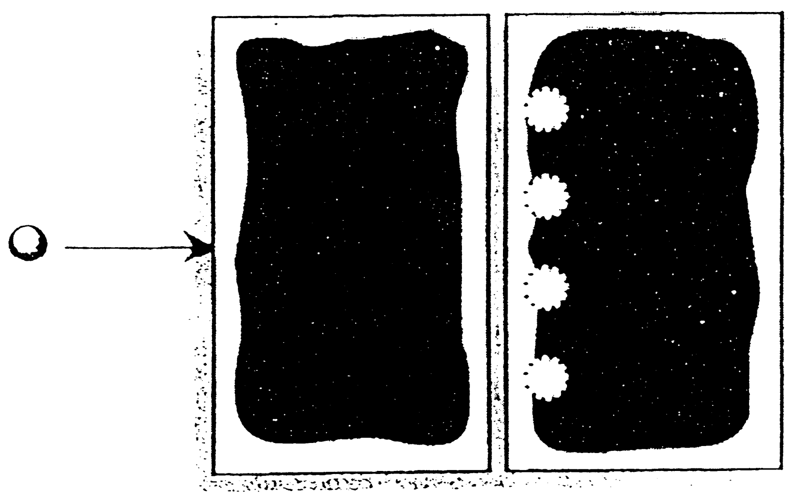
5. Roll an ordinary marble under your detector. Record your observations here.

____
____
____

To which particle's behavior is this observation similar?

____

Now construct a two-part detector that can be used to track "neutral" or "uncharged" particles by making a line of four or more magnetic marbles immediately beyond the first lid, and placing a second lid over them (see diagram below). Your two-stage detector will be complete when you have sprinkled iron filings in the second lid.



6. a) Roll an ordinary marble under the first detector. If it hits a magnetic marble, what does the resulting trail in the second detector tell you?

____
____
____
____

b) To which particles is this behavior similar?

____
____
____

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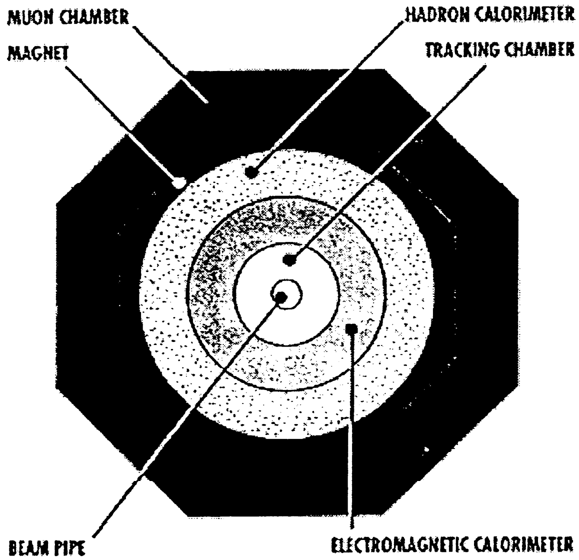
SCHEMATIC DIAGRAM OF A PARTICLE DETECTOR



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Tracking Unseen Particles

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 ScienceKit.)

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 and Answers
(steps 3 through 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.

A Cloudy Chamber

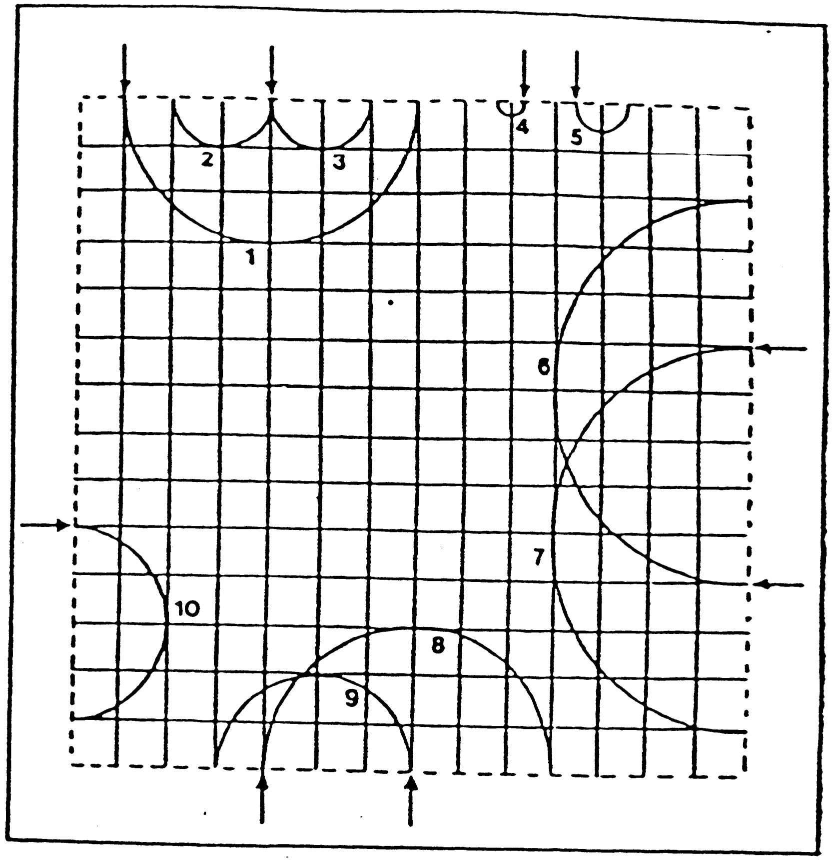
Name ____________________

A charged particle crossing a cloud chamber causes condensation of the vapor in the chamber, leaving a thin trail of droplets that marks the particle's path. If the chamber is placed within a magnetic field, the path is curved because of the magnetic force on the particle.

This figure is an overhead sketch of the paths of 10 charged particles that crossed a cloud chamber through which there was a magnetic field perpendicular to the plane of the paper. The mass, charge, and speed of the ten particles are given in the table as multiples of a unit mass m, a unit charge q, and a unit speed v.

Centripetal $F_c = mv^2/r$ = Force of magnetic field $F_m = qBv$, so r = __________, where B is constant.

The paths are drawn accurately on the grid, with the entrance points indicated by arrows. Match the particles to the paths. Oh, there is one serious problem: I cannot remember if the magnetic field was into or out of the drawing.



Particle	Mass	Charge	Speed	Your thought processes:	Track No.
A	m	-2q	8 v		
B	m	-q	v		
C	2 m	-2q	3 v		
D	m	-4q	v		
E	m	-q	2 v		
F	3 m	3q	3 v		
G	2 m	q	2 v		
H	0.5m	q	2 v		
I	2 m	q	v		
J	m	2q	v		

From Jearl Walker, "The Lonesome Trolley" and Other Physics Games," The Physics Teacher, December, 1987, p.574

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A Cloudy Chamber - Answers

Particle	Mass	Charge	Speed	(Thought Process) r = mv/q	Track No. (answer)
A	m	-2q	8 v	**-4**	**6**
B	m	-q	v	**-1**	**2**
C	2 m	-2q	3 v	**-3**	**8**
D	m	-4q	v	**-1/4**	**4**
E	m	-q	2 v	**-2**	**10**
F	3 m	3q	3 v	**3**	**1**
G	2 m	q	2 v	**4**	**7**
H	0.5m	q	2 v	**1**	**3**
I	2 m	q	v	**2**	**9**
J	m	2q	v	**1/2**	**5**

Hint: Notice that Particle D has the smallest radius, 1/4, so that is track 4. It has a negative charge, so all negative particles will curve clockwise. AND, the magnetic field is <u>into</u> the page, by the right-hand/left-hand rule. Continue in a similar matter with the other particles.

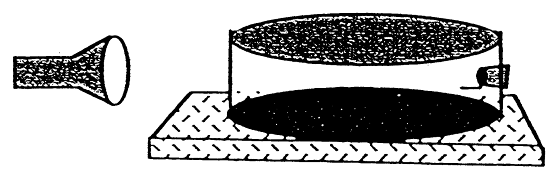
From Jearl Walker, "The Lonesome Trolley" and Other Physics Games.
" The Physics Teacher, December, 1987, p.574

Cloud Chamber

Name ____________________

Radioactive elements continually undergo a process of radioactive decay during which their nuclei emit high speed particles and rays. These are much too small to be seen under a microscope. A simple cloud chamber—one of the earliest types of particle detector—can help you experience particle tracks first hand!

First, the air in the chamber is saturated with alcohol vapor. When the high energy particles plow through the air, electrons are knocked loose from some of the atoms and form ions. Ions act as excellent centers for condensation. This condensation must be stimulated by cooling the air. The alcohol condenses on the ions, leaving a vapor trail which clearly reveals the path of the ray.



Materials:

- Cloud chamber - commercial* or home-made
- Methyl alcohol - (duplicating fluid)
- 45 V dc power supply (optional)
- Black construction paper
- Strong light source, flashlight or slide projector
- Dry ice** - a slab 2 cm thick and 20 cm square.
- Alpha and Beta sources (Use a uranium rock, a radioactive smoke detector, or other sources.)

Procedure:

1. To make your own cloud chamber, turn 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 the light.

2. Fill the bottom of the cloud chamber with methyl alcohol to depth of 1/2 cm or until it touches the bottom edge of the black paper that lines the sides. (If you have black dye, add it to the alcohol and stir until dissolved.)

3. Place the chamber on dry ice.

4. Place a radioactive rock inside or place a powdered radioactive source on a pin on a rubber stopper.

5. The light should be bright, not frosted, and not of such high wattage that it heats the chamber. Position it about 10 cm from the chamber and so it just skims the top of the alcohol surface.

6. Be patient. It takes several minutes for it to cool enough to be supersaturated. The precipitation of droplets (on dust, etc.) will subside and you will see tracks.

7. A 45 V power supply will clear the field of stray ions. It is not essential , but it is helpful. The positive lead should be attached to a metal strip on the bottom of the chamber, the negative to ground. (If the bottom were negative, positive ions would take longer time than the electron to reach the bottom, spreading out, leaving diffuse, non-recognizable tracks.) The tracks will be best just after the voltage source is removed after clearing the field.

8. When it has been in operation for about 1/2 hour, condensation will cover the top. Wipe the outside with a clean cloth. If you remove the cover, it will take 10 minutes or more for it to operate again.

9. Video-taping is an excellent way to capture the tracks for easier viewing, or those times when no tracks are visible!

10. Observe and sketch any tracks. Can you identify them?

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).

Extra: Using no source, observe the cosmic rays (or alpha particles from radon in the room and ground) and calculate how many natural cosmic rays are going through your body every hour. Show your work.

Cloud Chamber - Teacher's

See Student's introduction.

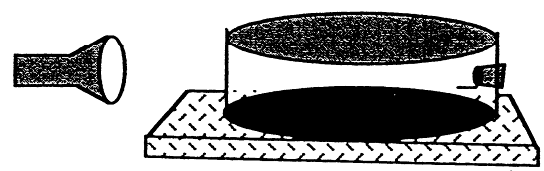
This can be very exciting, when the students see the actual tracks left by particles.

Objectives: The student should

1. **understand that he/she is not seeing radioactive particles, but the droplets that form on the ions caused by the radioactive particles.**

2. **understand that there is natural radiation**

3. **understand that detectors such as this simple one can give information about particles, even if the particles are not seen.**



4. **be able to detect differences in tracks. (Alpha particles with greater mass/energy make longer and heavier tracks than beta particles do.)**

Materials:

(Same as students' list.)

• Dry ice may be available in fishing stores and creameries.

• Alpha and Beta sources (Use a uranium rock, a radioactive smoke detector, or other sources. Coleman lantern mantles were radioactive until recently, but are no longer.)

* Cloud Chambers with a radioactive rock are available from many scientific catalogs.

Procedure: (Same as the student's)

In some chambers you will see many tracks, but other set-ups that are identical may not have tracks. With several cloud chambers and good radioactive sources, enough students should have tracks so that it successful. Have the students vary the lighting angle and be patient!

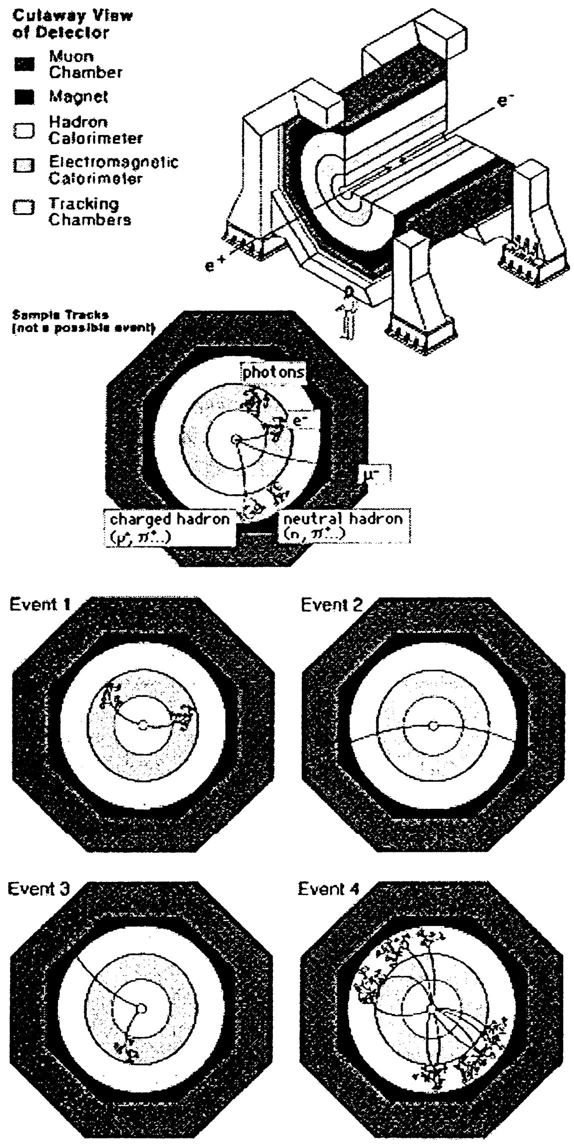
Extra: Using no source, observe the cosmic rays (or alpha particles from radon in the room and ground - **this depends on your location**) and calculate how many natural cosmic rays are going through your body every hour. Show your work.

Activity Seven -- Picturing Particles (Student Page)

Whether they are called *atom smashers, accelerators* or *colliders,* the massive devices used for research by particle physicists all produce new particles by colliding two high-energy particles with one another.

For this activity, imagine that an electron and positron are traveling at nearly the speed of light. They collide head-on, carrying equal and opposite momenta and produce many particles that spread out in all directions.

Surrounding the collision point of these particles in the accelerator is a multi-layered *particle detector*, shown here in a cutaway view. Detectors are the sensors used by particle physicists to gather information about the particles produced by an event. Each layer of the detector senses a different property of the particles. The tracking chamber shows the paths of charged particles. In the calorimeter layers, only the total energy deposited is measured; the actual tracks cannot be reconstructed. The electromagnetic calorimeter collects energy from photons, electrons and positrons. Hadrons deposit their energy in the hadron calorimeter.



Notice the large magnet in the detector. The magnetic field inside the magnet (parallel to the beam pipe) causes the paths of charged particles moving out from the collision point to curve. The paths of positive and negative particles curve in opposite directions.

Now imagine that you are a physicist trying to analyze the tracks shown in the four cross-section "event" illustrations at bottom left, which are taken from actual experiments. Use the labeled cross section of a detector, showing sample tracks of various particles, as a reference (along with the given "rules" of conservation).

Rules of the Game:

1) Charge is conserved. (The event started with a negative electron and a positive proton, so the total charge is always zero.)

2) Momentum is conserved. (The original particles had equal and opposite momenta, so the total momentum is always zero.)

After analyzing these event pictures, complete the following chart. Check off each column representing a detector layer where the track appears. Compare your findings with the particle tracks shown in the "Sample Tracks" cross section at left. Then answer the questions for each event below the chart.

Track	Tracking Chamber	Electromagnetic Calorimeter	Hadron Calorimeter	Muon Chamber
Event 1				
Event 2				
Event 3				
Event 4				

1. Events 1-4:
From your chart, what could the particles be?
Event 1 ____________________
Event 2 ____________________
Event 3 ____________________
Event 4 ____________________

2. In events 1 & 2, are the particles of the same or of opposite charges?
____
____

3. In event 3, the two tracks are not back to back. What does this tell you?
____
____
____
____

Act 7

Picturing Particles

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 7,"Tracking Unseen Particles". *Notice the event pictures in the transparancies, 215.30 to 215.42.*

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, Fundamentally Speaking, and again indicating their responses to each statement.

Student Accelerators and Detectors

Have students design their own accelerators and detectors.
Check the "Experimental Evidence" section of the Particles and Interactions software , the transparencies 215.21 to 2.15.29, and the background articles, 2.5 and 2.6.

Collider: Two "particles" could collide and the collisions could be classified and recorded.

Detector: One example of a layered detector is given here, in case you want the whole class to do it the same way. The students will be more creative if you do not tell them this example. The particles are marbles. The accelerator is a ramp or sloped track. The particles gain different amount of energy, depending on high up the track they start. Students can use photogates to time the final velocities.

This detector has three layers: vertex detector, Cerenkov detector, and a calorimeter. A vertex detector can be made easily by using momentum collision ramps (common in physics stockrooms) and carbon paper, arranged in a semi-circle several centimeters from the collision point. The students can work backwards from the tracks to determine the original point of collision.

Although this works like a layered detector, you will probably want to collect data for each part separately; the particles won't have enough energy to go through two or three of the layers.

The Cerenkov detector works on the same principle as a sonic boom. (In an actual Cerenkov detector light is emitted. See the detector article.) The particle, which is traveling faster than light <u>in that medium,</u> leaves a "wake". The faster the particle travels, the narrower the angle of the wake. Students can measure the angles of the wake (width) for marbles going through a pan of water, compared to the velocities that the marbles had. Video-taping it makes it easier to measure the angles of the water wakes.

The other layer is a calorimeter, in which the particle "deposits" energy. A thick carpet is used to stop the particle. The stopping distance is related to the particle's energy. Different carpets could be tried.

This can be a quantitative as you want. Even if you suggest this particular set-up, students should be encouraged to improve the "detectors" and the data-collection.

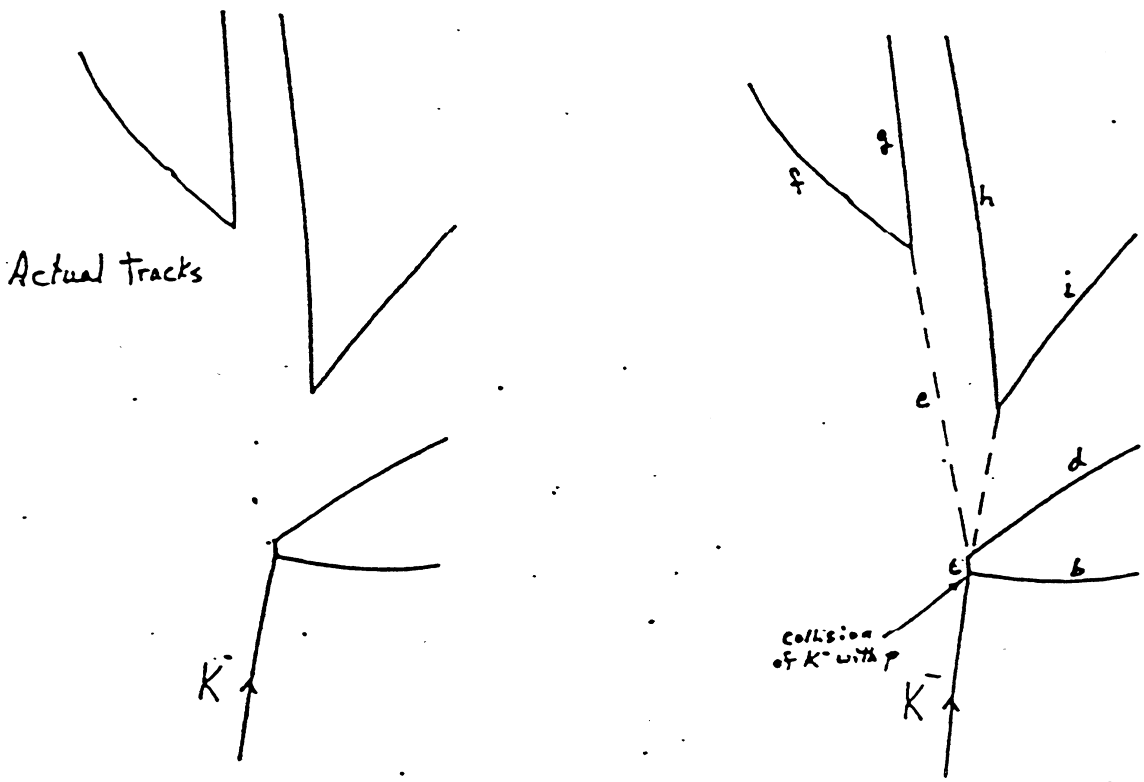
(Adapted from a lab presented at the SLAC Workshop, Summer, 1993, by Annette Rappleyea, San Francisco City College; and Sean Fottrell, Castilleja School, Palo Alto, CA.)

Activity 19: Bubble Chamber

Bubble Chamber Tracks

An old but easy-to-see method of studying particles used a bubble chamber, where the super cooled liquid would boil when the pressure was suddenly released. You do not see the particles but the bubbles that formed on the ions formed as the particles traveled through the liquid hydrogen. A kaon (K^-) comes from the bottom in this picture and hits a proton (p^+). Neutral particles do not leave tracks. The tracks for positive and negative particles curve in opposite directions due to the magnetic field. The particles that emerge must follow the conservation laws: electric charge, baryon number, lepton number, and mass/energy.

The questions will help you, as you solve for unknown particles.



Name ________________

1a. Does the K^- track curve to the right or the left? (Use a straight edge.) ___________

b. So, what is the direction of the magnetic field? ________________________

2a. What 3 paths result from the K^- and P^+ collision? ______ _____ ______

b. Why is the path of particle a invisible? ____________________________________

c. What is the charge of b?____________

d. b's path is more curved than that of K^-. Is it more or less massive than K^-? _____

(centripetal $F = mv^2/r$ = magnetic $\mathbf{F} = Q\ \mathbf{v}\ \mathbf{B}$,

so, $mv/r = QB$ which is constant. If r is large, the mass is ______.)

e. What is the charge of c? _____

f. What was the total charge of K^- and P^+? ____

g. What is the total charge of a, b, and c? _____

3. After a very short distance particle c decays to particles d and e.

a. What does that tell you about c's lifetime? __________________________

b. What is the charge of d? ______

c. What is the charge of e? _______

d. What is the total charge of d and e? ______

4. Particle d decays into f and g.

a. What is the charge of f? _____

b. Wht is the charge of g? ______

c. Which is more massive? _______ How do you know? ________________

5a. Which is more massive: h or i? _________

b. What is the charge of h? ______

c. What is the charge of i? ______

Given the following masses, identify one possible process. For each particle give its mass, symbol, and electric charge. (Realize that the K^- had kinetic energy as it entered the bubble chamber.)

$\pi^{\pm}$ (pion) = 140 MeV	π^o = 135 MeV	$K^{\pm}$ = 494 MeV	K^o = 498 MeV
Λ^o(lambda) = 116 MeV	Ξ^o (xi) = 1315 MeV	$\Xi^{\pm}$ = 1321 MeV	p^+ = 938 MeV

K^- + p^+ → a __498__ + b __140__ + c __1321__

a ↳ h ______ + i ______

c ↳ d _______ + e ________

d ↳ f ______ + g ______

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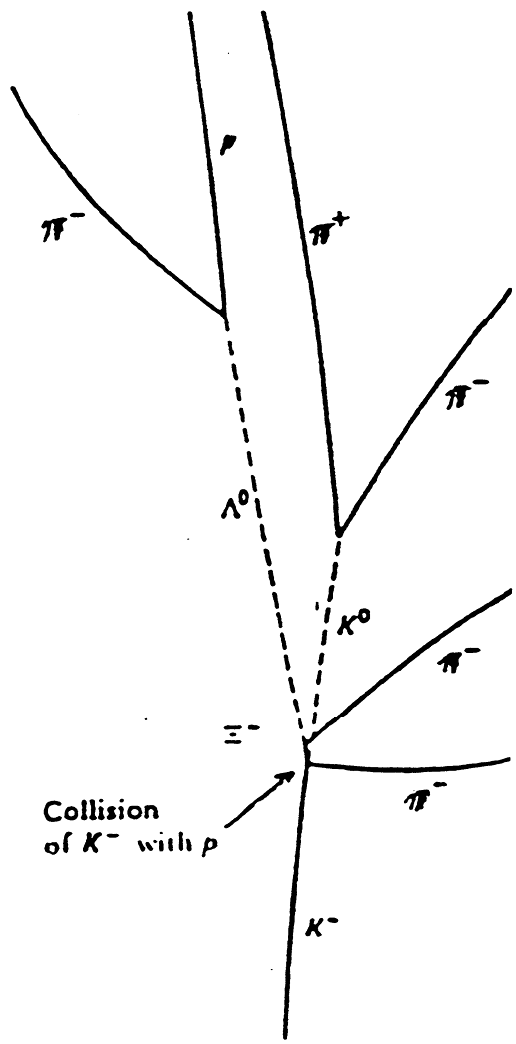
Bubble Chamber Tracks

This is from an out-of-date detector. However, the exercise is of value, as the students can solve for unknown particles better than with modern detectors where the data is given after being processed by computers. Most particles studied with modern detectors were not seen in bubble chambers, because they were so short-lived that they did not travel far enough to be seen in those detectors. The students might be interested in how these pictures were "read" before the days of computers; large numbers of low-paid students and housewives pored over the films, measuring the tracks with rulers, etc.

Do this activity after they have done the conservation laws. See Resources for more bubble chamber pictures. Have the students also do Activity 11, using modern detector pictures.

You may want to give the students the names of some of the particles if they are having trouble.



Answer:

K^- hits a p^+ → $\Xi^- + K^0 + \pi^+$

- K^0 → $\pi^+ + \pi^-$
- Ξ^- → $\pi^- + \Lambda^0$
  - Λ^0 → $\pi^- + p^+$

Check the conservation laws for each process:

	K^- +	p^+	→	Ξ^- +	K^0 +	π^+
Q(el. charge) :	-1	+1	=	-1	0	+1
Baryon no:	0	1	=	1	0	0
lepton no:	0	0	=	0	0	0

etc.

Extra: Have the students do Feynman diagrams for these processes, using the quark content (which was not known when this pictures was taken.)

!

Answers for student sheet:

1a. Does the K^- track curve to the right or the left? (Use a straight edge.) Right

b. So, what is the direction of the magnetic field? Into the paper

2a. What 3 paths result from the K^-, p collision? a b c

b. Why is the path of particle a invisible? Neutral particles don't leave tracks

c. What is the charge of b? +

d. b's path is more curved than that of K^-. Is it more or less massive than K^-? Less

(centripetal $F = mv^2/r$ = magnetic $F = Q\,\mathbf{v}\,\mathbf{B}$,

so, $mv/r = QB$ which is constant. If r is large, the mass is large .)

e. What is the charge of c? -1

f. What was the total charge of K^- and p? Zero

g. What is the total charge of a, b, and c? Zero

3. After a very short distance particle c decays to particles d and e.

a. What does that tell you about c's lifetime? It has a short lifetime

b. What is the charge of d? -1

c. What is the charge of e? Zero

d. What is the total charge of d and e? -1

4. Particle d decays into f and g.

a. What is the charge of f? -1

b. Wht is the charge of g? +1

c. Which is more massive? g How do you know? Its track curves less than that of f.

5a. Which is more massive: h or i? h

b. What is the charge of h? +1 c. What is the charge of i? -1

Given the following masses, identify one possible process. For each particle give its mass, symbol, and electric charge. (Realize that the K^- had kinetic energy as it entered the bubble chamber.)

$\pi^\pm$ (pion) = 140 MeV	π^o = 135 MeV	$K^\pm$ = 494 MeV	K^o = 498 MeV
Λ^o(lambda) = 116 MeV	Ξ^o (xi) = 1315 MeV	$\Xi^\pm$ = 1321 MeV	p = 938 MeV

K^- 494 (+KE!) + p 938 → a: K^o 498 + b: π^+ 140 + c: Ξ^- 1321

↳ h: π^+ 140 + i: π^- 140 (from a)

↳ d: π^- 140 + e: Λ^o 116 (from c)

↳ f: π^- 140 + g: p^+ 938 (from e)

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Activity 2b

Determine the Top Quark Mass

Name:

1. Draw your vector diagram here:

2. Fill in all the momentum values from your color plot in the table below. Add the measured value for the neutrino.

	Jet 1	Jet 2	Jet 3	Jet 4	Muon	Soft Muon	Neutrino
Momentum, Energy or Mass							

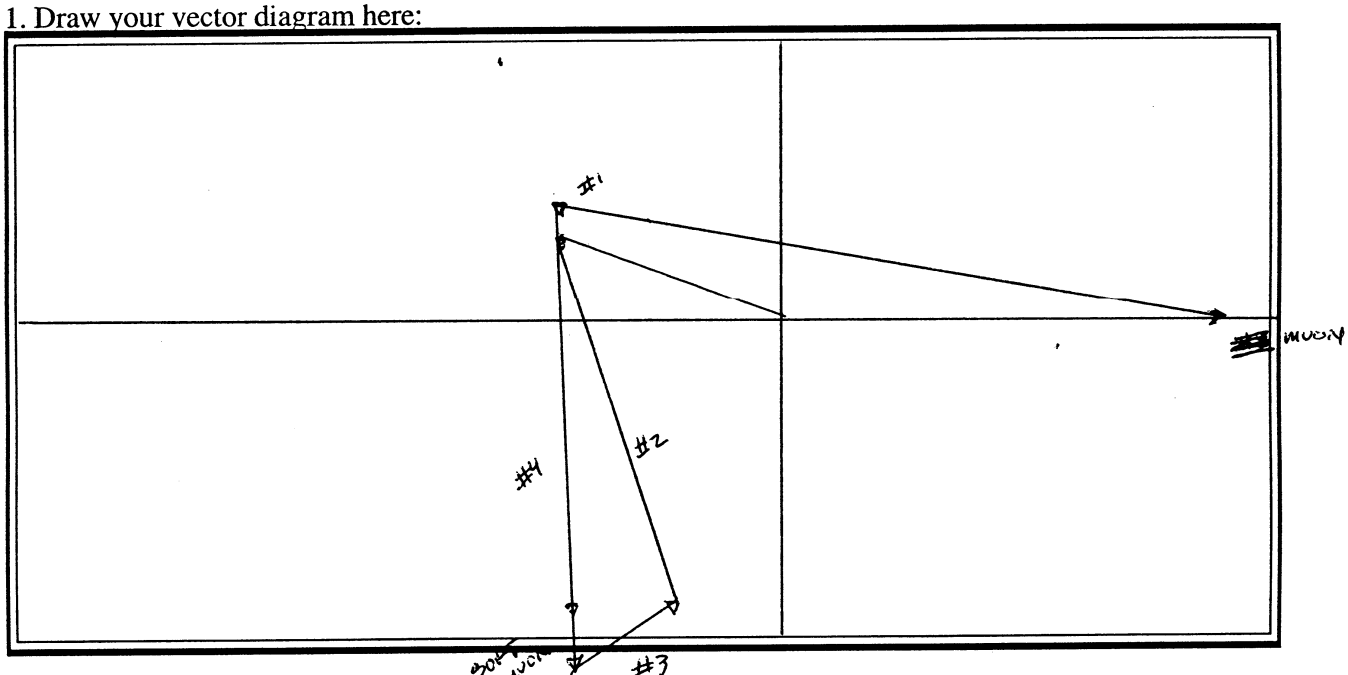
3. Based on your calculations, the mass of the top quark is :

ACTIVITY ~~#20~~ #21

Determine the Top Quark Mass

Name:

1. Draw your vector diagram here:



2. Fill in all the momentum values from your color plot in the table below. Add the measured value for the neutrino.

	Jet 1	Jet 2	Jet 3	Jet 4	Muon	Soft Muon	Neutrino
Momentum, Energy or Mass	95.5	54.8	17.0	58.6	61.2	7.3	33 ~~94.5~~

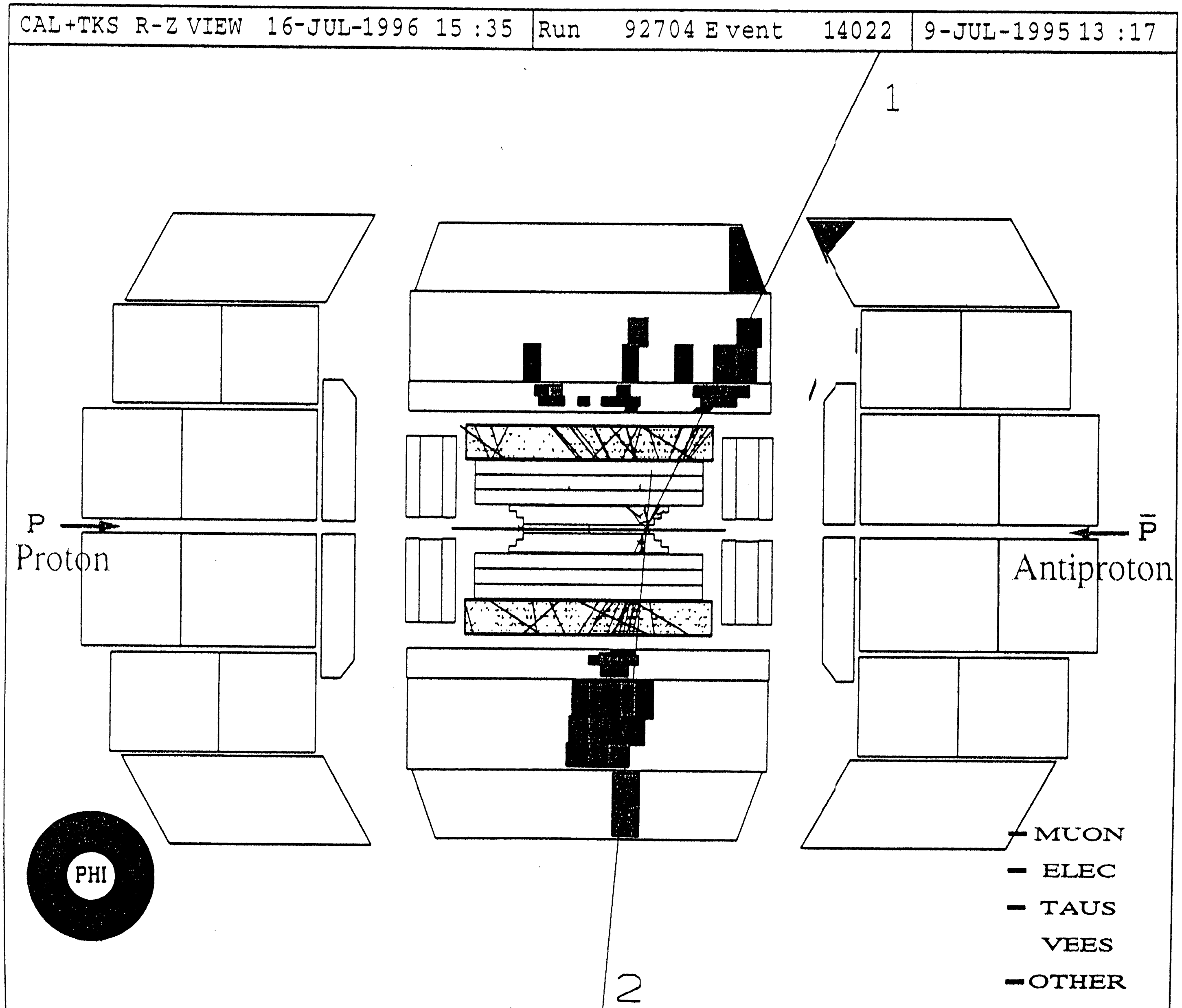
3. Based on your calculations, the mass of the top quark is :

#1	95.5
#2	54.8
#3	17.0
#4	58.6
MUON	61.2
SOFT MUON	7.3
NEUTRINO	33

327.4 ÷ 2 = 163.7

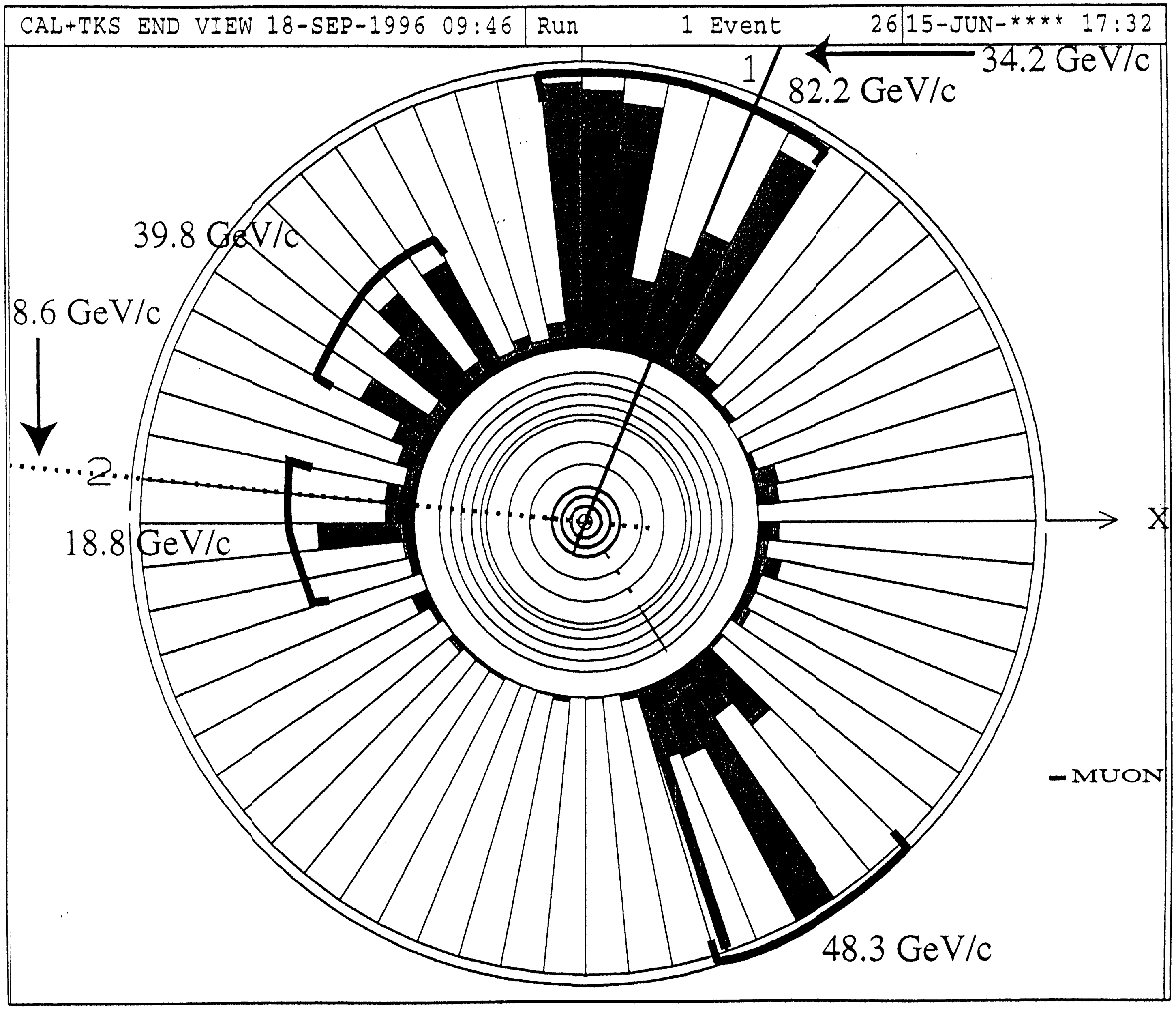
QN-112

D-Zero Detector at Fermi National Accelerator Laboratory - Side View



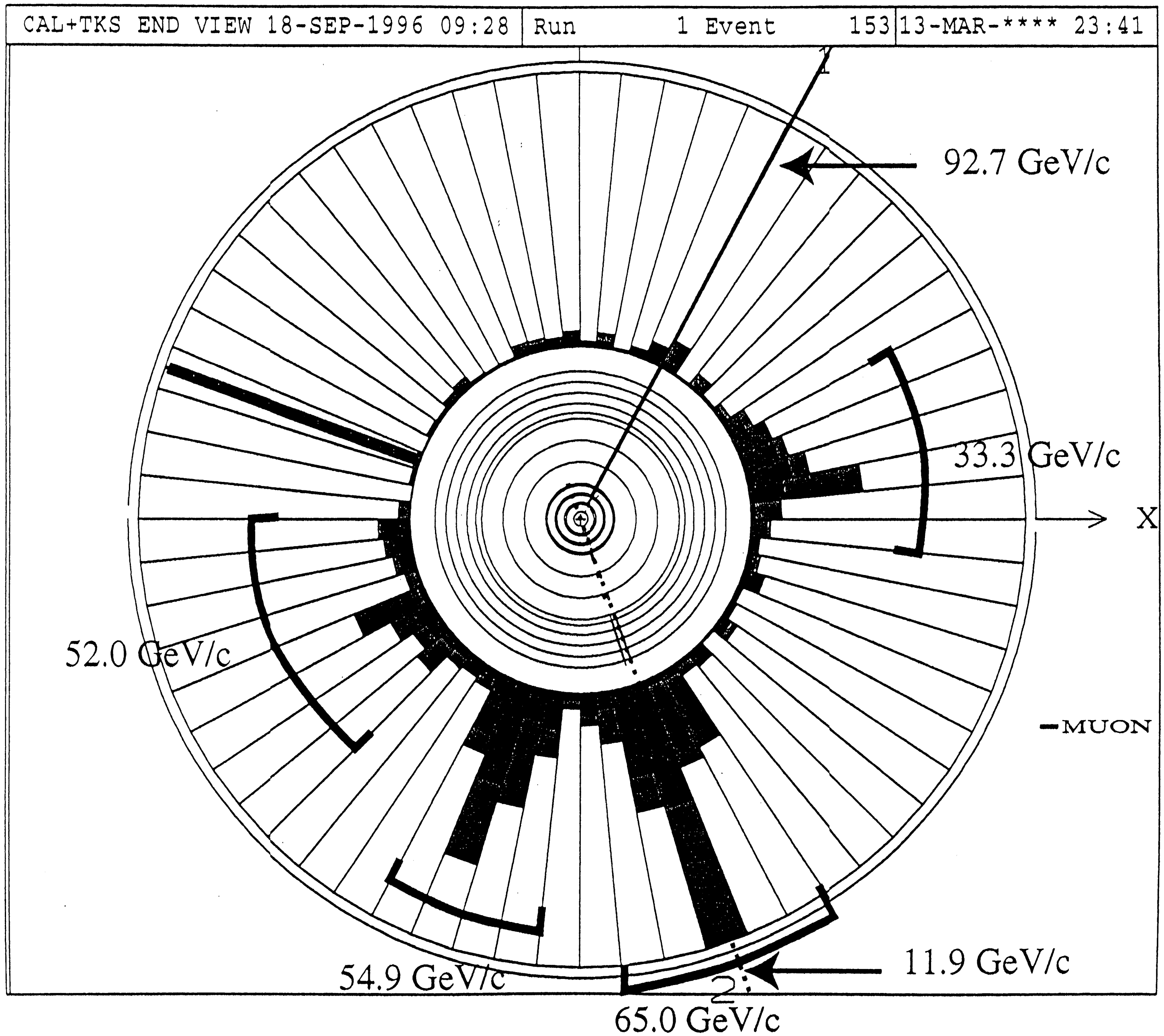
QN-113

D-Zero Detector at Fermi Na..onal Accelerator Laboratory



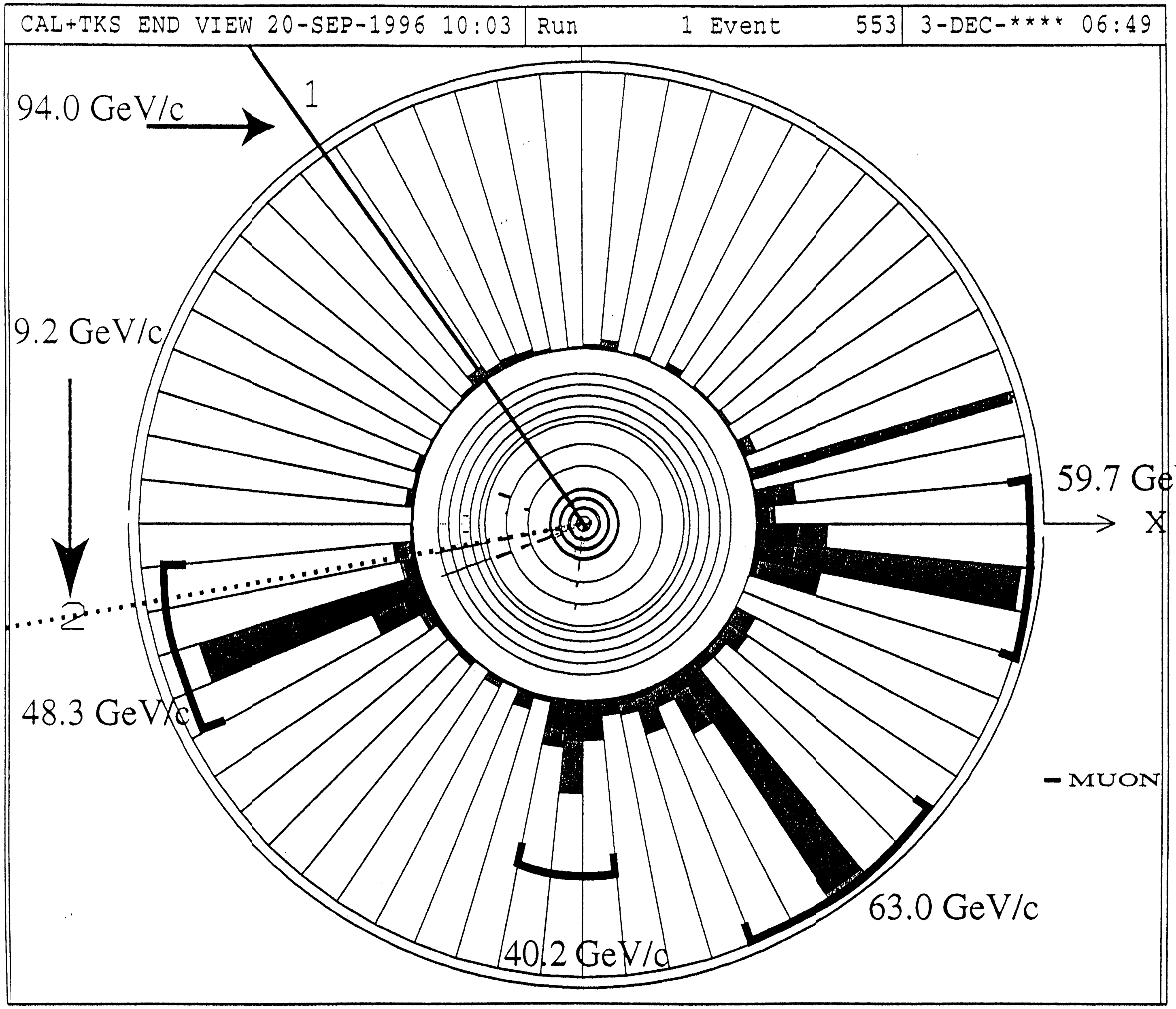
ØN-114

D-Zero Detector at Fermi National Accelerator Laboratory



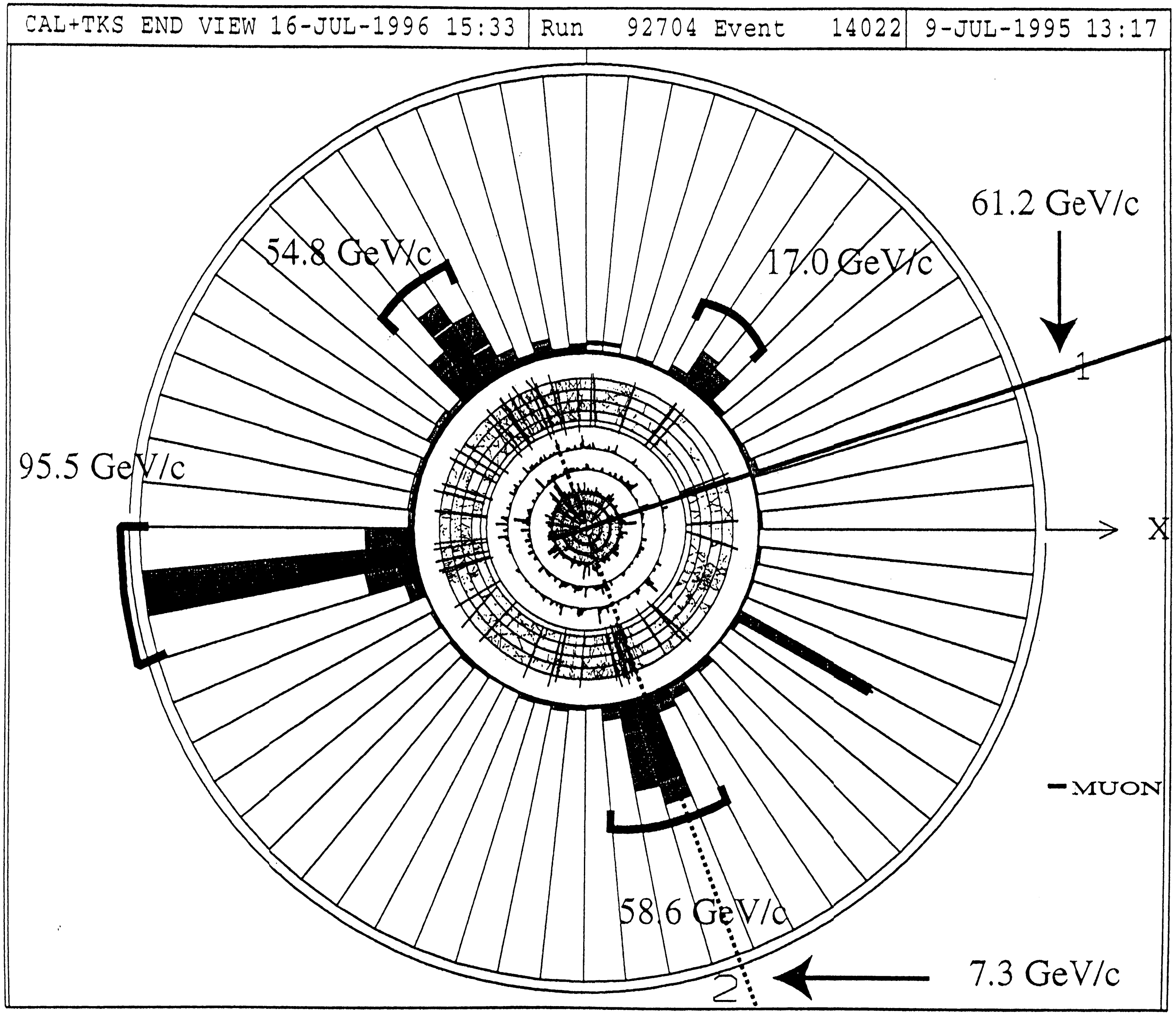
QN-115

D-Zero Detector at Fermi National Accelerator Laboratory



QN-116

D-Zero Detector at Fermi N .onal Accelerator Laboratory

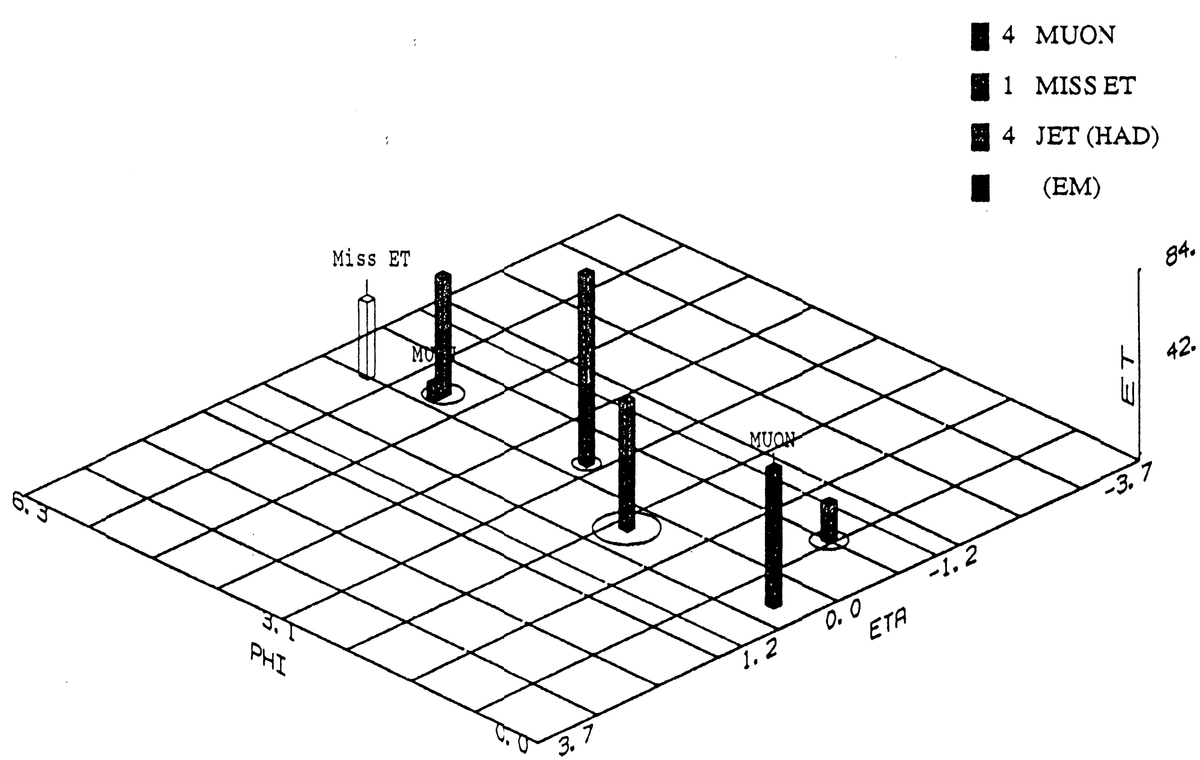


QN-117

D-Zero Detector at Fermi Nat' ıal Accelerator Laboratory

Lego Plot

DST LEGO 16-JUL-1996 15:32	Run 92704 Event 14022	9-JUL-1995 13:17



ET DST ETA-PHI

ON - 118