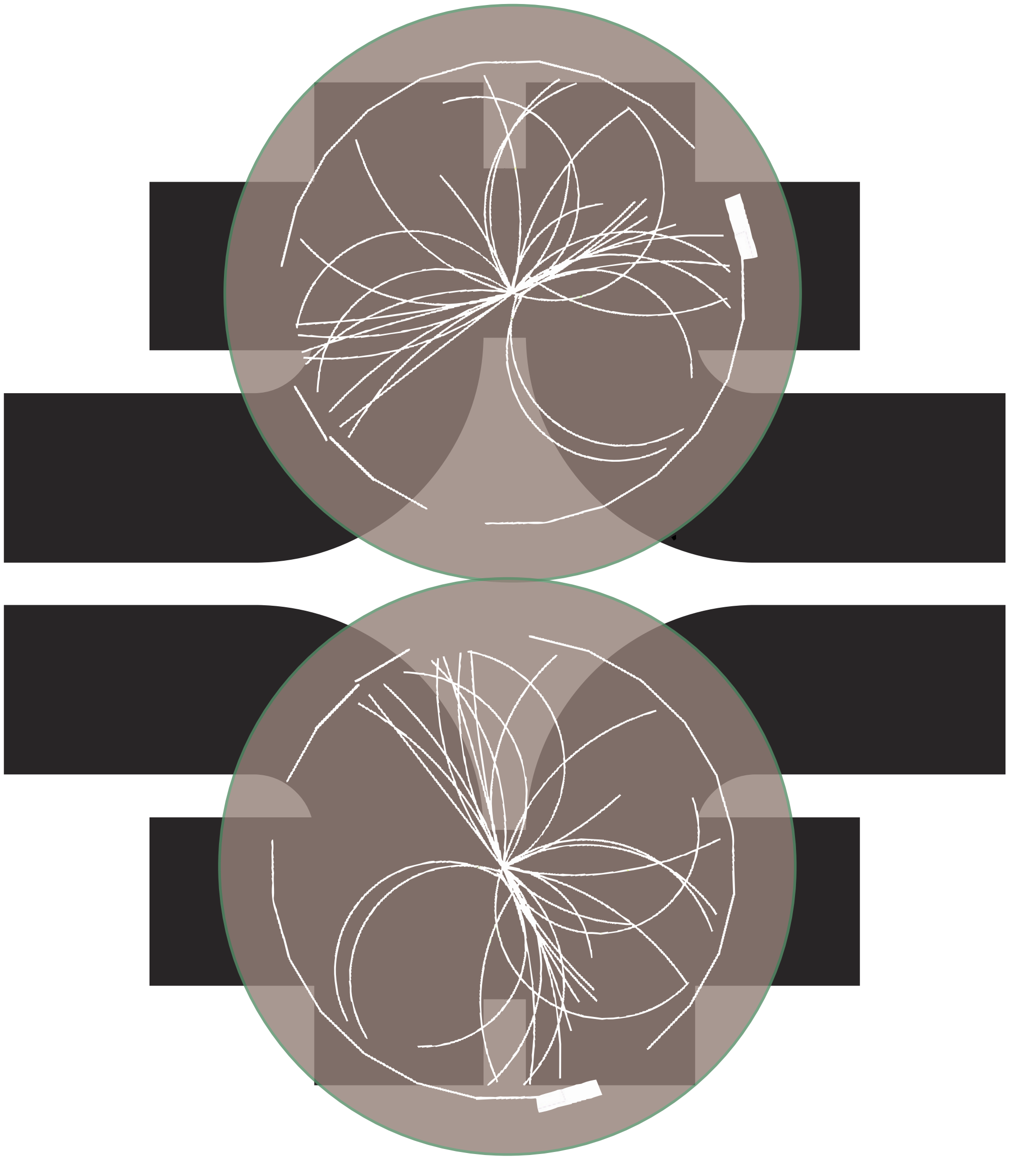
Topics in Modern Physics

Teacher Resource Materials



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Topics in Modern Physics

Teacher Resource Materials

Elementary Particles

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LEON M. LEDERMAN

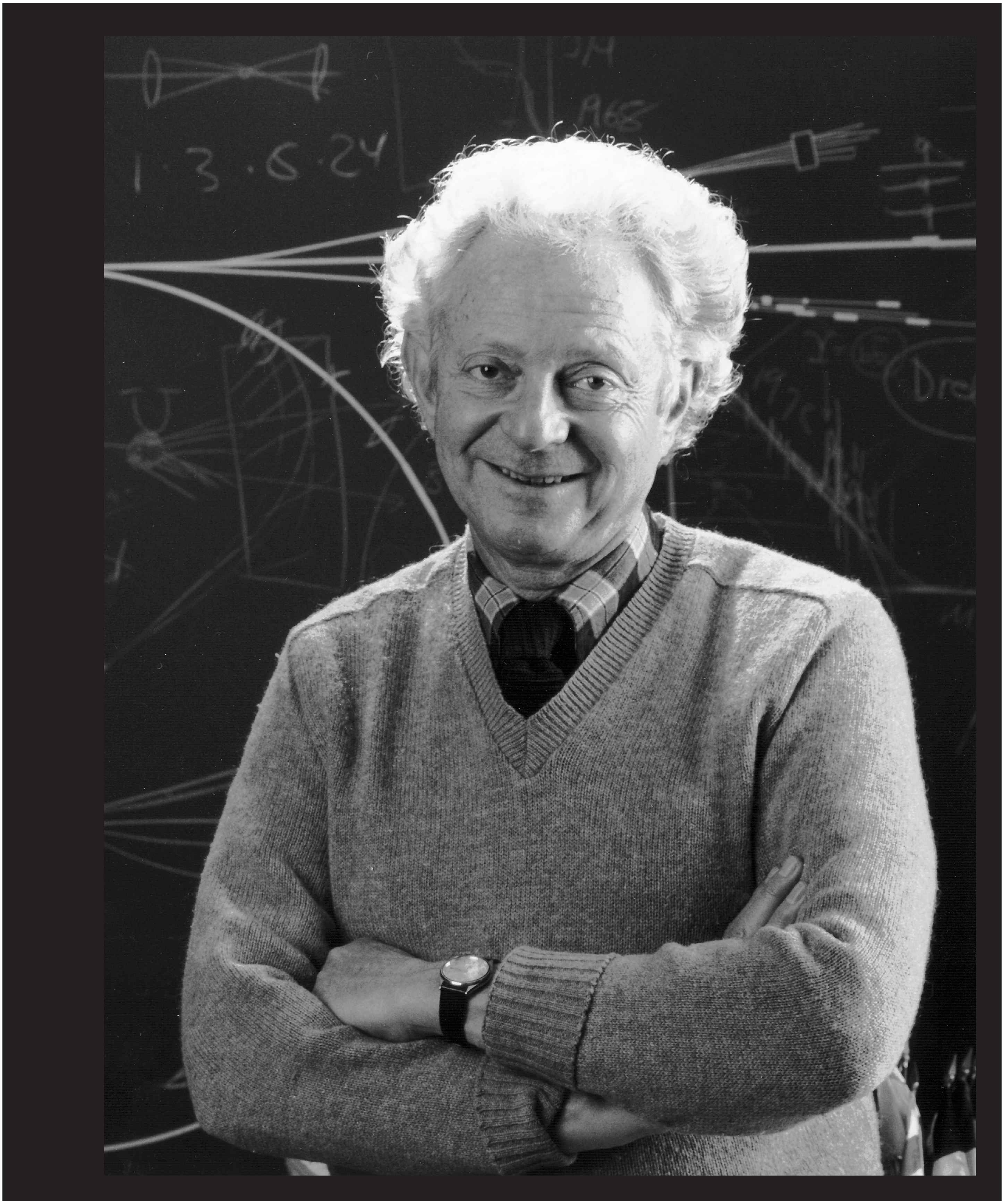
Leon M. Lederman, internationally known specialist in high-energy physics, is the director emeritus of Fermi National Accelerator Laboratory in Batavia, Illinois, and was the Eugene Higgins Professor at Columbia University. He has been associated with Columbia as a student and faculty member for more than thirty years, and he was director of Nevis Laboratories in Irvington, which was the Columbia physics department center for experimental research in high-energy physics from 1961 until 1979. With colleagues and students from Nevis, he has led an intensive and wide-ranging series of experiments which have provided major advances in the understanding of weak interactions. His research was based on accelerators at Nevis, Brookhaven, CERN, Berkeley, Rutherford, Cornell and Fermilab. His publication list runs to 200 papers. Lederman was the director of Fermi National Accelerator Laboratory from 1979 until 1989.

Lederman is a member of the National Academy of Sciences and has received numerous awards including the National Medal of Science (1965), the Elliot Cresson Medal of the Franklin Institute (1976), the Wolf Prize in Physics (1982), and the Nobel Prize in Physics (1988). He has served as founding member of the High-Energy Physics Advisory Panel and the International Committee for Future Accelerators.

LEON LEDERMAN ON SCIENCE EDUCATION

"I do not believe there is anything more important to the future of the nation than a population that is more science 'savvy' than we are now. From global climate change to genetic manipulation to the neurosciences' progress on the working of human minds, we have issues which have political, social and economic consequences of vast implications. For this we need science education K-100!"

August 1996


1 · 3 · 6 · 24
1968

INTRODUCTION

Before you is a set of resource materials that we hope will have a positive effect on modem physics education in the introductory physics classroom. The book is arranged with teacher materials accompanying each activity.

There are three major sections in this book.

Part I contains graphics that might be helpful to those teachers who choose to introduce certain topics to their students.

Part II contains activities that are fairly short in duration that could be used in a wide variety of ways.

Part III contains a very thorough class activity that would be appropriate in an involved treatment of particle physics.

After these sections is a resource page containing links to further resource materials that are available on the Web.

This book was formatted so that teachers can easily select and reproduce materials. The blank pages you will see throughout the document were placed to make it convenient to print a double-sided copy. Permission is granted to print and copy for non-profit purposes all materials in this book which have not been copyrighted elsewhere. Some teachers will choose to rearrange the various book sections. This book was also designed to be flexible in that way.

From 1996 Revision:

"Special thanks must be given to several parties who have been instrumental in helping to make this project a reality. Thanks go to the National Science Foundation, the Department of Energy Office of Research and Development, Fermi National Accelerator Laboratory, and the Friends of Fermilab. The encouragement and support of Marjorie Bardeen and Stanka Jovanovic are greatly appreciated. We thank former director Dr. Leon Lederman, present director Dr. John Peoples and the physicists and staff at Fermilab for their professional and technical assistance. Finally, thanks to the participants in the Conference on Teaching Modem Physics (see the list in Part III) for their ideas and inspiration and especially to the contributors whose work appears in this resource."

William Conway
Robert Grimm
Ward Haselhorst
JoAnn Johnson
Patrick LaMaster
James Ruebush
Walter Schearer
Brian Wegley

August 1996

		Matter		
		I	II	III
Quarks		Up u + 2/3 r, g, b ~3	Charm c + 2/3 r, g, b ~1,250	Top t + 2/3 r, g, b ~173,000
		Down d - 1/3 r, g, b ~6.5	Strange s - 1/3 r, g, b ~115	Bottom b - 1/3 r, g, b ~4,250
Leptons		Electron e^- -1 0.511	Muon μ -1 106	Tau τ -1 1,777
		Electron neutrino ν_e 0 < 0.000002	Muon neutrino ν_μ 0 < 0.000002	Tau neutrino ν_τ 0 < 0.000002

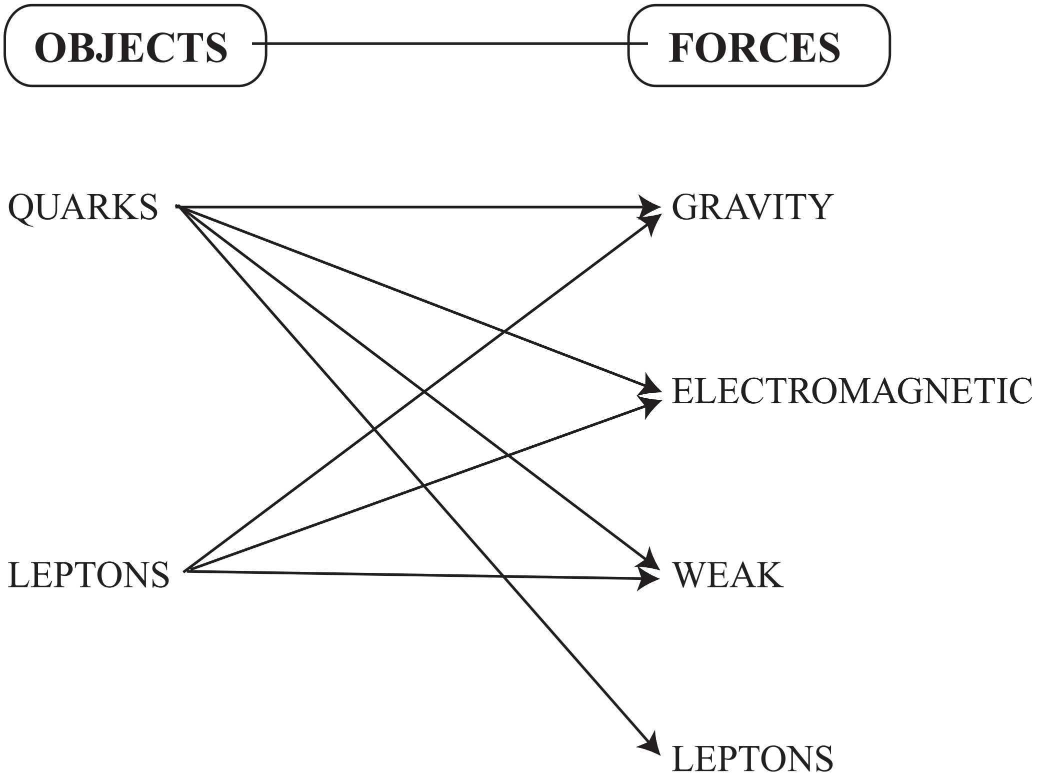
		Antimatter		
		I	II	III
Antiquarks		Antiup $\bar{u}$ - 2/3 c, m, y ~3	Anticharm $\bar{c}$ - 2/3 c, m, y ~1,250	Antitop $\bar{t}$ - 2/3 c, m, y ~173,000
		Antidown $\bar{d}$ + 1/3 c, m, y ~6.5	Antistrange $\bar{s}$ + 1/3 c, m, y ~115	Antibottom $\bar{b}$ + 1/3 c, m, y ~4,250
Antileptons		Positron e^+ +1 0.511	Antimuon $\bar{\mu}$ +1 106	Antitau $\bar{\tau}$ +1 1,777
		Electron antineutrino $\bar{\nu}_e$ 0 < 0.000002	Muon antineutrino $\bar{\nu}_\mu$ 0 < 0.000002	Tau antineutrino $\bar{\nu}_\tau$ 0 < 0.000002

Gauge Bosons	Force	Force Carrier	Rest Mass (GeV/c^2)	Charge	Relative Strength	Range (cm)	Spin	Color
	Strong	Gluons	0	0	1	$< 10^{-13}$	1	Yes
	Weak	W^+	80.4	+1	10^{-13}	$< 10^{-16}$	1	Neutral
		Z^0	91.2	0			1	
		W^-	80.4	-1			1	
	Electromagnetic	Photons	0	0	10^{-2}	Infinite	1	Neutral
	Gravitational	Gravitons	0	0	10^{-38}	Infinite	2	Neutral

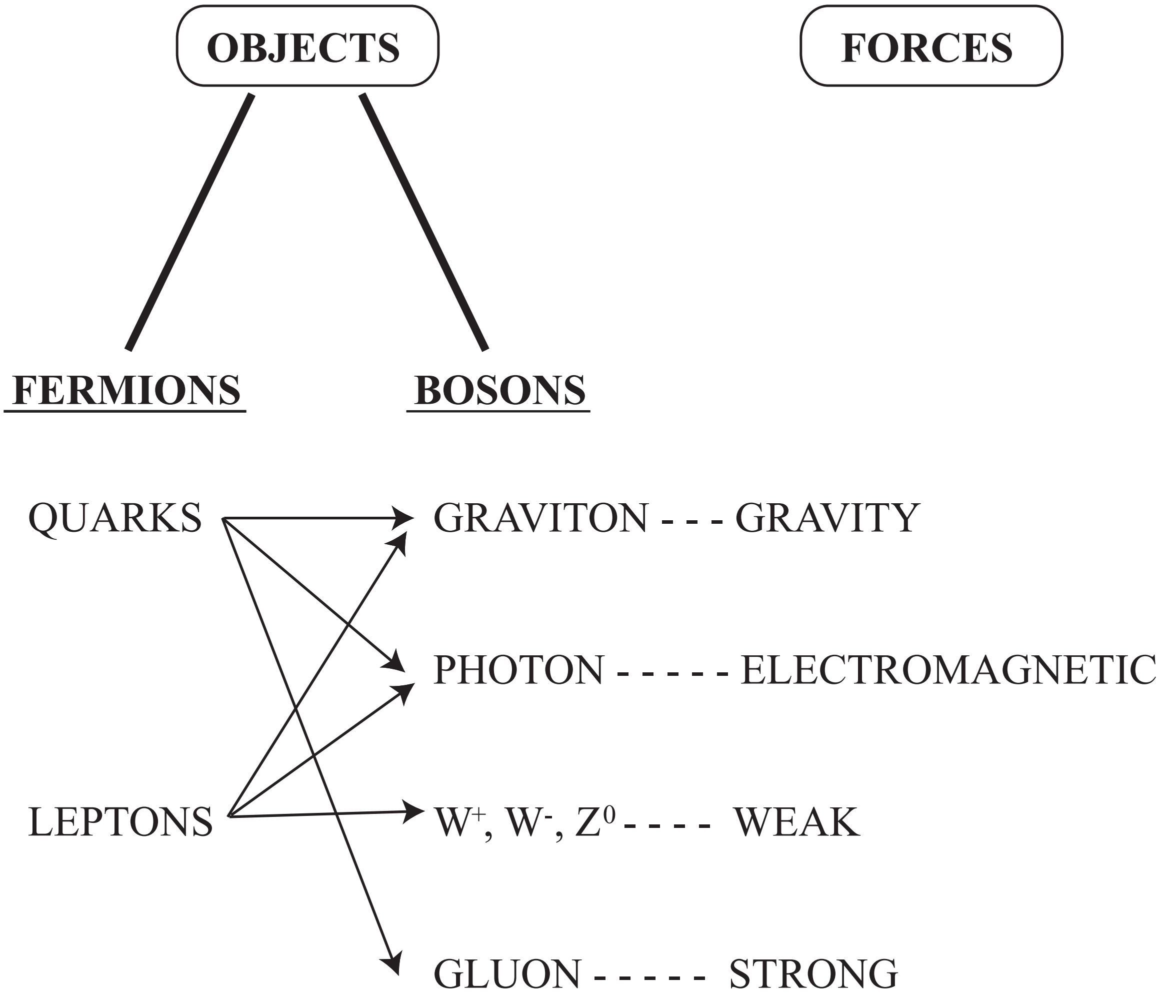
Legend

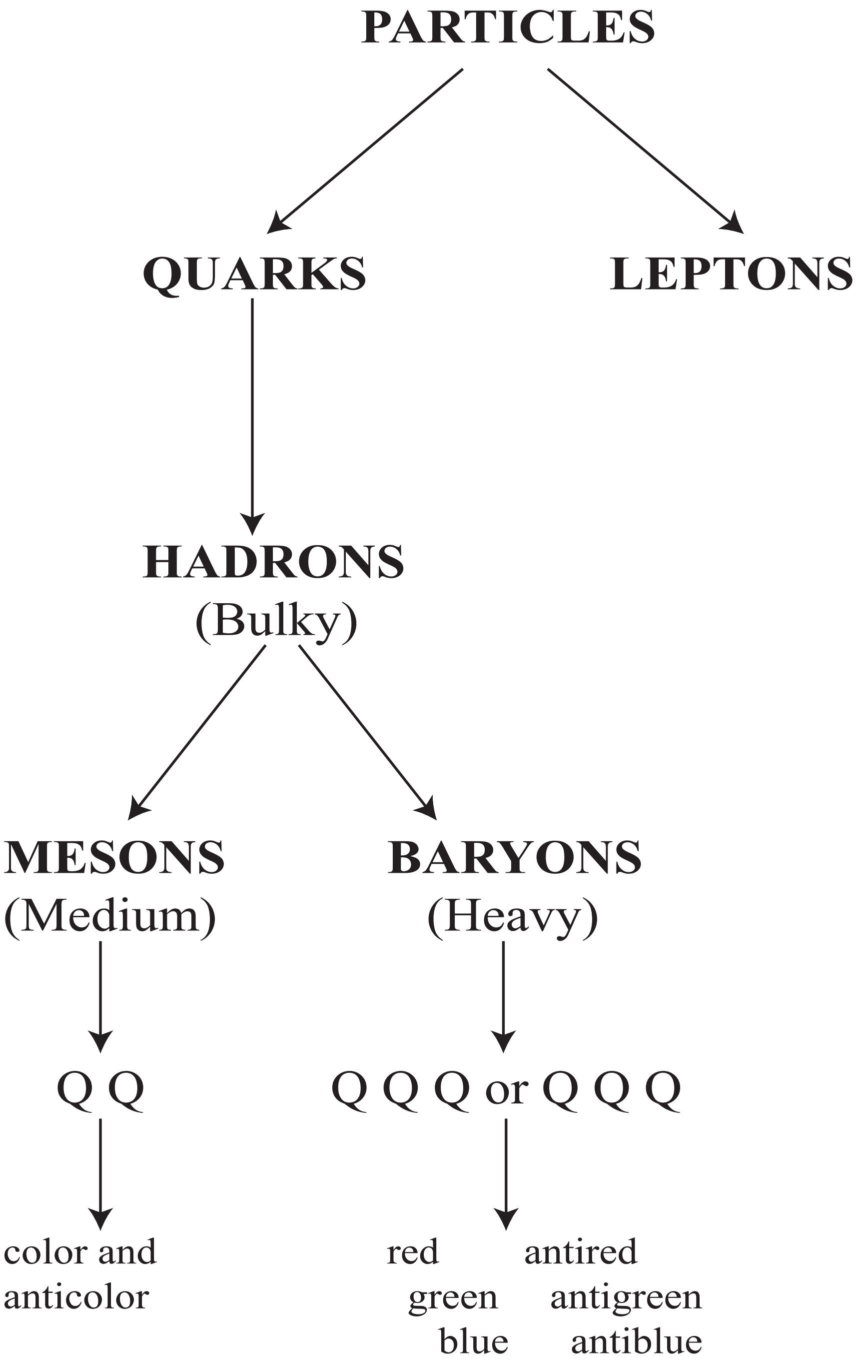
	I		← Generation
Name →	Up	+2/3	← Charge
		r, g, b	← Color
Symbol →	u	~3	← Rest Mass (MeV/c^2)

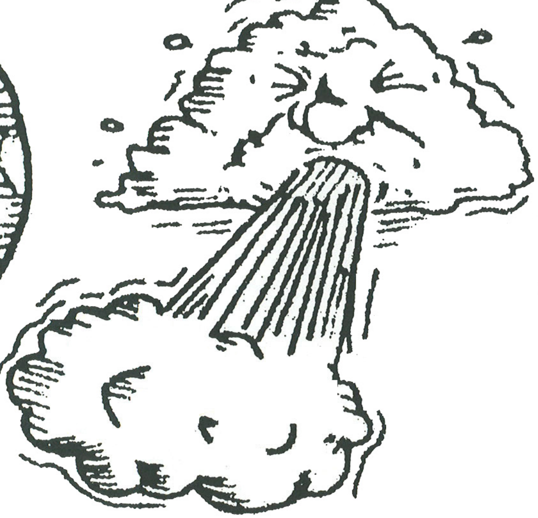
THE STANDARD MODEL

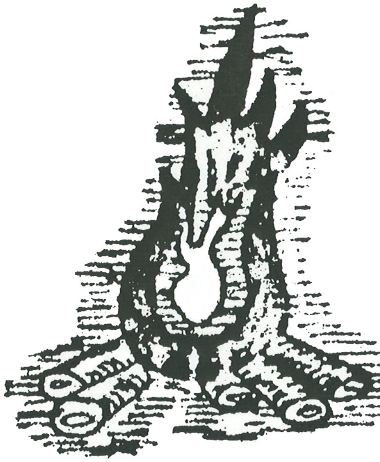


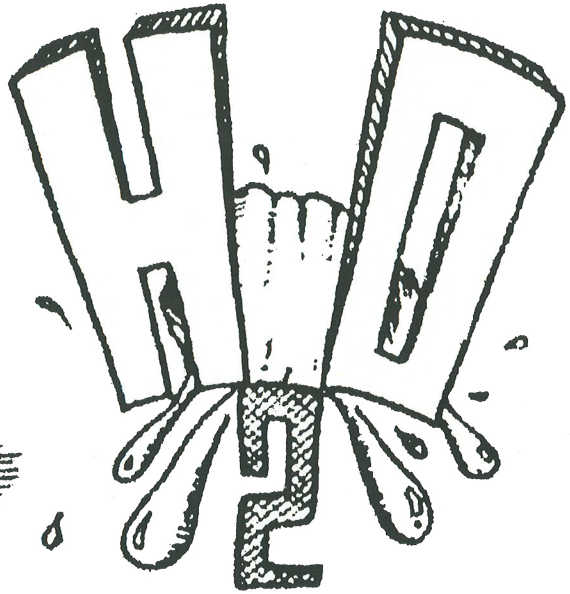
THE STANDARD MODEL

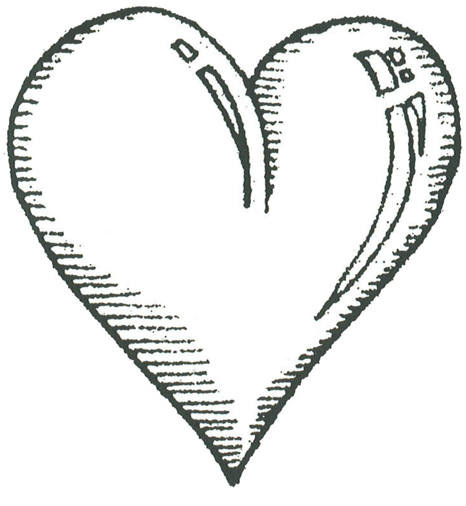



PARTICLES
QUARKS
LEPTONS
HADRONS
(Bulky)
MESONS
(Medium)
BARYONS
(Heavy)
Q Q
Q Q Q or Q Q Q
color and
anticolor
red
antired
green
antigreen
blue
antiblue






H2O



Teacher Notes

An Explanation of Graphics

The previous five pages represent several ideas that are easily presented to students as an introduction to particle physics. The pages may be used as the teacher sees fit and are designed in particular to be useful overheads. They are meant to allow the teacher a very free hand in explaining some of the basics of subnucleon physics.

Some notes on each of the pages follows.

Graphic One - Page 5 The Standard Model Chart

This chart lists the major players in the Standard Model. The six quarks that make up our world are listed under the heading “Matter.” A similar listing for the “Antimatter” particles completes the major portion of the chart. These particles are only found in groups in nature.

Below the quarks, the lighter particles, or leptons, are listed. These particles are found by themselves in nature.

Gauge bosons, or those particles that are responsible for carrying the basic forces of nature, are listed lower on the chart.

A great deal of information is included in this chart. The entire chart will make sense to one who completes the activity later in this book.

Graphic Two - Page 6 Objects and Forces Chart

This chart shows the connections between objects or particles and the forces that exist in nature. An arrow indicates that a particular particle responds to a particular force.

Graphic Three - Page 7 Objects, Bosons and Forces Chart

This chart also shows the connections between objects or particles and the forces that exist in nature as well as the bosons that carry the forces. An arrow indicates that a particular particle responds to a particular force utilizing the bosons shown.

Graphic Four - Page 8 Particle Classification Chart

This chart shows the formation of various classifications of particles. The chart shows how quarks combine to create other classifications of particles. Notice that leptons are stable by themselves.

Graphic Five - Page 9 The First Periodic Chart

This whimsicle chart shows the “Earth, Air, Fire and Water” periodic chart first thought to be complete by the ancients. These things were thought to be unbreakable. Of course, anyone who thought that was the complete list had their heart broken with the discovery of elements, protons or any other intermediate steps or later steps that have been taken by scientists over the years.

Teacher Notes

HOW DOES THE UNIVERSE WORK?

A PUZZLE ANALOGY

Introduction: The ability to see relationships and patterns in nature and to develop these into theories is a necessary skill of the particle physicist. Using experimental evidence, or the lack thereof, the physicist can develop theories to answer the basic question, "How does the universe work?" To answer that question, students need to answer two other questions.

1. **What are the basic objects?**

2. **What are the basic forces?**

In order to understand the reasoning by which physicists begin to determine the answers to these questions, the puzzle on the following page is presented. The puzzle uses the analogy of the "observed" and "not observed" as seen in particle interactions. The puzzle presents the same type of data to the student. However, in the puzzle the questions become:

1. **What are the shapes (basic objects) from which the observed figures are constructed?**

2. **What are the rules for connecting (basic forces) the shapes**?

The student now is free to study both the "observed" and "not observed" figures in an attempt to answer the two questions. Ask students to support their theories with examples from both the "observed" and "not observed" areas. Can their shapes be further reduced to more basic shapes? Once students feel confident about the answer to question 1, they can proceed with the development of rules for question 2. Remind students that the rules must explain both the "observed" and "not observed" figures. It is these connecting rules which lead to some figures being observed while others are not observed. As much can be learned from considering what is not observed as from what is observed.

Discuss possible theories with the entire group of students. Is there more than one theory? Which is the best theory? Why?

One possible solution is given on the next page. The basic shapes are triangles and squares. There are two connection rules. Triangles must connect on one, and only one, side. Squares must be connected on two, and only two, sides.

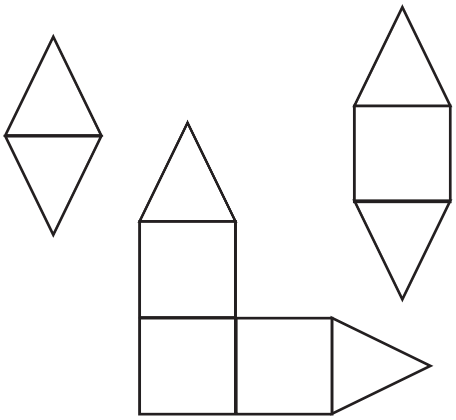
At this point it might be interesting to ask students to develop some additional "observable" figures, which follow the answers to the two basic questions. This is similar to the physicist looking for a previously unseen particle in an attempt to verify a theory.

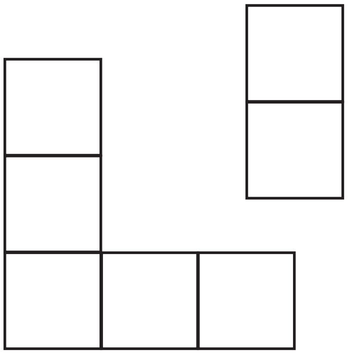
Puzzle adapted from Helen Quinn, "Of Quarks, Antiquarks, and Glue," *The Stanford Magazine.*

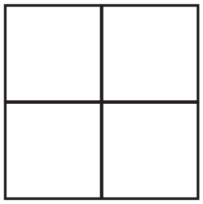
POSSIBLE PUZZLE SOLUTION

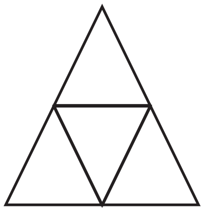
OBSERVED

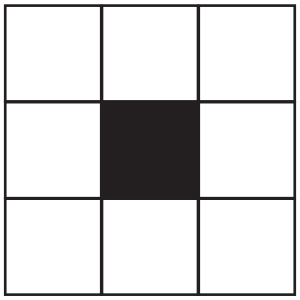
NOT OBSERVED

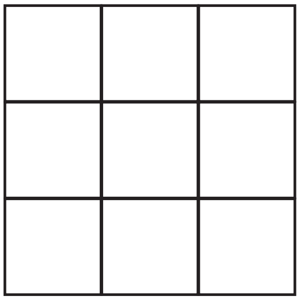


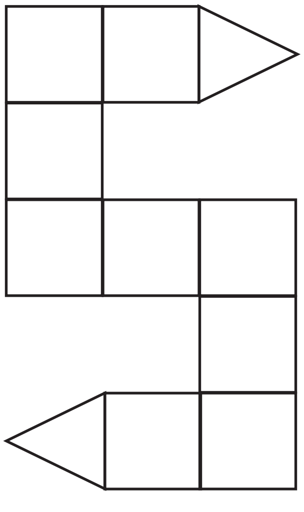


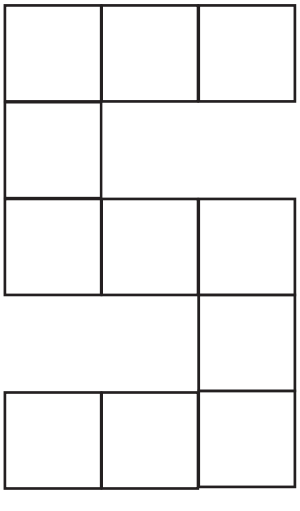












Student Worksheet

HOW DOES THE UNIVERSE WORK?

A PUZZLE ANALOGY

Introduction: The ability to see relationships and patterns in nature and to develop these into theories is a necessary skill of the particle physicist. Using experimental evidence, or the lack thereof, the physicist can develop theories to answer the basic question, "How does the universe work?" To answer that question, you need to answer two other questions.

1. **What are the basic objects?**

2. **What are the basic forces?**

Procedure: In order to understand the reasoning by which physicists begin to determine the answers to these questions, the puzzle on the following page is presented. The puzzle uses the analogy of the "observed" and "not observed" as seen in particle interactions. Your job is to determine the "rules of the universe" through an analogy of finding the rules for this puzzle.

The figures on the left of the page are observed, while the figures on the right have not been observed. The puzzle involves these two questions:

1. **What are the shapes (basic objects) from which the observed figures are constructed?**

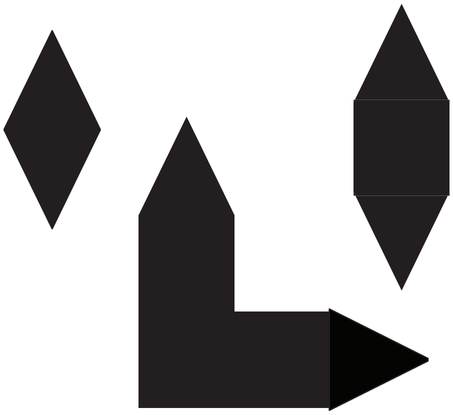
2. **What are the rules for connecting (basic forces) the shapes?**

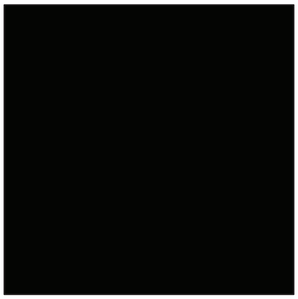
The same two shapes can be used to form both the "observed" and "not observed" figures. It is the connecting rules which lead to some figures being observed and others not being observed. Remember that you can learn as much from considering what is not observed (right column) as from what is observed (left column).

HOW DOES THE UNIVERSE WORK?

OBSERVED

NOT OBSERVED





Teacher Notes

$E = mc^2$ Student Activity

Introduction: Einstein's celebrated equation is verified daily in particle accelerators around the world. Physicists go about the business of converting energy into mass almost as commonly as high school students flip through channels on the television. Still, this revolutionary idea is not often treated as a classroom activity simply because it seems to be so difficult to convey in a "hands-on" manner. We are able to do just that using a special event from Fermilab's DZero detector. Most events analyzed by the physicists are more complex than this event nature serendipitiously supplied.

The idea that mass and energy are interchangeable is essential to those interested in understanding how two top quarks (actually a top and an antitop) are created from the collision of two protons (actually a proton and an antiproton). The experiment might be thought of as the collision of two ping-pong balls resulting in the production of two ball bearings of the same size but considerably greater mass. The highly energetic protons collide to create top quarks of about 180 times the mass of the protons. The energy of the less massive protons is converted into the huge mass of the resultant top quarks.

Perhaps the conversion between energy and mass makes more sense when one considers that the proton and antiproton pair were traveling so close to the speed of light that together they had about 1.8×10^{12} eV worth of energy to work with. This energy then becomes the mass of the newly discovered quarks.

Scientists measure the energy of these subatomic particles in units of electron volts. Electron volts are units of energy just as Joules are units of energy. They measure their mass in units of electron volts/c^2, energy divided by c^2 where c = the speed of light. Here, we are talking about mass and using the fact that $E = mc^2$ to write mass in units of eV/c^2. To simplify the units, physicists use a unit called a GeV (a giga electron volt, pronounced two ways, "gee ee vv" or "jev." 1 GeV equals 10^9/eV.

Scientists at Fermilab first discovered the top quark in 1995 when they collided protons and antiprotons with energies of 900 GeV/c^2. The masses of these particles scientists measured are shown below.

Mass of Proton	9.38×10^8 eV/c^2	.938 GeV/c^2
Mass of Top Quark	1.75×10^{11} eV/c^2	175 GeV/c^2

To help the students understand this idea, this activity examines the fingerprint of a top/antitop collision that took place in the DZero detector at Fermilab on July 9, 1995. An artist's rendition of the event is available on the Web, along with all the other graphics for this activity. To view the artist's rendition, point your browser to: *http://ed.fnal.gov/samplers/hsphys/activities/top_quark_index.shtml*. Scroll down to "Other Graphics." The link to the image is available in several different formats. A smaller, black and white version is included with the student activity page.

Make an overhead of this event to show the students what the production of a top and an antitop quark might look like if one were to see it in the Fermilab accelerator. It is important to point out that the top and antitop quarks are actually very short-lived particles. They quickly decay into daughter particles and then in turn into "granddaughter" and "great granddaughter" particles. It is these offpsring that are actually detected by the scientists at Fermilab.

This event shows that the top and antitop quarks (shown as t and t-bar respectively) are never actually directly detected because they decay so rapidly into four ëletsî (large blasts of particles) and a muon (green) and a neutrino (magenta), shown in the upper right of the picture.

This may appear first to be complex, but the mass of the top is easy to calculate from a computer-generated plot of the same event taken from the DZero detector.

Teacher Primer

This activity will build on your class's understanding of vector addition and depend upon only a short particle physics explanation from the instructor. The goal of this activity is simple. Your students will determine the mass of the top quark.

Go to the website for the Calculate the Top Quark Mass activity: *http://ed.fnal.gov/samplers/hsphys/activities/top_quark_index.shtml*. Under "Data and Graphics," there are three views of one event called **Run 92704 Event 14022**. These are computer-generated pictures that represent the event discussed previously. To help visualize the event, you may wish to first look at the color plot labeled **Event 92704 14022 R-Z View**, which gives a perspective from the side of the detector. Next, look at the plot called **Event 92704 14022 End View.** Here the event is viewed in only two dimensions, as seen from the end of the detector. Finally, you may view the color plot called **Event 92704 14022 Lego**, which shows how the debris could be mapped if the **End View** were unwrapped starting at the "X" axis.

Once you are familiar with the three views, you should focus attention on the **Event 92704 14022 End View**. This view is most similar to the artist's drawing and will be the working document for this activity. Notice the four blue and red "jets," which are the four jets shown on the artist's picture of the event above. You will also notice a solid green line, which represents the muon's track. If you look closely at the jet near the bottom of the picture, you will also see a green dotted line. This is a "soft muon" that is hidden in a jet. Also notice that all of the momenta have been measured and are written on the plot.

You will also see that the computer has calculated the energy of the neutrino and drawn it on the diagram in magenta. Neutrinos are not detectable in most cases, so their existence is found by looking at the total momentum of the system in a collision, though the momenta of the particles are far from zero. The total momentum is equal to zero before and after the collision. The process of finding the missing momentum is what your students will do to determine the mass of the top quark. Notice that the momentum for this particle is not included on the picture.

Teacher Instructions for Classroom Presentation

Show the students the artist's picture of the event followed by the three color plots just mentioned. As the complexity of the event might be confusing the first time through, all of this activity will focus only on the **Event 92704 14022 End View**.

Part I: Calculations of Momenta of Products of the Collision

The momentum of each jet or particle was determined by computer and is printed on the color **End View** plots. These numbers will be used in creating a vector diagram of the debris that comes from the collision as students attempt to find the momentum of the "undetectable" neutrino.

Explain to the students that this is an exercise in momentum conservation. They are to determine the momentum of the "undetectable" neutrino by adding up the vectors with directions shown on the diagram and magnitudes indicated by the numbers listed. The result should be a value close to the same number the computer determines for each event. These values for the actual event and several computer-simulated events, each of which has an **End View** plot available at the website, are listed below for the teacher's reference.

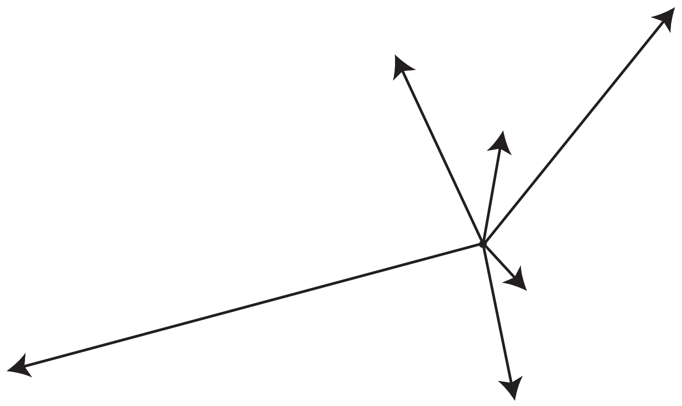
Actual Event	14022	momentum of neutrino	53.9 GeV/c
Computer-Simulated Event	26	momentum of neutrino	76.1 GeV/c
Computer-Simulated Event	153	momentum of neutrino	43.6 GeV/c
Computer-Simulated Event	553	momentum of neutrino	45.3 GeV/c

The direction of each neutrino may be verified by examining the color plots. Please be aware that the students will not all get the exact values given above nor will they get the precise directions shown on the pictures. This is due to their selection of the directions of the debris in the first place as well as effects introduced by problems similar to the one noted below [1].

Still, after vector diagrams are drawn by various groups of students, a reasonable value for the momentum of each of neutrino may be found.

An example of a possible vector diagram for event 14022 is shown below for the teacher's convenience.

Vector Diagram of Event



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[1] It is important to realize that this only works if the debris has no motion in the direction of the beams which we define as the z direction. The event takes place in a plane perpendicular to the axis of the proton and antiproton. The color plot labeled **Event 92704 14022 Lego** shows that Mother Nature was indeed kind in giving us this type of event. Notice that all of the tracks happen to lie close to the ETA = 0.0 axis. This allows us to approximate this as a two-dimensional problem. You will also see that there is some "noise" seen on the computer plot. This will adversely affect your vector diagram and represents the uncertainty that is present in any experiment.

Background Energy, Mass and Momentum Calculations for the Teacher

In order for your students to find the mass of the top quark, they need to understand that their discovery of the missing momentum of the neutrino is crucial. This value gives them all they need to find the mass of the top quark. You will need to supply them with the following information. In all honesty, much of this material is beyond the scope of high school physics, (and many college courses as well), but the leap is not so great that it cannot be done. Perhaps a bit of faith is needed here. The teacher is certainly the best judge.

A common relation in high-energy physics is the following:

$$E^2 - p^2 = m^2$$

The reason energy, momentum and mass are shown as equal is actually due to the convention of choosing a system where the speed of light, c, is set equal to one. In this case, where particles are traveling with speeds of almost c, $E = mc^2$ becomes $E = m$ and $p = mv$ becomes $p = mc$ or $p = m$. This does change scale somewhat to be sure, but it allows for a simpler conversion between energy, mass and momentum.

In our particular case, it follows that one should write energy and momentum in terms of the mass of the top quark.

$$E^2 - p^2 = (2m_t)^2$$

When one observes that the net momentum before the collision is the same as the momentum after and that value is zero, we write:

$$E^2 = (2m_t)^2$$

or, taking the square root of both sides,

$$E = 2m_t$$

Because almost all of the energy of the collision is the result of top and antitop decay, we simply add the energies of the four jets, the soft muon, the muon and the muon neutrino before dividing by the two tops (actually a top and an antitop quark) to obtain the mass of the most recently discovered quark.

Students will use the values they calculated for momentum (now as energy values) and incorporate their new value for the missing neutrino (in bold print below) before adding all the energies as scalars to find 2mt.

61.2 GeV + 7.3 GeV + 95.5 GeV + 58.6 GeV +

54.8 GeV + 17.0 GeV + **53.8 GeV** = 348.2 GeV

348.2 GeV/2 = 174.1 GeV, which is very close to the currently accepted value of about 175 GeV. As was indicated, the "missing momentum" may be found in a more careful analysis of the event as well as a better understanding of the event.

This relatively simple procedure may be repeated by your students in events generated by the Fermilab computers that were directed to simulate various collisions that would show this type of event.

Conclusion: The final result of this exercise should be that the students have gained some experience in using actual data to see how scientists analyze collisions. Further, your students will begin to understand that the latest pieces in the Standard Model puzzle have been assembled from the energy in the Fermilab collider. Mass does indeed come from energy as Einstein predicted.

Student Worksheet

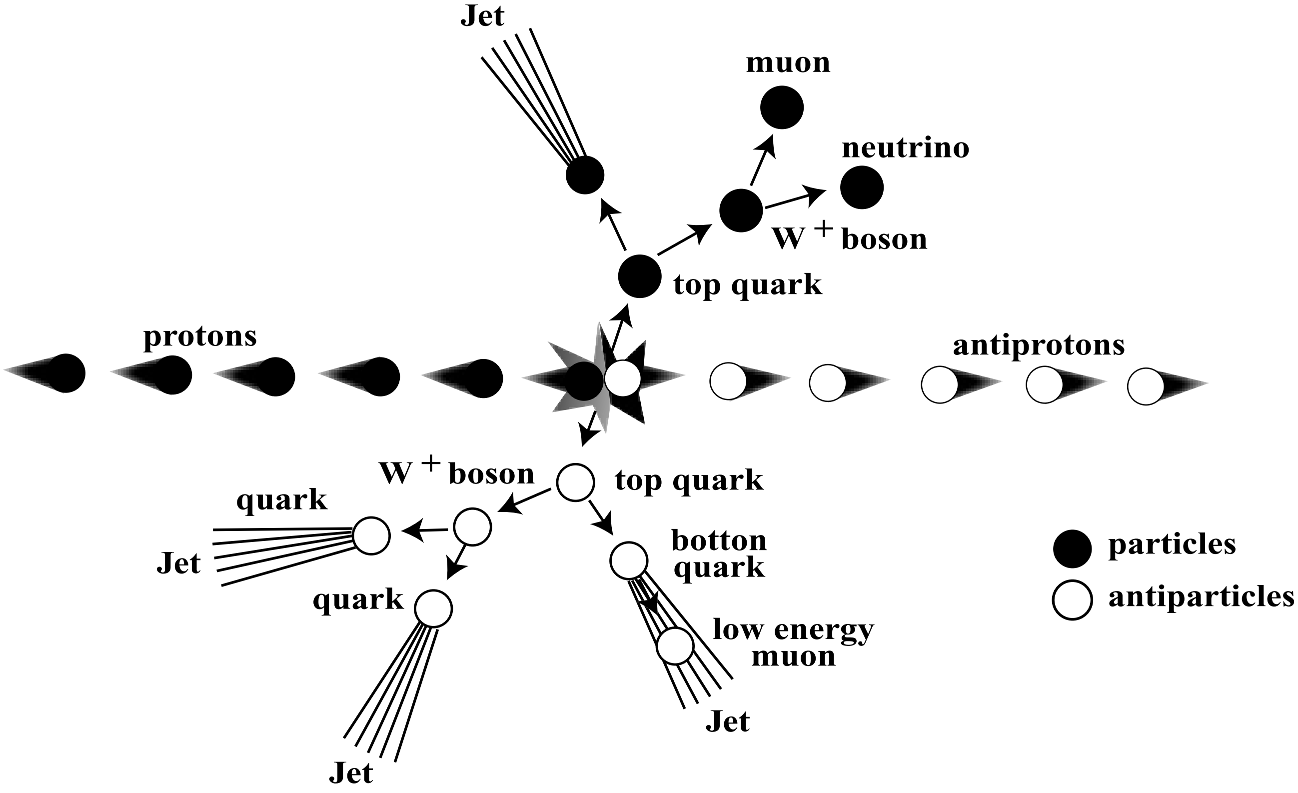
$E = mc^2$ Used in the Creation of the Most Massive Quark Yet Discovered! Analysis of DZero Data from Fermi National Accelerator Laboratory

Introduction: Today, you will use Einstein’s famous equation and actual experimental data collected in 1995 from a special event that is two-dimensional rather than three-dimensional to determine the mass of the top quark. The top quark is the most massive quark ever discovered.

Procedure - Part One: You will be given a computer-generated plot of a collision between a proton and an antiproton. You will need to determine the momentum of each bit of debris that comes from the collision. Be sure to remember that momentum has direction!

The collision may be represented in a general way as shown below. Your plot will show this “top signature” but may not show the debris going in the directions shown here.

While this event looks complex at first, it may be summarized by noting that a proton and antiproton collide to create a top-antitop pair that exists for a very short time. Almost immediately the very massive top and antitop decay into the constituents that are known as their signature. These include four “jets” (large blasts of particles) that are the result of decays of W bosons and some less massive quarks. It is important to note that one of the jets will often contain a low energy or “soft” muon. Soft muons help identify jets as bottom quark jets. In addition, a muon and a neutrino come out as debris from the collision.



A Top-Antitop Quark Event from the DZero Detector at Fermilab

You will notice that there is no information given about the neutrino except the magenta tower indicating its direction on the color plot. While scientists can predict with confidence that it comes out of the collision, it cannot be detected very easily. Still, a careful consideration of the momenta before the collision and after the collision may give you a clue about how much momentum this particle has!

Procedure - Part Two: Make a momentum vector diagram to determine the momentum of the muon neutrino. Be sure to remember that the total momentum of the system must be zero, so any "missing" momentum must belong to the neutrino.

Question 1. What is the momentum of the missing neutrino?

Procedure - Part Three: It turns out that if you are careful about your choice of units, it is possible to equate momentum and energy in a way that is similar to the way mass and energy are related. Specifically, it may be shown that the momentum you measured above is the same numerical value as the energy or mass of the particle. In other words,

$$E \text{ (in GeV)} = p \text{ (in GeV/c)} = m \text{ (in GeV/}c^2\text{)}$$

This shows then that the total energy that came from the **two** top quarks that were formed is equal to the *numerical sum* of all the momenta discovered in the collision.

Fill in all the momentum values from your color plot in the table below. Finally, add the measured value for the neutrino that you just determined at the end of this table.

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

Question 2. What do you determine the mass of the top quark to be?

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 <u>multiples of three</u> 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
<u>16</u>	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 it 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.

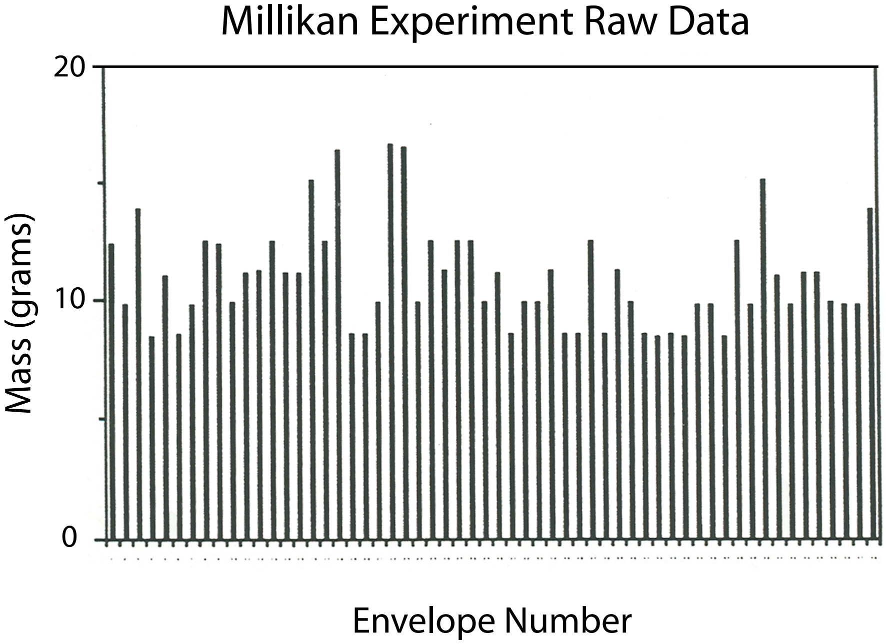
Some helpful data and graphs follow:

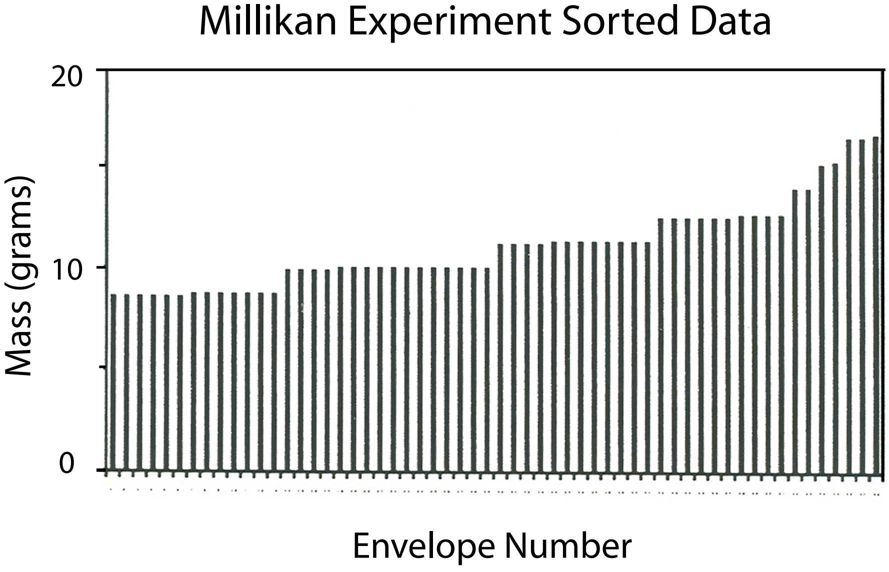
MILLIKAN RAW DATA

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

MILLIKAN 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	1 00	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


Millikan Experiment Raw Data
20
10
0
Mass (grams)
Envelope Number


Millikan Experiment Sorted Data
20
10
0
Mass (grams)
Envelope Number

Student Worksheet

Fundamental Units

Introduction: 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.

Procedure:

1. You will be given a number of envelopes. **Do <u>not</u> open the envelopes!** Measure the mass of each envelope to the nearest 0.1 gram and record the mass below and on the board.

2. Record the masses of all the envelopes from your class.

3. List all of the envelope masses in ascending order. Envelope #1 will be the lightest.

4. Construct a bar graph of envelope # (horizontal axis) versus envelope mass.

5. What do you notice about the envelope masses on the finished graph?

6. List the "average" mass for each of the envelope "types."

7. What is the mass difference between the successive averages found in step 6?

8. What does this difference represent? Explain.

Teacher Notes

A Laboratory Exercise in Indirect Measurement

Introduction: Modern physics depends heavily on indirectly determining physical properties of objects. The following activity may help convince students that indirect determinations are important methods of obtaining accurate information. This exercise can be used as an introduction to a discussion of the Rutherford model of the atom. This activity simulates an experiment in particle physics where a target material would be bombarded by high-speed particles and the collisions studied. It gives students a chance to use a “Monte Carlo” technique.

Problem: Determine the radius of a single target circle indirectly.

Procedure: Use copies of either of the circle sets on the following pages. Have students place the circled paper on the floor, face down over a sheet of carbon paper. Working in pairs, have students drop marbles or ball bearings from head height so that they hit the paper within the marked boundaries. The sphere must be caught after the first bounce. Repeat this at least 100 times. It may be more convenient to drop the marbles from just above the paper; however, one should then take care to distribute the hits as randomiy as possible over the entire target area.

Analysis: Have students count the total number of dots on the paper within the marked rectangular boundaries (hits) as well as the number of dots which are completely within a circle (circle hits). Determine the total area of the paper within the marked boundaries (rectangular area), and count the total number of circles on the paper. If we have uniform circles and a random distribution of hits, then we can assume:

$$\frac{\text{circle hits}}{\text{hits}} = \frac{\text{area of all circles}}{\text{rectangular area}}$$

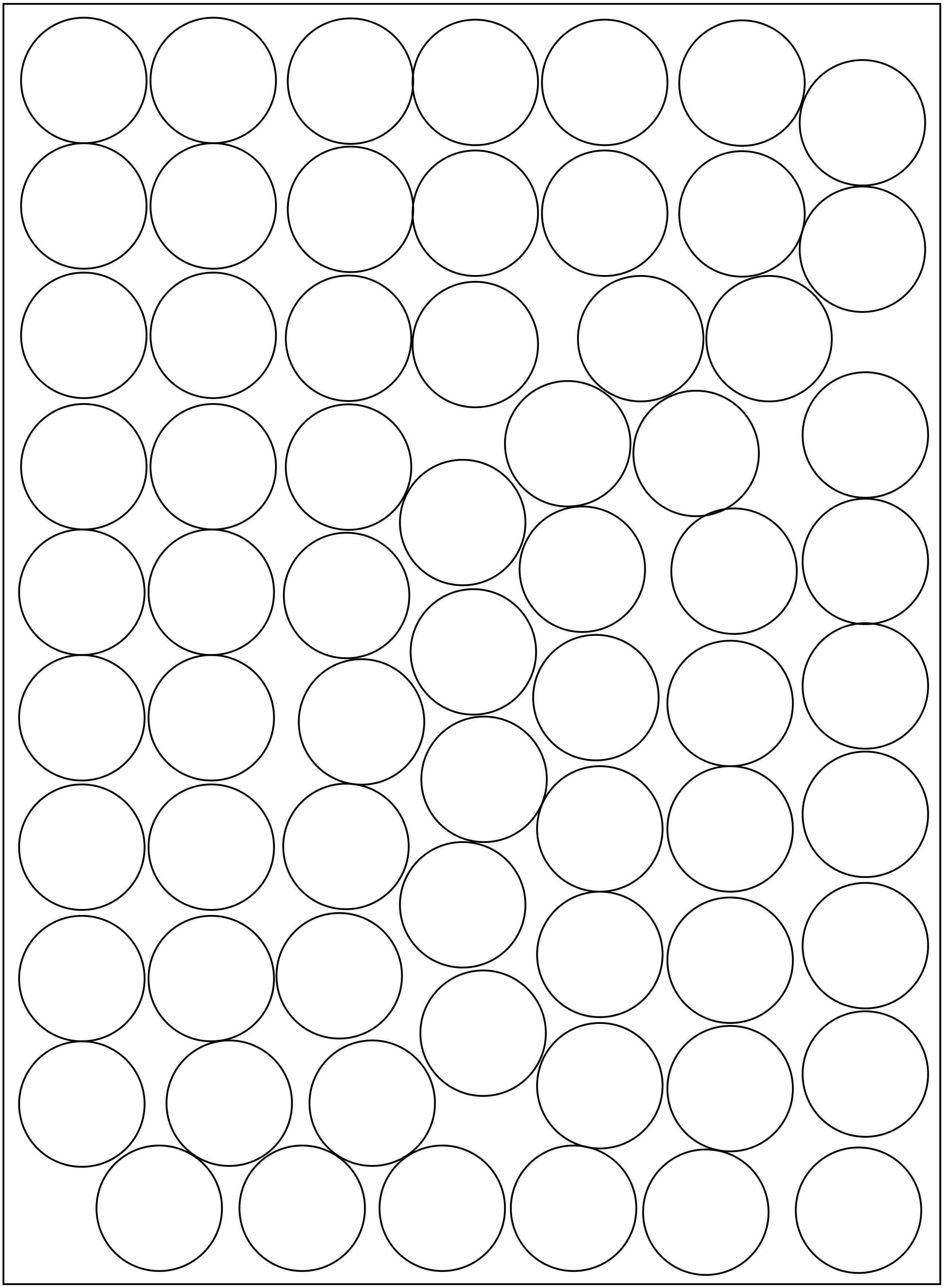
Therefore you can calculate:

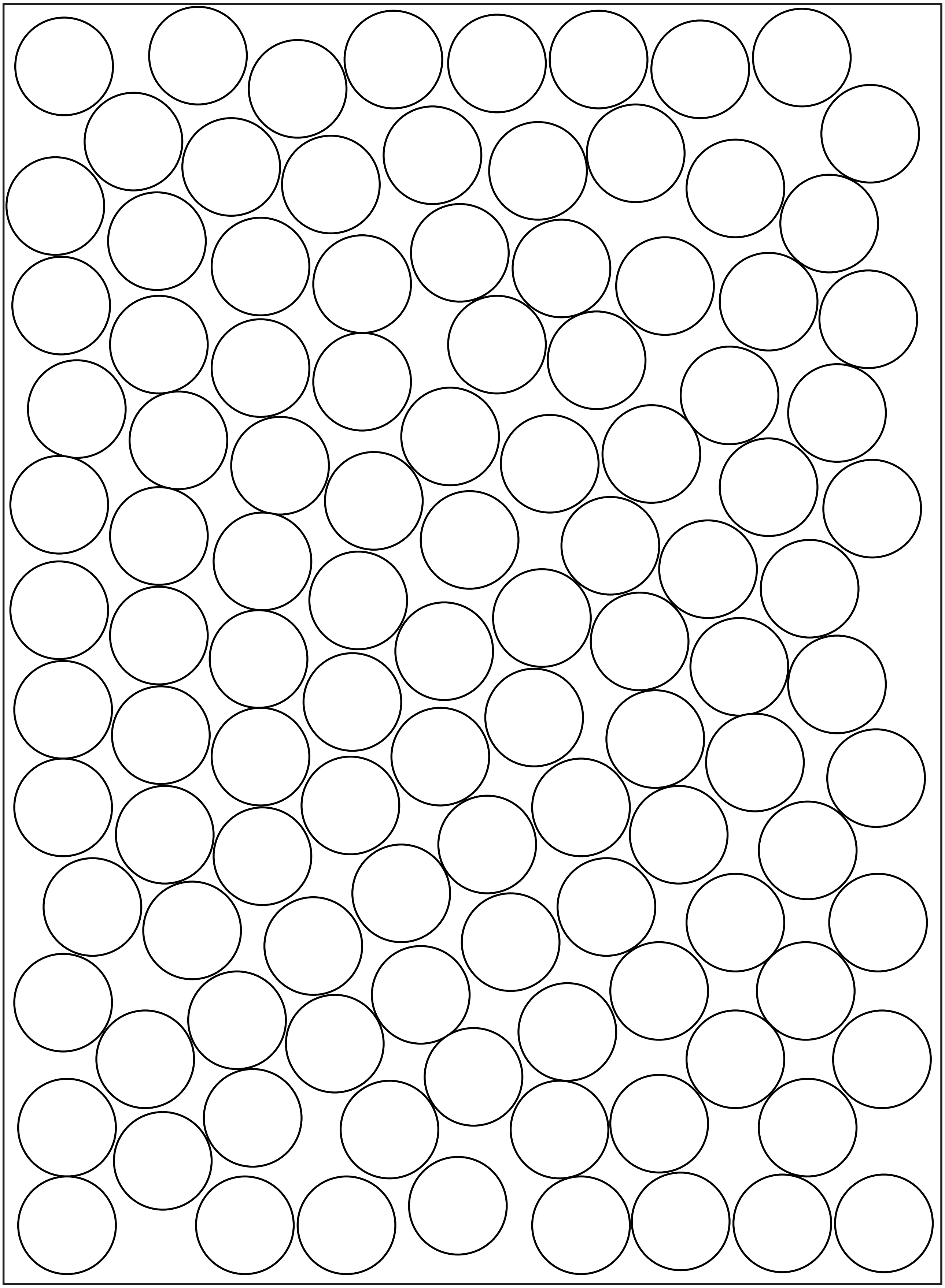
$$\text{total area of all the circles} = \frac{\text{(circle hits) (rectangular area)}}{\text{(hits)}}$$

Subsequently you can calculate:

$$\text{area of one circle} = \frac{\text{(total area of all the circles)}}{\text{(total number of circles)}}$$

The area of one circle can be used to calculate the radius of a circle: area = $3.14(\text{radius})^2$. This calculated radius may then be compared with a direct radius measurement.





Student Worksheet

A Laboratory Exercise in Indirect Measurement

Introduction: Modern physics depends heavily on indirectly determining physical properties of objects. The following activity will help convince you that indirect determinations are important methods of obtaining accurate information.

Problem: Determine the radius of a single target circle indirectly.

Procedure: Use copies of either of the circle sets given to you by your teacher. Place the circled paper on the floor, face down over a sheet of carbon paper. Drop marbles or ball bearings from head height so that they hit the paper within the marked boundaries. The sphere must be caught after the first bounce. Repeat this at least 100 times. It may be more convenient to drop the marbles from just above the paper; however, one should then take care to distribute the hits as randomly as possible over the entire target area.

Analysis: Count the total number of dots on the paper within the marked rectangular boundaries (hits) as well as the number of dots which are completely within a circle (circle hits). Determine the total area of the paper within the marked boundaries (rectangular area), and count the total number of circles on the paper. If we have uniform circles and a random distribution of hits, then we can assume:

$$\frac{\text{circle hits}}{\text{hits}} = \frac{\text{area of all circles}}{\text{rectangular area}}$$

Therefore you can calculate:

$$\text{total area of all the circles} = \frac{\text{(circle hits) (rectangular area)}}{\text{(hits)}}$$

Subsequently you can calculate:

$$\text{area of one circle} = \frac{\text{(total area of all the circles)}}{\text{(total number of circles)}}$$

The area of one circle can be used to calculate the radius of a circle: area = 3.14(radius)^2. This calculated radius may then be compared with a direct radius measurement.

Teacher Notes

An In-Depth Look at the Standard Model

The following 28 pages are a very thorough look at the current state of understanding of many aspects of the Standard Model of particle physics.

For the teacher, these pages may prove to be a great “primer” to be completed before dedicating a large amount of classroom time to the study of particle physics. This is almost certainly a more thorough treatment than is offered in undergraduate curricula in particle physics.

The pages may also be used by students working in groups or individually. The directions are clear and many examples are given. In any case, this exercise will give a very clear understanding of all of the particles and how they interact to whomever works through these pages.

	Matter I	 II	 III		Antimatter I	 II	 III
Quarks	Up u + 2/3 r, g, b ~3	Charm c + 2/3 r, g, b ~1,250	Top t + 2/3 r, g, b ~173,000	Antiquarks	Antiup $\overline{u}$ - 2/3 c, m, y ~3	Anticharm $\overline{c}$ - 2/3 c, m, y ~1,250	Antitop $\overline{t}$ - 2/3 c, m, y ~173,000
	Down d - 1/3 r, g, b ~6.5	Strange s - 1/3 r, g, b ~115	Bottom b - 1/3 r, g, b ~4,250		Antidown $\overline{d}$ + 1/3 c, m, y ~6.5	Antistrange $\overline{s}$ + 1/3 c, m, y ~115	Antibottom $\overline{b}$ + 1/3 c, m, y ~4,250
Leptons	Electron e^- -1 0.511	Muon μ -1 106	Tau τ -1 1,777	Antileptons	Positron e^+ +1 0.511	Antimuon $\overline{\mu}$ +1 106	Antitau $\overline{\tau}$ +1 1,777
	Electron neutrino ν_e 0 < 0.000002	Muon neutrino ν_μ 0 < 0.000002	Tau neutrino ν_τ 0 < 0.000002		Electron antineutrino $\overline{\nu}_e$ 0 < 0.000002	Muon antineutrino $\overline{\nu}_\mu$ 0 < 0.000002	Tau antineutrino $\overline{\nu}_\tau$ 0 < 0.000002

Gauge Bosons

Force	Force Carrier	Rest Mass (GeV/c^2)	Charge	Relative Strength	Range (cm)	Spin	Color
Strong	Gluons	0	0	1	$< 10^{-13}$	1	Yes
Weak	W^+	80.4	+1	10^{-13}	$< 10^{-16}$	1	Neutral
	Z^0	91.2	0			1	
	W^-	80.4	-1			1	
Electromagnetic	Photons	0	0	10^{-2}	Infinite	1	Neutral
Gravitational	Gravitons	0	0	10^{-38}	Infinite	2	Neutral

Legend

	I		← Generation
Name →	Up	+2/3	← Charge
		r, g, b	← Color
Symbol →	u	~3	← Rest Mass (MeV/c^2)

THE STANDARD MODEL OF ELEMENTARY PARTICLES CHART
THE ULTIMATE PERIODIC TABLE
WHAT CAN WE LEARN FROM IT?

This activity can be done as a lecture-discussion presentation or can be used by individual students to learn about the Standard Model from the Standard Model of Elementary Particles Chart.

To the student: The purpose of this activity is to familiarize yourself with the Standard Model of Elementary Particles by studying the Standard Model of Elementary Particles Chart, referred to from now on as the Chart. You will need to have a copy of the Chart on page 2 in front of you to do this activity.

As you look at the Chart, you will see that it is divided into four sections. The two top sections list a total of 24 elementary particles. You will need information from these two sections to answer the following questions.

1. The two top sections are labeled ________________ and __________________ .
2. For the time being, let's disregard the right hand side of the Chart and look at the left side labeled Matter. This category is further divided into two groups of six particles. These groups of particles are given the names _________________ and _______________ .
3. List the flavors (names) of the six quarks.

   _______________ , _______________ , _______________ ,

   _______________ , _______________ , _______________

4. List the flavors (names) of the six leptons.

   _______________ , _______________ , _______________ ,

   _______________ , _______________ , _______________

5. The symbol for each quark is ____________________________ .
6. Using the Chart, write the symbols for the following particles:

up quark ________	down quark _______
top quark _______	charm quark _______

7. Look at the leptons on the Chart. Their symbols (except for the electron) are Greek letters. Fill in the symbols below.

lepton	symbol	name of Greek letter
muon	_______	mu
tau	_______	tau
neutrino	_______	nu

   Since there are three different neutrinos, how do their symbols distinguish them from one another? ______________________________

   Write the symbol for an electron neutrino: ___________

8. Given the list of particles below, circle the quarks. (Do this without looking at the Chart if you can.)

up, neutrino, electron, down, tau, charm, strange

9. Using the legend in the lower right-hand corner of the Chart, write down the charge and approximate mass of each of the following:

PARTICLE	CHARGE	MASS
up		
strange		
top		
electron		
tau		
electron neutrino		

10. Why can mass be measured in MeV/c^2 ?

11. Using the Chart complete the following: _______________ have charges that are integers, and _______________ have charges that are fractions.

12. Baryons are particles that are made from quarks. The most common baryons are the neutron and the proton. Applying the law of conservation of charge (that is, no charge can be created or destroyed), what is the minimum number of quarks that must be joined to make up one baryon that has a charge of either +1, -1, or 0? _________
Show the proof of your answer here.

CHECK THIS ANSWER WITH THE INSTRUCTOR BEFORE CONTINUING.

13. List three combinations of quarks that will give you a baryon with a charge of:
a) +1 b) -1 c) 0

EXAMPLE: A baryon composed of ccs has a charge of +2/3 + 2/3 - 1/3 = +1.

QUARK COMBINATIONS FOR:

+1	-1	0
________	________	________
________	________	________
________	________	________

14. The quarks and leptons in column 1 of the Chart make up all the stable matter such as protons and neutrons. (Neutrons are stable relative to other particles, although they can decay.) Apply this information to write the quark configuration for a proton and for a neutron.

proton _______________ neutron _______________

15. Which leptons are found in Column (or Family) I? ______________ Do you think these are stable too? __________________

16. The quarks from Columns II and III form particles that have lifetimes that are much shorter than the proton and neutron, yet they do live long enough to be detected. These particles can be formed from quarks from all three columns. The flavor of the quarks is determined by charge, mass and by the presence or absence of certain properties that are not completely understood but have been given the following names: strangeness, charm, beauty or bottomness and truth or topness. To use the quark model to build these baryons, you need more information about the baryons and the quarks. This information is found on the "Quark & Lepton Properties" (page 35) and "Baryon Properties" (page 36) charts. You can get these charts from your instructor. (You will note that truth and beauty are not on the latter chart because no baryons have been detected that possess these properties, although there are other particles called mesons that do.)

    EXAMPLE: Determine the quark configuration of a sigma minus (Σ^-). From the chart we find that the sigma minus has a charge of -1, mass of 1197, and strangeness of -1. A strange quark is needed for the strangeness of -1. The strange quark also has a charge of -1/3. Since charm, beauty and truth are all zero, the other quarks must come from column I and have a charge of -1/3 each. Only the down quark qualifies. Conservation of mass is not violated since the mass of the three quarks is less than the mass of the sigma minus. Therefore, the quark configuration of the sigma minus is <u>dds</u>.

    Determine the quark configuration for the following:

    Lambda zero (Λ^0)

    Omega minus (Ω^-)

    Xi minus (Ξ^-)

    Check your answers to #16 before going on to #17.

17. Perhaps you were bothered in #16 that a baryon could contain two quarks of the same kind. Since the Pauli Exclusion Principle prohibits an atom from containing two electrons with the same quantum numbers, you may have wondered if this would apply in some way to quarks in a baryon. Well, the answer is yes. Although a baryon may contain two or three quarks of the same flavor, these quarks differ in another property. Scientists are not certain of the physical significance of this property, but in the Standard Model it is given the name color. Quarks are assigned the colors of red, green or blue. Each baryon contains a quark of each color to form the color white. Where on the Chart does it indicate the colors of the quarks?

    ____

    Do leptons have color? __________

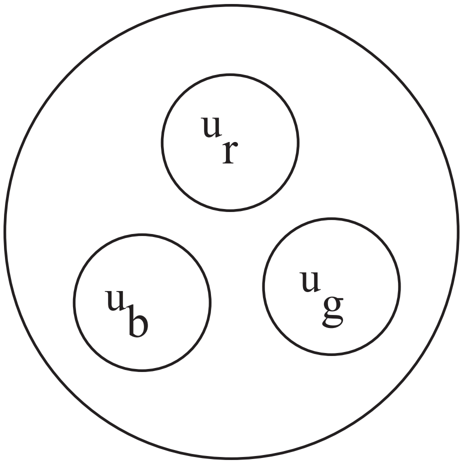
18. Sketch the baryons in #14 and #16 and assign colors to the quarks. Let circles represent the baryons and smaller circles represent the quarks. EXAMPLE: Proton representation:

Neutron:
(n)

Lambda zero
(Λ^0)

Xi minus
(Ξ^-)

Omega minus
(Ω^-)



19. Now let's look at the right side of the Chart, marked Antimatter. Using the Chart, explain how the antiparticles differ from the particles in:

a) Charge ________________________________
b) Mass __________________________________
c) Symbol ________________________________
(Which particle is an exception?) ______________________
d) Color _________________________________

20. An antibaryon is made from antiquarks.
EXAMPLE: The antiquark configuration for an antiproton is uud since it has a charge of -1; strangeness = 0.

Write the antiquark configuration and make diagrams as in #18 for the following:

Antineutron ($\bar{\eta}$)

Antisigma minus ($\bar{\Sigma}^-$)

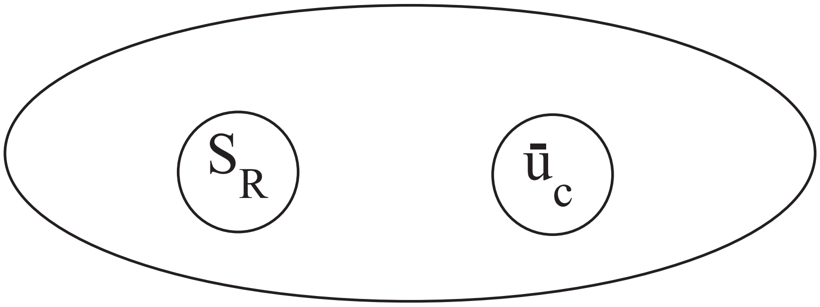
Antiomega plus ($\bar{\Omega}^+$)

HAVE THESE ANSWERS CHECKED BEFORE YOU CONTINUE.

21. Mesons are particles that are short-lived but nevertheless detected. They are composed of one quark and one antiquark. Their colors are complementary; that is, they must add up to be white or neutral.

EXAMPLE: K minus (K^-) has charge = -1, strangeness = -1, charm = 0, beauty = 0, truth = 0. K minus is composed of an s quark (strangeness = -1, charge = -1/3) and an antiup quark (charge = -2/3).

$s\bar{u}$ (red + cyan = white)



Using the “Quark & Lepton Properties” (page 35) and “Meson Properties” (page 40) charts, write and draw the quark configuration of the following mesons:

Anti K zero ($\overline{K}^0$)

B zero (B^0)

Eta (η^0)

D plus (D^+)

Can you have more than one configuration for any of these?_____ If so, write out all possibilities.

22. The Chart in the bottom left-hand corner lists the Gauge bosons. These are the carriers of the four fundamental forces in nature. List the four forces and their carriers.

FORCE	CARRIER
____________________	____________________________
____________________	____________________________
____________________	____________________________
____________________	____________________________

23. Which particles are charged? ________________

24. Which force has the shortest range? __________

25. Which force(s) is/are affected by the color? ________________

26. Which force is the weakest? _____________

27. Which force holds the quarks together to form baryons? ___________________

THE ULTIMATE PERIODIC TABLE
Answer Key

1. matter, antimatter
2. quarks, leptons
3. up, charm, top
   down, strange, bottom
4. electron, muon, tau
   electron neutrino, muon neutrino, tau neutrino
5. the first letter of its name
6. u, d, t, c
7. μ, τ, ν, subscript, ν_e
8. up, down, charm, strange
9. +2/3, 3 MeV/c^2
   -1/3, 115 MeV/c^2
   +2/3, 175,000 MeV/c^2
   -1, 0.511 MeV/c^2
   -1, 1784 MeV/c^2
   0, $< 3\times10^{-6}$ MeV/c^2
10. mass-energy equivalence
11. leptons, quarks
12. 3; two quarks will have a total charge of +1/3, +4/3, or -2/3.
13. Some of the possible combinations are: +1 (ucd, utb, ucs); -1 (dsb, dds, ddb); 0 (uds, cdb, tsb)
14. proton = uud, neutron = udd
15. electron, electron neutrino, yes
16. uds, sss, dss
17. second row between charge and mass; no
18. Neutron: udd; Lambda zero: uds; Xi minus: dss; Omega minus: sss. Each sketch should have one quark labeled with a subscript “r,” one with a subscript “g” and one with a subscript “b.”
19. a) opposite b) same c) same symbol with line over it, positron d) cyan, magenta, yellow
20. Antineutron: $\bar{u}\bar{u}\bar{d}$; Antisigma minus: $\bar{u}\bar{u}\bar{s}$; Antiomega plus: $\bar{s}\bar{s}\bar{s}$. Each sketch should have one quark labeled with a subscript “c,” one with a subscript “m” and one with a subscript “y.”
21. Anti K zero: $s\bar{d}$; B zero: $d\bar{b}$; Eta: $u\bar{u}$ or $d\bar{d}$; D plus: $c\bar{d}$. Each sketch should have the quark labeled with a subscript “r,” “g” or “b” and the antiquark labeled with a subscript “c,” “m” or “y.”
22. strong, gluons
    weak, W^+, W^-, Z^o
    electromagnetic, photons
    gravity, gravitons
23. W^+, W^-
24. weak
25. strong
26. gravity
27. strong

QUARK PROPERTIES

Quark Flavor	Symbol	Charge	Mass (MeV/c^2)	Baryon Number	Strangeness	Charmness	Bottomness	Topness
Up	u	+2/3	~3	+1/3	0	0	0	0
Down	d	-1/3	~6.5	+1/3	0	0	0	0
Strange	s	-1/3	~115	+1/3	-1	0	0	0
Charm	c	+2/3	~1,250	+1/3	0	1	0	0
Bottom	b	-1/3	~4,250	+1/3	0	0	-1	0
Top	t	+2/3	~175,000	+1/3	0	0	0	1
Antiup	$\bar{u}$	-2/3	~3	-1/3	0	0	0	0
Antidown	$\bar{d}$	+1/3	~6.5	-1/3	0	0	0	0
Antistrange	$\bar{s}$	+1/3	~115	-1/3	1	0	0	0
Anticharm	$\bar{c}$	-2/3	~1,250	-1/3	0	-1	0	0
Antibottom	$\bar{b}$	+1/3	~4,250	-1/3	0	0	1	0
Antitop	$\bar{t}$	-2/3	~175,000	-1/3	0	0	0	-1

LEPTON PROPERTIES

Lepton Flavor	Symbol	Charge	Mass (MeV/c^2)	Electron Number	Muon Number	Tau Number
Electron	e^-	-1	0.511	1	0	0
Muon	μ	-1	106	0	1	0
Tau	τ	-1	1,777	0	0	1
Electron neutrino	ν_e	0	$< 3 \times 10^{-6}$	1	0	0
Muon neutrino	ν_μ	0	< 0.2	0	1	0
Tau neutrino	ν_τ	0	< 20	0	0	1
Positron	e^+	+1	0.511	-1	0	0
Antimuon	$\bar{\mu}$	+1	106	0	-1	0
Antitau	$\bar{\tau}$	+1	1,777	0	0	-1
Electron antineutrino	$\bar{\nu}_e$	0	$< 3 \times 10^{-6}$	-1	0	0
Muon antineutrino	$\bar{\nu}_\mu$	0	< 0.2	0	-1	0
Tau antineutrino	$\bar{\nu}_\tau$	0	< 20	0	0	-1

Additional data may be found in *The Review of Particle Physics*, published by the Particle Data Group at Lawrence Berkeley Laboratory. *The Review of Particle Physics* is available online at: http://pdg.lbl.gov/pdg.html

BARYON PROPERTIES

Use the Quark Properties chart to determine the quark composition of the following baryons. A method for determining baryon composition is shown on the following page. Use your answers from this exercise to fill the appropriate circles on the Baryon Composition exercise that follows.

Baryon Name	Symbol	Charge	Mass (MeV/c^2)	Strange-ness	Charm-ness	Spin	Baryon Number
Proton	p	+1	938	0	0	1/2	+1
Antiproton	$\bar{p}$	-1	938	0	0	1/2	-1
Neutron	n	0	940	0	0	1/2	+1
Antineutron	$\bar{n}$	0	940	0	0	1/2	-1
Lambda	Λ^0	0	1116	-1	0	1/2	+1
Antilambda	$\bar{\Lambda}^0$	0	1116	+1	0	1/2	-1
Charmed lambda plus	Λ_c^+	+1	2285	0	1	1/2	+1
Sigma plus	Σ^+	+1	1189	-1	0	1/2	+1
Antisigma minus	$\bar{\Sigma}^-$	-1	1189	+1	0	1/2	-1
Sigma zero	Σ^0	0	1193	-1	0	1/2	+1
Antisigma zero	$\bar{\Sigma}^0$	0	1193	+1	0	1/2	-1
Sigma minus	Σ^-	-1	1197	-1	0	1/2	+1
Antisigma plus	$\bar{\Sigma}^+$	+1	1197	+1	0	1/2	-1
Xi zero	Ξ^0	0	1315	-2	0	1/2	+1
Antixi zero	$\bar{\Xi}^0$	0	1315	+2	0	1/2	-1
Xi minus	Ξ^-	-1	1321	-2	0	1/2	+1
Antixi plus	$\bar{\Xi}^+$	+1	1321	+2	0	1/2	-1
Omega minus	Ω^-	-1	1672	-3	0	3/2	+1
Antiomega plus	$\bar{\Omega}^+$	+1	1672	+3	0	3/2	-1
Delta zero	Δ^0	0	1234	0	0	3/2	+1
Antidelta zero	$\bar{\Delta}^0$	0	1234	0	0	3/2	-1
Delta minus	Δ^-	-1	1232	0	0	3/2	+1
Delta plus	Δ^+	+1	1233	0	0	3/2	+1
Delta two plus	Δ^{++}	+2	1231	0	0	3/2	+1
Sigma star plus	Σ^{*+}	+1	1383	-1	0	3/2	+1
Sigma star zero	Σ^{*0}	0	1384	-1	0	3/2	+1
Sigma star minus	Σ^{*-}	-1	1387	-1	0	3/2	+1
Xi star minus	Ξ^{*-}	-1	1535	-2	0	3/2	+1
Xi star zero	Ξ^{*0}	0	1532	-2	0	3/2	+1

DETERMINING BARYON COMPOSITION

1. Baryons consist of three quarks.
2. If the baryon number is +1, you have $\bar{Q}\ \bar{Q}\ Q$.
3. If the baryon number is -1, you have Q Q Q.
4. What is the charge on the baryon?
5. What combinations of three quark charges (±2/3, ± 1/3) will yield the total charge on the baryon?
6. What does the baryon mass indicate about possible quark combinations?
7. A spin of 3/2 will account for a larger mass.
8. What do the strangeness, charm, beauty (bottomness), and truth (topness) numbers indicate?

Example:

What is the quark composition of the Σ^0?

a) The baryon number is +1. Therefore it consists of three quarks.

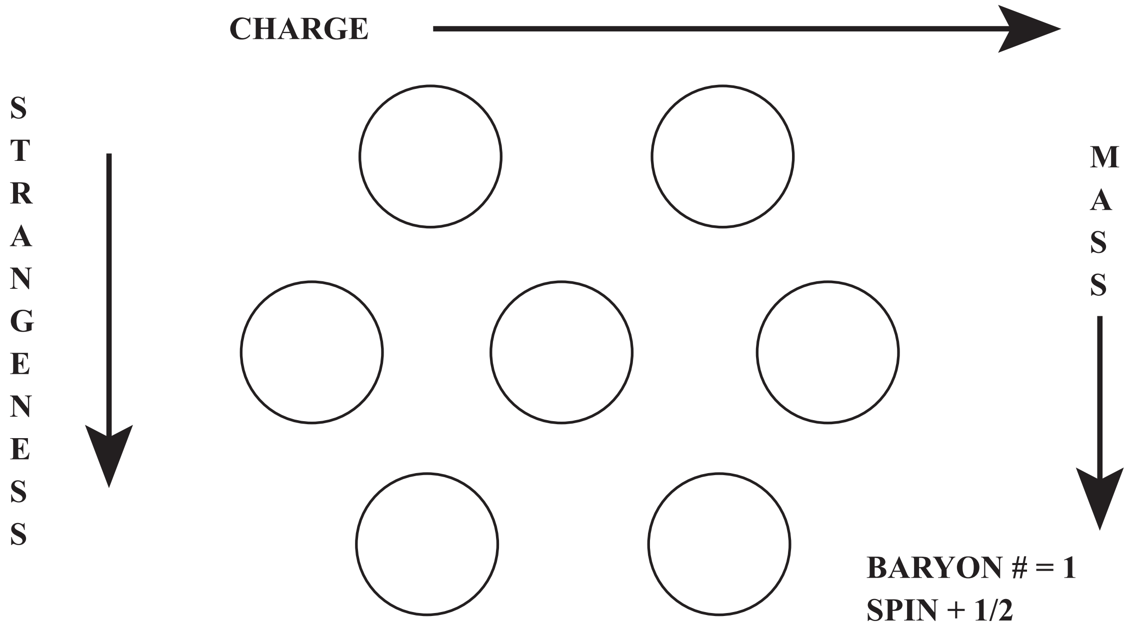
b) The charge is zero. To get this total charge, the quarks must have charges of +2/3, -1/3 and -1/3 respectively. The +2/3 quark could be up, charm or top. The -1/3 quarks could be down, strange or bottom.

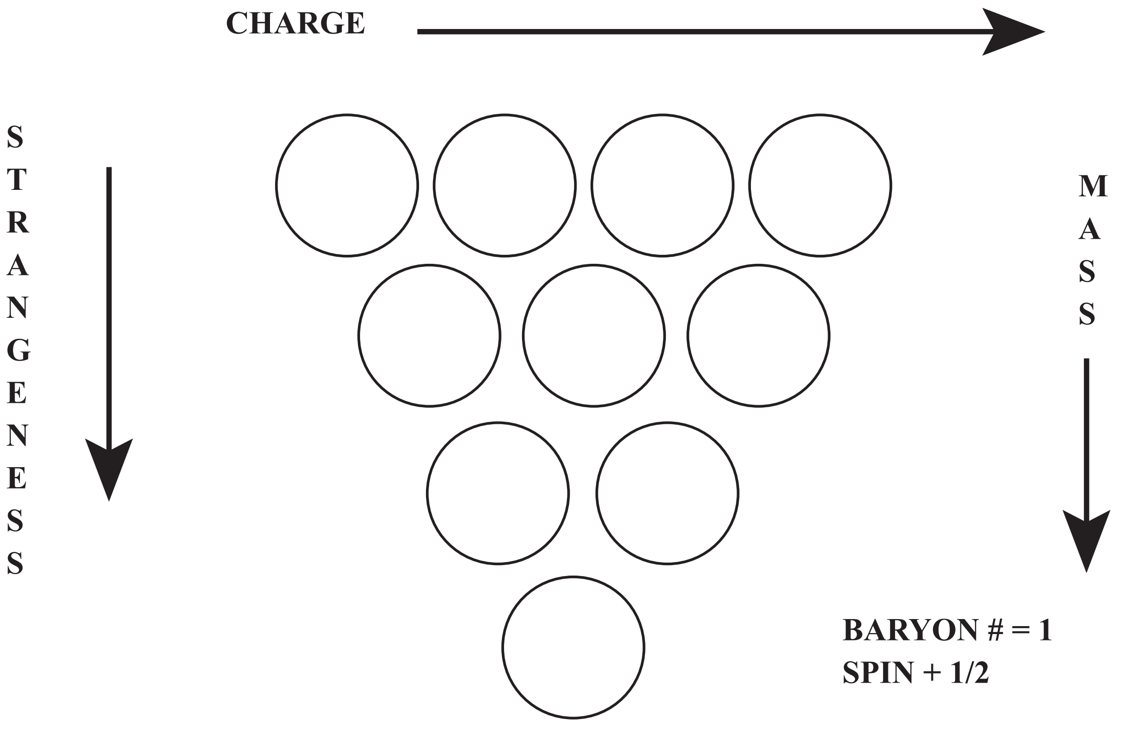
c) The mass is 1192 MeV. This eliminates the more massive charm, bottom and top quarks. Therefore the +2/3 quark must be up. The -1/3 quark could be either down or strange.

d) The strangeness is -1. Therefore one, and only one, strange quark must be included.

e) The composition is up, strange, down (**usd**).

BARYON COMPOSITION

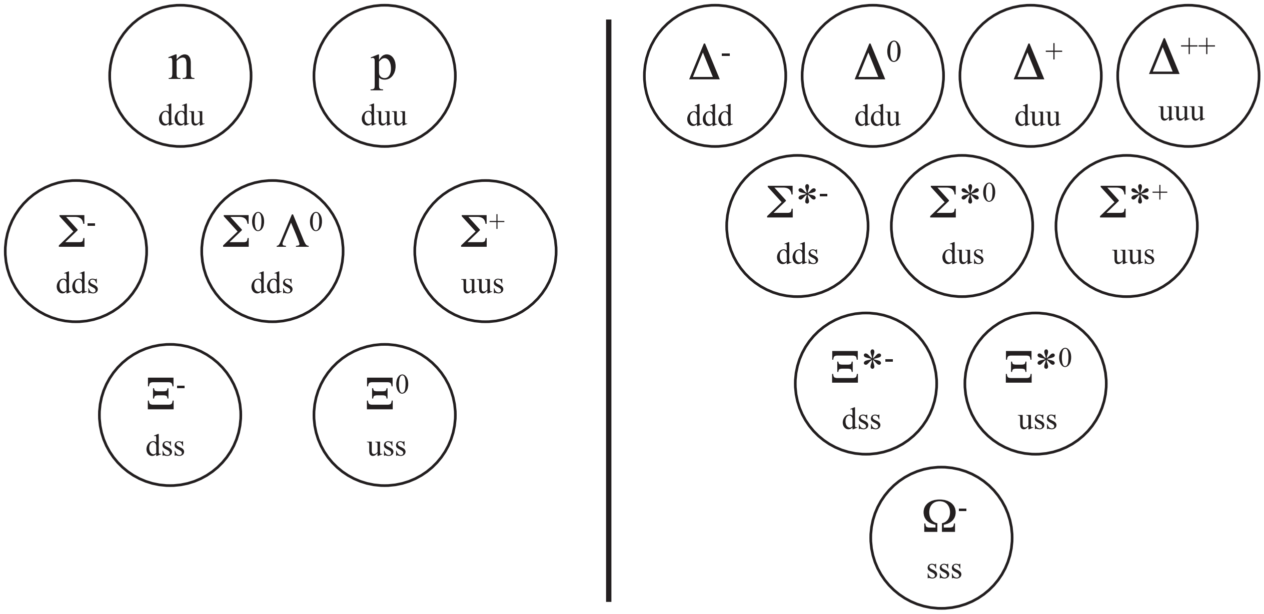




The “Baryon Composition” sheet is designed to be used after the”Baryon Properties” sheet has been completed. It will show the relationships among the various baryons in terms of mass, charge, strangeness and composition. Note that the upper set of baryons have a spin of 1/2, while the lower grouping has a spin of 3/2. Use your answers from the “Baryon Properties” sheet to fill each circle with the name of the baryon and its quark composition. The circles should be filled in a pattem whereby charge increases from left to right and both mass and strangeness increase from top to bottom.

BARYON PROPERTIES AND BARYON COMPOSITION ANSWER KEYS

BARYON NAME	COMPOSITION	BARYON NAME	COMPOSITION
Proton	duu	Xi Minus	dss
Antiproton	$\bar{d}\bar{u}\bar{u}$	Antixi Plus	$\bar{d}\bar{s}\bar{s}$
Neuton	ddu	Omega Minus	sss
Antineutron	$\bar{d}\bar{d}\bar{u}$	Antiomega Plus	$\bar{s}\bar{s}\bar{s}$
Lambda	dus	Delta Zero	ddu
Antilambda	$\bar{d}\bar{u}\bar{s}$	Antidelta Zero	$\bar{d}\bar{d}\bar{u}$
Charmed Lambda Plus	duc	Delta Minus	ddd
Sigma Plus	uus	Delta Plus	duu
Antisigma Minus	$\bar{u}\bar{u}\bar{s}$	Delta Two Plus	uuu
Sigma Zero	dus	Sigma Star Plus	uus
Antisigma Zero	$\bar{d}\bar{u}\bar{s}$	Sigma Star Zero	dus
Sigma Minus	dds	Sigma Star Minus	dds
Antisigma Plus	$\bar{d}\bar{d}\bar{s}$	Xi Star Minus	dss
Xi Zero	uss	Xi Star Zero	uss
Anti Zero	$\bar{u}\bar{s}\bar{s}$		



MESON PROPERTIES

Use the Quark Properties chart to determine the quark composition of the following mesons. A method for determining meson composition is shown on the following page. Use your answers from this exercise to fill the appropriate circles on the “Meson Composition” exercise that follows.

Meson Name	**Symbol**	**Charge**	**Mass (MeV/c^2)**	**Strange-ness**	**Charm-ness**	**Bottom-ness**	**Top-ness**
Pi zero	π^0	0	135	0	0	0	0
Pi minus	π^-	-1	140	0	0	0	0
Pi plus	π^+	+1	140	0	0	0	0
Rho	ρ	0	775	0	0	0	0
Eta	η	0	548	0	0	0	0
K zero	K^0	0	498	+1	0	0	0
Anti K zero	$\overline{K}^0$	0	498	-1	0	0	0
K plus	K^+	+1	494	+1	0	0	0
K minus	K^-	-1	494	-1	0	0	0
D zero	D^0	0	1864	0	+1	0	0
Anti D zero	$\overline{D}^0$	0	1864	0	-1	0	0
D plus	D^+	+1	1869	0	+1	0	0
D minus	D^-	-1	1869	0	-1	0	0
D strange plus	D_s^+	+1	1969	+1	+1	0	0
D strange minus	D_s^-	-1	1969	-1	-1	0	0
J/Psi	J/Ψ	0	3097	0	0	0	0
B zero	B^0	0	5279	0	0	+1	0
Anti B zero	$\overline{B}^0$	0	5279	0	0	-1	0
B plus	B^+	+1	5279	0	0	+1	0
B minus	B^-	-1	5279	0	0	-1	0
Phi	ϕ	0	1019	0	0	0	0
Upsilon	Υ	0	9460	0	0	0	0

DETERMINING MESON COMPOSITION

1. Mesons consist of a quark and an antiquark (Q Q).
2. What is the charge on the meson?
3. What combinations of quark and antiquark charges (±2/3, ±1/3) will yield the total charge on the meson?
4. What does the meson mass indicate about possible quark/antiquark combinations?
5. What do the strangeness, charm, beauty (bottomness) and truth (topness) numbers indicate?

Example:

What is the composition of D^-?

a) It is a meson, so we have QQ.

b) The charge is -1. Therefore the quark/antiquark charges must be -1/3 and -2/3. We must have a quark charge of - 1/3 (down, strange or bottom) and an antiquark charge of -2/3 (antiup, anticharm or antitop).

c) The mass is 1869 MeV. This eliminates the bottom and antitop.

d) The charm is -1. This requires the anticharm.

e) The strangeness is zero. This eliminates the strange quark.

f) We are left with the down/anticharm (dc) combination for the D^-.

MESON COMPOSITION

The “Meson Composition” sheet is designed to be used after the “Meson Properties” sheet has been completed. It will show the quark composition relationships among the various mesons. In the table below, insert the names of the known mesons formed from each quark/antiquark combination.

	$\bar{u}$	$\bar{d}$	$\bar{c}$	$\bar{s}$	$\bar{t}$	$\bar{b}$
u	π^0 ρ^0 η^0					
d		π^0 ρ^0 η^0				
c						
s						
t						
b						

MESON PROPERTIES AND MESON COMPOSITION

Answer Keys

Meson Name	Composition Quark/Antiquark		Meson Name	Composition Quark/Antiquark	
Pi Zero	u/d	$\bar{u}/\bar{d}$	D Plus	c	$\bar{d}$
Pi Minus	d	$\bar{u}$	D Minus	d	$\bar{c}$
Pi Plus	u	$\bar{d}$	F Plus	c	$\bar{s}$
Rho	u/d	$\bar{u}/\bar{d}$	F Minus	s	$\bar{c}$
Eta	u/d	$\bar{u}/\bar{d}$	J/Psi	c	$\bar{c}$
K Zero	d	$\bar{s}$	B Zero	d	$\bar{b}$
Anti K Zero	s	$\bar{d}$	Anti B Zero	b	$\bar{d}$
K Plus	u	$\bar{s}$	B Plus	u	$\bar{b}$
K Minus	s	$\bar{u}$	B Minus	b	$\bar{u}$
D Zero	c	$\bar{u}$	Phi	s	$\bar{s}$
Anti D Zero	u	$\bar{c}$	Upsilon	b	$\bar{b}$

* * *

	$\bar{u}$	$\bar{d}$	$\bar{c}$	$\bar{s}$	$\bar{t}$	$\bar{b}$
u	π^0 ρ^0 η^0	π^+ ρ^+	$\overline{D^0}$	K^+		B^+
d	π^- ρ^-	π^0 ρ^0 η^0	D^-	K^0		B^0
c	D^0	D^+	J/Ψ	F^+		
s	K^-	$\overline{K^0}$	F^-	ϕ		
t						
b	B^-	$\overline{B^0}$				Ψ

ANALYSIS OF ELEMENTARY PARTICLE REACTIONS

In order to analyze elementary particle reactions at a beginning level, you must consider conservation of charge, baryon number, electron number, muon number and tauon number. Energy is also conserved but may appear in a variety of forms, some of which forms are difficult to quantify. Therefore you will need to examine kinetic energy before the reaction. If there is only minimal initial kinetic energy (as in decays), then the rest energy (mass) total for the products should be less than the rest energy of the reactant. In a strong interaction, strangeness also will be conserved.

Example:

Complete the reaction:

Property	Λ^0	p	+	e^-	+	?
Charge	0	+1		-1		***0***
Mass (MeV)	1116	938		.5		***<177***
Baryon Number	1	1		0		***0***
Electron Number	0	0		+1		***-1***
Muon Number	0	0		0		***0***
Tauon Number	0	0		0		***0***

In order to conserve the various properties, the unknown particle will need the properties indicated in ***bold italics***. Therefore it must be the electron's antineutrino ($\bar{\upsilon}_e$).

ELEMENTARY PARTICLE REACTIONS - I

Use the conservation laws to supply the missing particle(s) in each of the following reactions.

A) WEAK, NON-LEPTONIC DECAYS OF HADRONS

1. K^+ π^+ +
2. Λ^0 n +
3. K^0 π^+ +
4. Λ^0 ρ^+ +
5. Σ^+ ρ^+ +
6. K^+ π^+ + π^+ +
7. Ξ^0 Λ^0 +
8. K^0 π^0 +
9. Σ^+ n +
10. Ω^- Ξ^0 +
11. Ξ^- Λ^0 +
12. Σ^- n

B) WEAK, LEPTONIC DECAYS OF HADRONS AND LEPTONS

13. π^+ μ^+ +
14. π^0 γ + e^+ +
15. π^- π^0 + e^- +
16. K^+ ν_μ +
17. K^0 π^+ + ν_e +
18. n ρ^+ + e^- +

19. μ^- e^- + +

20. Λ^0 ρ^+ + e^- +

21. τ^+ μ^+ + +

22. D^0 K^0 + π^+ +

C) STRONG, HADRONIC REACTIONS (Assume sufficient incident energy.)

23. n + ρ^+ ρ^+ + ρ^+ +

24. ρ^+ + ρ^+ ρ^+ + π^+ +

25. ρ^+ + π^+ Σ^+ +

26. π^0 + ρ^+ ρ^+ + π^+ +

27. K^- + ρ^+ Σ^+ +

28. K^- + ρ^+ Σ^- +

29. K^- + ρ^+ Λ^0 +

30. π^- + ρ^+ n + π^- +

ELEMENTARY PARTICLE REACTIONS - II

Indicate the validity of each of the following decay processes. For any reactions which are not valid, state a reason.

1. K^- $\mu^- + \nu_\mu$
2. π^+ $\mu^+ + \nu_\mu$
3. Λ^0 $\rho^+ + \pi^-$
4. π^- $\chi + \nu_e$
5. π^- $\mu^- + \nu_\mu$
6. n $\rho^+ + \pi^-$
7. Σ^+ $n + \pi^0$
8. n $\rho^+ + e^- + \nu_e$
9. μ^+ $e^- + \nu_e + \nu_\mu$
10. K^+ $\mu^+ + \pi^0 + \nu_e$
11. π^0 $e^+ + e^- + \nu_e$
12. μ^- $e^- + \nu_e + \nu_\mu$
13. Ξ^0 $\Lambda^0 + \pi^0$
14. K^0 $\pi^0 + \pi^0 + \pi^+$
15. Λ^0 $n + \pi^0 + \nu_e$

ELEMENTARY PARTICLE REACTIONS
Answer Keys

SHEET I

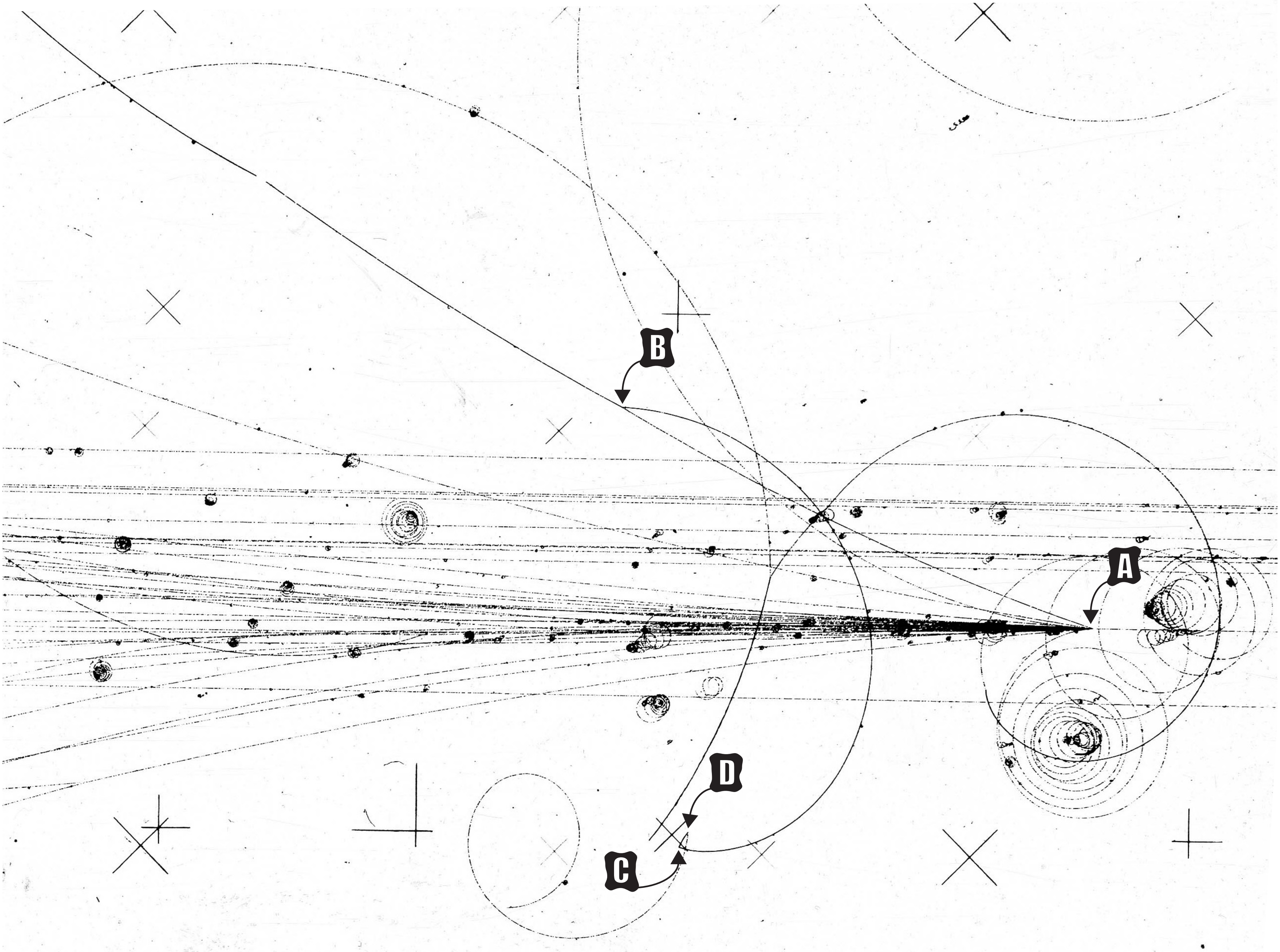
1. Pi Zero
2. Pi Zero
3. Pi Minus
4. Pi Minus
5. Pi Zero
6. Pi Minus
7. Pi Zero
8. Pi Zero
9. Pi Plus
10. Pi Minus
11. Pi Minus
12. Pi Minus
13. Muon Neutrino - See “Bubble Chamber Track Analysis” (pages 55-56). This reaction occurs at point C.
14. Electron
15. Electron Antineutrino
16. Mu Plus
17. Electron
18. Electron Antineutrino
19. Electron Antineutrino & Muon Neutrino
20. Electron Antineutrino
21. Tauon Antineutrino & Muon Neutrino
22. Pi Minus
23. Pi Minus
24. Neutron
25. K Plus
26. Pi Minus
27. Pi Minus
28. Pi Plus
29. Pi Zero

SHEET II

1. Valid
2. Valid - See “Bubble Chamber Track Analysis” (pages 55-56).
   This reaction occurs at point C.
3. Valid
4. Invalid - Charge, muon family number and electron family number are not covered.

5 Invalid

6. Valid
7. Invalid - Charge is not conserved.
8. Valid
9. Invalid - Electron family number is not conserved. See “Bubble Chamber Track Analysis”
   (pages 55-56). The corrected version of this reaction occurs at point D.
10. Invalid - Muon family number and electron family number are not conserved.
11. Invalid - Electron family number is not conserved.
12. Invalid - Electron family number is not conserved.
13. Valid
14. Invalid - Charge is not conserved.
15. Invalid - Electron family number is not conserved.



B
A
D
C

BUBBLE CHAMBER TRACK ANALYSIS

In this October, 1973 photo, 300 GeV protons are incident in the 30-inch hydrogen bubble chamber. The electron spirals are counter-clockwise. Therefore, clockwise deflection indicates a positive charge.

1. At point A we have a proton-proton interaction which produces a π^+ and many other particles.

2. The π^+ moves to B, where it recoils from an elastic collision with a proton.

3. The recoiling π^+ slows as it travels to C. At C it decays according to the reaction:

   $\pi^+ \longrightarrow \mu^+ + \nu_\mu$. The lack of forward momentum beyond point C indicates the likelihood of a decay of a particle (π^+) which was essentially at rest. Note that this is reaction 13 from the worksheet “Elementary Particle Reactions - I (page 50), as well as being reaction 2 from the worksheet “Elementary Particle Reactions - II (page 52).

4. The μ^+ produced at point C travels to point D. At D it decays according to the reaction:

   $\mu^+ \longrightarrow e^+ + \bar{\nu}_e + \nu_\mu$. Note that this is the corrected version of reaction 9 from the worksheet “Elementary Particle Reactions - II” (page 52).

NAME ___________________

WHAT DID YOU LEARN? ELEMENTARY PARTICLES

Part A - True or False

____ 1. Earth, air, fire and water are not currently considered as the fundamental particles of nature.

____ 2. The fundamental particles of modem physics are the proton, neutron and electron.

____ 3. Quarks have electrical charges equal to 1/3 or 2/3 of the electron or proton charge.

____ 4. All leptons are electrically neutral.

____ 5. For every particle type, there is believed to exist an antiparticle type.

____ 6. The mass of an elementary particle is typically expressed in terms of its energy equivalent in joule units.

____ 7. An antiparticle has the same mass as its particle counterpart.

____ 8. Quark flavors include: up, down, charm, strange, top and bottom.

____ 9. The electron, muon and tauon are the only known leptons.

____ 10. Three types of neutrinos are believed to exist.

____ 11. The graviton is a theoretically massless particle that has yet to be observed.

Part B - Match each particle type in Column I with the best description in Column II.

	Column I	Column II
____	12. hadrons	A. fundamental particles bound in groups of two or three by the strong force
____	13. mesons	B. fundamental particles not affected by the strong force
____	14. baryons	C. composed entirely of particles of neutral electrical charge
____	15. quarks	D. three quarks in combination
____	16. leptons	E. general group consisting of mesons and baryons
		F. one quark and one antiquark in combination

Part C - Match each fundamental force in Column I with its carrier in Column II.

	Column I	Column II
____	17. gravitational	A. weak bosons (weakons)
____	18. strong nuclear	B. photons
____	19. weak nuclear	C. gravitons
____	20. electromagnetic	D. klingons
		E. gluons

VERSION 1

For questions #21-26 use your knowlege of quark and lepton properties and the conservation laws, as well as the particle data at the bottom of the page.

Determine the quark (or antiquark) composition of the following particles.

	Baryon	**Charge**	**Mass (MeV)**	**Spin**	**Strange-ness**	**Charm-ness**	**Bottom-ness**	**Composition**
21.	-1	-1	1235	3/2	0	0	0	
22.	0	-1	1971	0	-1	-1	0	

Complete the following reactions.

23. $p + \pi^+ \longrightarrow \Sigma^+ +$ ________

24. $K^+ \longrightarrow \nu_\mu +$ ________

For the following reactions, indicate which are valid. If a reaction is not valid, state a reason.

25. $\pi^0 \longrightarrow e^+ + \mu^-$ ________

26. $\Xi^0 \longrightarrow \Lambda^0 + \pi^0$ ________

PARTICLE DATA

NAME	BARYON #	CHARGE	MASS (MEV)	SPIN	STRANGENESS	CHARM
π^0	0	0	135	0	0	0
π^-	0	-1	140	0	0	0
π^+	0	+1	140	0	0	0
K^0	0	0	498	0	1	0
K^+	0	+1	494	0	1	0
K^-	0	-1	494	0	-1	0
p	1	+1	938	1/2	0	0
n	1	0	940	1/2	0	0
Λ^0	1	0	1116	1/2	-1	0
Σ^+	1	+1	1189	1/2	-1	0
Σ^0	1	0	1192	1/2	-1	0
Σ^-	1	-1	1197	1/2	-1	0
Ξ^-	1	-1	1321	1/2	-2	0
Ξ^0	1	0	1315	1/2	-2	0

VERSION 2

For questions #21-26 use your knowlege of quark and lepton properties and the conservation laws, as well as the particle data at the bottom of the page.

Determine the quark (or antiquark) composition of the following particles.

	Baryon	Charge	Mass (MeV)	Spin	Strange-ness	Charm-ness	Bottom-ness	Composition
21.	1	0	1385	3/2	-1	0	0	
22.	0	-1	1869	0	0	-1	0	

Complete the following reactions.

23. $K^+ + p \longrightarrow \Sigma^+ +$ ________

24. $\pi^0 \longrightarrow \mu^+ +$ ________

For the following reactions, indicate which are valid. If a reaction is not valid, state a reason.

25. $n \longrightarrow p + e^- + \bar{\nu}_e$ ________

26. $\mu^+ \longrightarrow e^- + \nu_e + \bar{\nu}_\mu$ ________

PARTICLE DATA

NAME	BARYON #	CHARGE	MASS (MEV)	SPIN	STRANGENESS	CHARM
π^0	0	0	135	0	0	0
π^-	0	-1	140	0	0	0
π^+	0	+1	140	0	0	0
K^0	0	0	498	0	1	0
K^+	0	-1	494	0	-1	0
K^-	0	-1	494	0	-1	0
p	1	+1	938	1/2	0	0
n	1	0	940	1/2	0	0
Λ^0	1	0	1116	1/2	-1	0
Σ^+	1	+1	1189	1/2	-1	0
Σ^0	1	0	1192	1/2	-1	0
Σ^-	1	-1	1197	1/2	-1	0
Ξ^-	1	-1	1321	1/2	-2	0
Ξ^0	1	0	1315	1/2	-2	0

VERSION 3

For questions #21-26 use your knowlege of quark and lepton properties and the conservation laws, as well as the particle data at the bottom of the page.

Determine the quark (or antiquark) composition of the following particles.

	Baryon	**Charge**	**Mass (MeV)**	**Spin**	**Strange-ness**	**Charm-ness**	**Bottom-ness**	**Composition**
21.	1	0	1530	3/2	-2	0	0	
22.	0	0	5274	0	0	0	-1	

Complete the following reactions.

23. $\pi^- + p \longrightarrow n + \pi^- +$ ________

24. $K^0 \longrightarrow \pi^+ + \nu_e +$ ________

For the following reactions, indicate which are valid. If a reaction is not valid, state a reason.

25. $\pi^- \longrightarrow \mu^- + \nu_\mu$ ________

26. $\Lambda^0 \longrightarrow n + \pi^0 + \nu_e$ ________

PARTICLE DATA

NAME	BARYON #	CHARGE	MASS (MEV)	SPIN	STRANGENESS	CHARM
π^0	0	0	135	0	0	0
π^-	0	-1	140	0	0	0
π^+	0	+1	140	0	0	0
K^0	0	0	498	0	1	0
K^+	0	+1	494	0	1	0
K^-	0	-1	494	0	-1	0
p	1	+1	938	1/2	0	0
n	1	0	940	1/2	0	0
Λ^0	1	0	1116	1/2	-1	0
Σ^+	1	+1	1189	1/2	-1	0
Σ^0	1	0	1192	1/2	-1	0
Σ^-	1	-1	1197	1/2	-1	0
Ξ^-	1	-1	1321	1/2	-2	0
Ξ^0	1	0	1315	1/2	-2	0

WHAT DID YOU LEARN?
ELEMENTARY PARTICLES

Answer Keys

Part A

1. True
2. False
3. True
4. False
5. True
6. False
7. True
8. True
9. False
10. True
11. True

Part B

12. E
13. F
14. D
15. A
16. B

Part C

17. C
18. E
19. A
20. B

Version 1

21. $\bar{u}\bar{u}\bar{d}$
22. $s\bar{c}$
23. K^+
24. μ^+
25. Invalid; electron and muon numbers are not conserved.
26. Valid

Version 2

21. uds
22. $d\bar{c}$
23. π^-
24. ν_μ
25. Valid
26. Invalid; charge and electron number are not conserved.

Version 3

21. ssd
22. $\bar{d}b$
23. π^+
25. Invalid; muon number is not conserved.
26. Invalid; electron number is not conserved.

RESOURCES

Several resource materials that go hand-in-hand with this book have been made available on the Internet.

The $E = mc^2$ Activity (Calculate the Top Quark Mass Activity) on pages 15-22 can be found at the Fermilab Education Office website with all the accompanying data and graphics.
http://ed.fnal.gov/samplers/hsphys/activities/top_quark_index.shtml
The overheads can be made from this pdf file: *http://ed.fnal.gov/samplers/hsphys/tmp08-trans.pdf*

Have you or your students ever wondered where the quirky names we see in modern physics come from? Lynne Zielinski has written an article giving an overview of how modern theoretical ideas got their names.
http://quarknet.fnal.gov/folklore.htm

Other valuable physics resources can be found through the QuarkNet program at the Fermilab Education Office website.

A list of QuarkNet online resources is available at *http://quarknet.fnal.gov/biblio.shtml*.
The QuarkNet print bibliography is available at *http://quarknet.fnal.gov/biblio2.html*.