Materials for

Teaching Modern Physics

Prepared by:

QuarkNet Teachers from
Fermilab and the University of Chicago

July 2006

Dear Colleague:

Thank you for taking this opportunity to look through this collection of educational materials. The goal of QuarkNet is to get more modern physics into the high school classroom. Our group realizes that with all the topics a typical teacher needs to cover in a given year, sometimes reaching modern physics is a difficult task. We took that in mind as we created this packet. We have offered a variety of worksheets, activities, labs, and lesson plans that a teacher can use throughout the year, but incorporate modern physics. We have also included some complete plans for modern physics units that would be good for the end of the year.

While these activities have been tested in our own classrooms, we welcome input from you. We would like to know what works, what doesn't, and how we can improve our product. Please complete the survey below and return it through the mail or by e-mail by June 15, 2007. Even if you've only used one idea, your input will be of value to us. Thank you in advance for all your help; your insights will help enhance this collection of educational materials and along the way will educate more of our youth about modern physics!

Sincerely,

The Chicago QuarkNet Section

Please return survey to:

Jennifer Ciaccio
231 West Potomac Avenue
Lombard, IL 60148
E-mail: jaciaccio@sbcglobal.net

Please rate the following with (0) being poor and (10) being excellent.

Worksheets:

1 2 3 4 5 6 7 8 9 10

Activities/Labs:

1 2 3 4 5 6 7 8 9 10

Unit Plans:

1 2 3 4 5 6 7 8 9 10

Organization of the Material:

1 2 3 4 5 6 7 8 9 10

Please turn the page over for the rest of the survey.

Which activities did you use in your classroom? Please comment on each of them. If you need more room, please answer on a separate sheet of paper.

What did you find most helpful about this educational packet?

What did you find least helpful about this packet?

Are there any other comments you would like to make that would help us?

Please fill out the following information so that our group can keep track of where the educational packets have been distributed. Thank you!

Name: ____

School: ____

Address: ____

____

E-mail: ____

Grades and classes that you teach:

____

____

____

Materials for

Teaching Modern Physics

Prepared by:

QuarkNet Teachers from
Fermilab and the University of Chicago

July 2006

QuarkNet Curriculum
Chicago-Fermilab Section

Jennifer Ciaccio – West Chicago High School
Richard DeCoster – Niles West High School
Deborah Lojkutz – Joliet West Township High School
Laura Nickerson – Illinois Mathematics and Science Academy
Joshua Norten – Cary-Grove High School
Elizabeth Ramseyer – Niles West High School
Annette Rubino – West Chicago Community High School
Daniel Rubino – Glenbard North High School
Donald Lincoln - Fermilab

QuarkNet is a nationwide program that connects high school physics teachers to scientists working at high-energy physics experiments. The goal is to bring this cutting-edge physics to the students. Teachers meet throughout the year with researchers at universities and research facilities.

Our Chicago QuarkNet group meets at Fermilab and has enjoyed our collaboration with the scientists there. In the spring of 2004, our group decided that to bring high-energy physics into the high school classroom, we needed to write some specific curriculum for teachers. We focused on two concepts to achieve that goal. Our first was to write a specific weeklong unit that a teacher could use, which focuses on the basics of high-energy physics. We feel that web resources, activities, worksheets and test questions are essential to a physics teacher who may not have the time to create such a plan from scratch. Our next goal is to give teachers the opportunity to sprinkle high-energy physics topics into the yearlong curriculum. We have written larger items such as labs and activities. We have also created something as simple as momentum problems using high-energy physics as the topic. In either, the teacher can spark enthusiasm in students by bringing in topics that will excite and inform them, as they are the current topics in the physics world.

Our group hopes that this curriculum will be helpful to you in the classroom and will spark interest in your students.

Sincerely,

The Chicago QuarkNet Section

QuarkNet Curriculum
Chicago-Fermilab Section
Sorted by Topics

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* This activity does not include answers.

Astronomy

Resources

* This activity does not include answers.

Units

* This activity does not include answers.

QuarkNet Curriculum
Chicago-Fermilab Section
Sorted by Activity

Problems & Worksheets

Labs & Activities

* This activity does not include answers.

* This activity does not include answers.

* This activity does not include answers.

The Quark Zoo

Goal:

Practice your ability to observe patterns as you interact with your new colleagues.

Procedure:

1. Determine the rules by which quarks join with other quarks.
2. Record any other observations.
3. Record any questions your group may have as a result of your observations.

Allowed Quark Groups:

$u\ u\ d$	$\bar{u}\ d$	$u\ \bar{s}$	$\bar{u}\ \bar{d}\ \bar{d}$	$\bar{d}\ c$
$\bar{u}\ s$	$\bar{u}\ \bar{u}\ \bar{d}$	$u\ d\ b$	$u\ \bar{b}$	$\bar{u}\ \bar{u}\ \bar{c}$
$\bar{d}\ \bar{s}\ \bar{c}$	$u\ d\ s$	$u\ d\ d$	$u\ \bar{d}$	

Rules:

Observations:

Questions:

The Quark Zoo
Teacher's Notes & Set-up

<u>Instructions for teacher to give to students</u>:

Many rules or discoveries in science result from the observation of patterns. At Fermilab, scientists energize protons and then smash them into energized antiprotons. The energy that results from this collision reorganizes into different particles. These particles are groups of quarks (one of the smallest building blocks of matter).

Study the groups of quarks these scientists have seen. . . .

<u>Materials</u>:

Each group is given a Quark Zoo worksheet. You may also want to prepare a set of cards with each allowed quark group written on a card so that students could sort and categorize them during the activity.

Results:

- 5 different quarks
- "Bar" only joins with an "antibar" or with two other "bars"
- u & d quarks are very common.

Teacher Comments:

- There are six…u&d….s&c…b&t *(NOTE: T is missing; discuss with students why it is hard to find; it's not common.)*
- Baryons vs. Mesons
- Protons vs. neutrons
- (Electrons are leptons.)

. . . Now we can move onto the standard model!!!

Student Worksheet
Constant Velocity Problems

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1. The MINOS experiment involves sending a beam of neutrinos at the speed of light to the Soudan iron mine 420 miles away. Calculate the amount of time for a massless neutrino to go from Fermilab to Soudan.

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2. The Fermilab accelerator forces protons to travel in a circular orbit with radius 1 km. If the protons are traveling essentially at the speed of light, how many times does the proton complete the circle per second? How long does one orbit take? How many orbits are in 12 hours (which is the normal time the beam lasts)? How far does the proton travel in the 12 hours?

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3. How far does a photon go in one millionth of a second?

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4. An evil alien assassin intends to shoot the president of Earth. His weapon of choice is a particle beam, consisting of particles traveling at 1/3 the speed of light. The assassin's culture requires that he simultaneously warn his target by flashing a bright light in his eyes, giving him an opportunity to duck. If the assassin, sitting on the moon's surface, simultaneously flashes his light and fires his weapon at the president, how long will the president have to react between the time he sees the light and the particle beam that would hit him?

---

5. Cosmic rays are created in the upper atmosphere when a proton from outer space hits an air molecule. After the collision, the cosmic rays consist of photons and muons. The photons travel at the speed of light, while the muons travel at 99.5% the speed of light. If the cosmic rays are created at an altitude of 20 km and travel so that they hit the ground at an angle of 30°, calculate the difference in arrival time between the muons and photons.

Teacher's Key
Constant Velocity Problems

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1. The MINOS experiment involves sending a beam of neutrinos at the speed of light to the Soudan iron mine 420 miles away. Calculate the amount of time for a massless neutrino to go from Fermilab to Soudan.

   Easy solution: *Use speed of light = 186,000 miles/second, with t = d/v and t = 2.26 ms.*
   Next solution: *Convert distance to meters and use metric speed of light.*

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2. The Fermilab accelerator forces protons to travel in a circular orbit with radius 1 km. If the protons are traveling essentially at the speed of light, how many times does the proton complete the circle per second? How long does one orbit take? How many orbits are in 12 hours (which is the normal time the beam lasts)? How far does the proton travel in the 12 hours?

   Need to calculate the distance around the ring. From speed and time, you calculate total distance. Divide distance by circumference and get number of orbits. For second part, divide circumference by velocity.

Circumference of ring $C = 2\pi r = 6.28$ km
Total distance in one second = $d = v\,t = (3 \times 10^8 \text{ m/s})(1 \text{ s}) = 3 \times 10^8$ m
Total number of orbits = $(3 \times 10^8 \text{ m})/6280 = 47770.7$ orbits

Time for one orbit = $t = d/v = (6280 \text{ m})/(3 \times 10^8 \text{ m/s}) = 2.1 \times 10^{-5}$ s

First calculate total time: $T = (12 \text{ hr})(3600 \text{ s/hr}) = 43200$ s
Total distance = 1.3×10^{13} m
Number of orbits = $(1.3 \times 10^{13} \text{ m})/6280 = 2.1 \times 10^9$

Total distance = $d = vt = (3 \times 10^8 \text{ m/s})(43200 \text{ s}) = 1.3 \times 10^{13}$ m

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3. How far does a photon go in one millionth of a second?

Simple velocity problem: $d = vt = (3 \times 10^8 \text{ m/s})(10^{-6} \text{ s}) = 3 \times 10^2$ m

---

4. An evil alien assassin intends to shoot the president of Earth. His weapon of choice is a particle beam, consisting of particles traveling at 1/3 the speed of light. The assassin's culture requires that he simultaneously warn his target by flashing a bright light in his eyes, giving him an opportunity to duck. If the assassin, sitting on the moon's surface, simultaneously flashes his light and fires his weapon at the president, how long will the president have to react between the time he sees the light and the particle beam that would hit him?

Need to calculate the two times and calculate the difference between them. Use an earth-moon orbit distance of 3.84×10^8 m. The two velocities are the speed of light (3×10^8 m/s) and 1/3 that velocity (3×10^8 m/s).

Time calculation is $t = d/v$.

$t(\text{light}) = (3.84 \times 10^8 \text{ m})/(3 \times 10^8 \text{ m/s}) = 1.28$ s

$t(\text{beam}) = (3.84 \times 10^8 \text{ m})/(1 \times 10^8 \text{ m/s}) = 3.84$ s

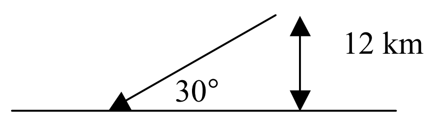
Arrival time difference = 3.84 - 1.28 = 2.56 s

---

5. Cosmic rays are created in the upper atmosphere when a proton from outer space hits an air molecule. After the collision, the cosmic rays consist of photons and muons. The photons travel at the speed of light, while the muons travel at 99.5% the speed of light. If the cosmic rays are created at an altitude of 20 km and travel so that they hit the ground at an angle of 30°, calculate the difference in arrival time between the muons and photons.

First calculate the path length.

$\sin(30°) = 12/L \rightarrow L = 24$ km



Now calculate the two times and find the difference between them.

Use $t = d/v$

$t(\text{photon}) = (24000 \text{ m})/(3 \times 10^8 \text{ m/s}) = 80\ \mu$s

$t(\text{photon}) = (24000 \text{ m})/(0.995 \times 3 \times 10^8 \text{ m/s}) = 80.4\ \mu$s

The difference is 80.4 – 80 = 0.4 μs = 400 ns.

Free Fall and Projectiles

Sample Problem:

Billy stands on the Tacoma Narrows Bridge kicking stones into the water below. If Billy kicks a stone with a horizontal velocity of 3.5 m/s, and it lands in the water a horizontal distance of 5.4 m from where Billy is standing,

A. What is the height of the bridge?

B. If the stone had been kicked harder, how would this affect the time it would take to fall?

Homework:

1. A car drives straight off of a cliff that is 50 m high. The police at the scene of this accident note that the point of impact is 90 m from the base of the cliff. How fast was the car traveling when it left the cliff?

2. In physics lab, Dimo rolls a 10-g marble down a ramp and off the table with a horizontal velocity of 3 m/s. The marble falls in a cup placed 2 m from the table's edge. How high is the table?

3. Cindy drops a cherry pit out the car window 1 m above the ground while traveling down the road at 18 m/s. (Neglect air resistance.)

   a. How far horizontally from the initial dropping point will the pit hit the ground?

   b. If the car continues to travel at the same speed, where will the car be in relation to the pit when it lands?

Free Fall and Projectiles
KEY

Sample Problem:

Billy stands on the Tacoma Narrows Bridge kicking stones into the water below. If Billy kicks a stone with a horizontal velocity of 3.5 m/s, and it lands in the water a horizontal distance of 5.4 m from where Billy is standing,

Horizontal	**Vertical**
v = 3.5 m/s	**v_i = 0 m/s**
d = 5.4 m	**d = ?**
t = 1.54 s	**t = 1.54s**
	a = -9.8 m/s^2

A. What is the height of the bridge?

$$d = v_i t + 1/2at^2$$
$$d = 0 + 1/2(-9.8 m/s^2)(1.54s)^2$$
$$d = 11.7 m$$

B. If the stone had been kicked harder, how would this affect the time it would take to fall?

It would not affect the time. It will be the same time since it's the same drop, just a greater horizontal distance.

Homework:

1. A car drives straight off of a cliff that is 50 m high. The police at the scene of this accident note that the point of impact is 90 m from the base of the cliff. How fast was the car traveling when it left the cliff?

$$d = v_i t + 1/2at^2$$
$$-90 m = 0 + 1/2(-9.8 m/s^2)t^2$$
$$t = 4.28 s$$

$$v = d/t = 90 m / 4.28 s = 21 m/s$$

2. In physics lab, Dimo rolls a 10-g marble down a ramp and off the table with a horizontal velocity of 3 m/s. The marble falls in a cup placed 2 m from the table's edge. How high is the table?

v = d/t 3 m/s = 2 m / t t = 0.67 s

$$d = 0 + 1/2(-9.8 m/s^2)(0.67s)^2 = 2.2 m$$

3. Cindy drops a cherry pit out the car window 1 m above the ground while traveling down the road at 18 m/s. (Neglect air resistance.)

$d = v_i t + 1/2at^2$

$-1\ m = 0 + 1/2(-9.8 m/s^2)t^2$

$t = 0.45\ s$

a. How far horizontally from the initial dropping point will the pit hit the ground?

$v = d/t$

$18\ m/s = d / 0.45s$

$d = 8.13\ m$

b. If the car continues to travel at the same speed, where will the car be in relation to the pit when it lands?

In the same place if there is no air resistance.

Conservation of Momentum

Sample Problems:

Adrian and Iqbal have a combined mass of 200 kg and are zooming along in a 100-kg amusement park bumper car at 10 m/s. They bump Ethan's car, which is sitting still. Ethan has a mass of 50 kg. After the elastic collision, Adrian and Iqbal continue ahead with a speed of 4 m/s. How fast is Ethan's car bumped across the floor?

If an 800-kg sports car slows to 13 m/s to check out an accident scene and the 1200-kg pick-up truck behind him continues traveling at 25 m/s, with what velocity will the two move if they lock bumpers after a rear-end collision?

Ruth, a 65-kg skin diver, shoots a 2-kg spear with a speed of 15 m/s at a fish who darts quickly away without getting hit. How fast does Ruth move backwards when the spear is shot?

Homework:

1. A 100-g marble strikes a 25-g marble that is at rest on a smooth horizontal surface. In the impact, the speed of the larger marble is reduced from 100 cm/s to 60 cm/s. What is the speed of the smaller marble immediately after impact?

2. Running at 2 m/s, Chris, the 50-kg running back, collides with Yoon, the 90-kg defensive lineman, who is traveling at 7 m/s in the other direction. Upon collision, Yoon continues to travel forward at 1 m/s.

   How fast is Chris knocked backward?

3. A 55-kg swimmer is standing on a stationary 210-kg floating raft. The swimmer runs off the raft at a speed of 5 m/s.

   Explain what happens to the raft using numbers and formulae.

4. A 50-g sticky mass strikes a 1-kg block and sticks to it. If the sticky mass and the block travel with a speed of 10 m/s after the collision, what is the speed of the sticky mass before it struck the block?

Conservation of Momentum
KEY

Sample Problems:

$$m_1v_{1i}+m_2\,v_{2i} = m_1v_{1f} + m_2v_{2f}$$

Adrian and Iqbal have a combined mass of 200 kg and are zooming along in a 100-kg amusement park bumper car at 10 m/s. They bump Ethan's car, which is sitting still. Ethan has a mass of 50 kg. After the elastic collision, Adrian and Iqbal continue ahead with a speed of 4 m/s. How fast is Ethan's car bumped across the floor?

(300 kg)(10 m/s) + (150 kg)(0 m/s) = (300 kg)(4 m/s) + (150 kg) v
v = 12 m/s

If an 800-kg sports car slows to 13 m/s to check out an accident scene and the 1200-kg pick-up truck behind him continues traveling at 25 m/s, with what velocity will the two move if they lock bumpers after a rear-end collision?

(800 kg)(13 m/s) + (1200 kg)(25 m/s) = (800 kg + 1200 kg) v
v = 20.0 m/s

Ruth, a 65-kg skin diver, shoots a 2-kg spear with a speed of 15 m/s at a fish who darts quickly away without getting hit. How fast does Ruth move backwards when the spear is shot?

0 = (65 kg) v + (2 kg)(15 m/s)
v = -0.46 m/s

Homework:

1. A 100-g marble strikes a 25-g marble that is at rest on a smooth horizontal surface. In the impact, the speed of the larger marble is reduced from 100 cm/s to 60 cm/s. What is the speed of the smaller marble immediately after impact?

   (100 g)(100 cm/s) + (25 g)(0 cm/s) = (100g)(60 cm/s) + (25 g) v
   v = 160 cm/s

2. Running at 2 m/s, Chris, the 50-kg running back, collides with Yoon, the 90-kg defensive lineman, who is traveling at 7 m/s in the other direction. Upon collision, Yoon continues to travel forward at 1 m/s. How fast is Chris knocked backward?

   (50 kg)(2 m/s) + (90 kg)(-7 m/s) = (50 kg) v +(90 kg)(- 1 m/s)
   v = -8.8 m/s

3. A 55-kg swimmer is standing on a stationary 210-kg floating raft. The swimmer runs off the raft at a speed of 5 m/s. Explain what happens to the raft using numbers and formulae.

$$\mathbf{0 = (55\ kg)(5\ m/s) + (210\ kg)\ v}$$
$$\mathbf{v = -1.3\ m/s}$$

4. A 50-g sticky mass strikes a 1-kg block and sticks to it. If the sticky mass and the block travel with a speed of 10 m/s after the collision, what is the speed of the sticky mass before it struck the block?

$$\mathbf{(0.50\ kg)\ v + (1\ kg)(0\ m/s) = (0.50\ kg)(10\ m/s) + (1\ kg)(10\ m/s)}$$
$$\mathbf{v = 210\ m/s}$$

Conservation of Momentum Lab

<u>Goal</u>:

To perform an elastic collision between two balls and to compare the **vector momentum** of the system of two balls after the collision with the vector momentum before the collision. You need to know that **P** = M*v and that momentum is a vector. You also need to know the basic equations of projectile motion.

<u>Part 1 - 1D Collision</u>

1. Clamp the device to the table with "C" clamp. Rotate the end flange to the side so the ball can roll down the ramp and shoot off into the air without hitting the end flange.

2. Tape a piece of paper on the floor beneath the lower end of the device. Place a piece of carbon paper over the paper. Drop a metal ball <u>straight down</u> from the lower end of the device onto a piece of carbon paper that is on the floor. The ball will leave a mark on the paper. Call this **point A**.

3. Let metal ball roll down the ramp, off the device and hit the floor. Place a piece of carbon paper on top of a piece of paper on the floor where the ball hit the paper and repeat the ball roll. The second roll will leave a mark on the paper at **point B**.

4. Now rotate the flange back into place and adjust the set screw on the flange. Place the second metal ball on the recess of the set screw. Adjust the height of the set screw so that when ball 1 rolls down the ramp and hits ball 2 on the set screw, the second ball flies off and hits the floor very near [within a centimeter or so] of point B. This ensures that the collision between ball 1 and ball 2 is an elastic collision. <u>Do not change the level of the set screw</u>.

5. Measure to three significant figures the distance between the floor and the bottom of the balls just as the ball flies off the device. Calculate the time the ball is in the air.

<u>Part 2 – 2D Collision</u>

1. Rotate the flange to one side a bit. Place ball 2 on the set screw. Roll ball 1 down the ramp and it will hit ball 2. Both balls will fly off the apparatus and onto the floor. Notice about where each ball hits. Place a piece of carbon paper on the sheet of paper on the floor at these points. Call where ball 1 hits **point C** and where ball 2 hits **point D**.

2. <u>Do not change the set screw</u>. Repeat the previous step, but now with the carbon paper in place. Check to see that points C and D are recorded on the paper.

Analysis to prove that momentum was conserved in both dimensions:

1. Draw a line from A to B and measure its length: AB = _____________ m.

2. Repeat for lines A to C: AC = __________________ m and
   A to D: AD = _____________ m.

3. Use a protractor to measure the angle between line AB and line AC.
   Call this theta 1 = ________ degrees.

4. Use a protractor to measure the angle between line AB and line AD.
   Call this theta 2 = _____________ degrees.

5. Calculate the speeds before and after the collision.
   V1, before = AB/t = _____________ m/s

   V2, before = 0.00 m/s

   V1, after = AC/t = ________________ m/s

   V2, after = AD/t = ________________ m/s.

6. Calculate the horizontal and vertical components of each V1 and V2 in step 5.

7. Use graphical or trigonometric addition of vector to determine if $\mathbf{P}_{\text{before}} = \mathbf{P}_{\text{after}}$.

$$\mathbf{P}_{\text{before}} = \mathbf{m^*V}_{1\ \text{before}} + \mathbf{m^*V}_{2\ \text{before}}$$

and

$$\mathbf{P}_{\text{after}} = \mathbf{m^*V}_{1\ \text{after}} + \mathbf{m^*V}_{2\ \text{after}}.$$

Note that since the mass of ball 1 = mass of ball 2, the mass value is not important here. For convenience, use m = 1.

Student Worksheet
Circular Motion Problems

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1. A proton in the Fermilab Tevatron (a circular particle accelerator) has a momentum of 980 GeV/c. If the radius of the Tevatron is 1 km (it is), calculate the magnetic field necessary to accomplish this.

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2. The Fermilab accelerator is designed to use magnetic fields to make protons orbit in a circular path with a radius of 1 km. The magnetic field strength can be changed. If protons are injected into the accelerator with an initial energy of 120 GeV and are accelerated to a final energy of 980 GeV, calculate the ratio of the final to initial magnetic field.

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3. A particle physics detector consists of a circular region of radius 50 cm filled with air, surrounded by an extended region filled with metal. The air-filled region contains a magnetic field with strength 2 T, directed out of the page in the attached diagram. A proton is emitted from the center of the circle with momentum p in the plane of the paper and directed radially outwards from the center. Calculate the maximum p for which the proton will not hit the metal region.

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4. The Fermilab accelerator is designed to accelerate protons in a circular orbit with radius 1 km and to a momentum p. The new LHC accelerator accelerates protons to a momentum seven times that of the Fermilab accelerator. If the radius of circular motion followed by a proton in the LHC is 4.3 km, calculate the ratio of the magnetic field of the Tevatron to the LHC.

Teacher's Key
Circular Motion Problems

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1. A proton in the Fermilab Tevatron (a circular particle accelerator) has a momentum of 980 GeV/c. If the radius of the Tevatron is 1 km (it is), calculate the magnetic field necessary to accomplish this.

   Need to convert "particle physics" momentum to "normal" momentum. Then it is a simple case of using the formula for circular motion.

$$\mathbf{p = 980\ GeV/c = (980 \times 10^{9}\ eV)\ (1.602 \times 10^{-19}\ J/eV)/(3 \times 10^{8}\ m/s) =}$$
$$\mathbf{5.2 \times 10^{-16}\ kg\ m/s}$$

$$\mathbf{F = m\ v^2/r = q\ v\ B \rightarrow p = q\ r\ B \rightarrow B = p/(q\ r) = 3.3\ T}$$

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2. The Fermilab accelerator is designed to use magnetic fields to make protons orbit in a circular path with a radius of 1 km. The magnetic field strength can be changed. If protons are injected into the accelerator with an initial energy of 120 GeV and are accelerated to a final energy of 980 GeV, calculate the ratio of the final to initial magnetic field.

$$\mathbf{F = m\ v^2/r = q\ v\ B \rightarrow p = q\ r\ B \rightarrow B = p/(q\ r)}$$

Thus,

$$\mathbf{B_{final}/B_{initial} = [p/(q\ r)]_{final} / [p/(q\ r)]_{initial} = 980/120}$$

$$\mathbf{B_{980\ GeV} = 8.2\ B_{120\ GeV}}$$

---

3. A particle physics detector consists of a circular region of radius 50 cm filled with air, surrounded by an extended region filled with metal. The air-filled region contains a magnetic field with strength 2 T, directed out of the page in the attached diagram. A proton is emitted from the center of the circle with momentum p in the plane of the paper and directed radially outwards from the center. Calculate the maximum p for which the proton will not hit the metal region.

   This problem is mildly tricky, as one can do it a hard way and an easy way. The first thing to realize is that if the radius of the magnetic field region is 50 cm, then a particle originating at the center of the cylinder will have to travel with a radius of curvature of 25 cm to fit fully within the magnetic region. The next thing one has to do is to convert the "particle physics momentum," with its units of GeV/c to "normal momentum."

However, to do it the "normal way," one uses:

$$\mathbf{F = m\,v^2/r = q\,v\,B \rightarrow p = q\,r\,B}$$

$$\mathbf{p = (1.6 \times 10^{-19}\ C)\ (0.25\ m)\ (2\ T) = 0.8 \times 10^{-19}\ kg\ m/s}$$

Converting to "particle physics momentum":

$$\mathbf{p_{particle} = p_{normal} \times [3 \times 10^{8}\ m/s] / [1.6 \times 10^{-19}\ J/eV] =}$$
$$\mathbf{1.\ 5 \times 10^{8}\ eV/c = 0.15\ GeV/c}$$

An alternate approach is to use:

$$\mathbf{p = q\,r\,B = p_{particle\ physics} \times [q/c] \rightarrow p_{particle\ physics} = c\,r\,B}$$

(which will give a momentum in units of eV/c.)

To make the more useful GeV/c, multiply by the conversion for GeV/eV (10^{-9}). This gives a nice and final result:

$$\mathbf{p_{particle\ physics} = 0.3\ r\ B}$$

where r is in meters, B is in Tesla and $p_{particle\ physics}$ is in GeV/c.

---

4. The Fermilab accelerator is designed to accelerate protons in a circular orbit with radius 1 km and to a momentum p. The new LHC accelerator accelerates protons to a momentum seven times that of the Fermilab accelerator. If the radius of circular motion followed by a proton in the LHC is 4.3 km, calculate the ratio of the magnetic field of the Tevatron to the LHC.

$$\mathbf{F = m\,v^2/r = q\,v\,B \rightarrow p = q\,r\,B \rightarrow B = p/(q\,r)}$$

Thus,

$$\mathbf{B_{LHC}/B_{Tevatron} = [p/(q\ r)]_{LHC} / [p/(q\ r)]_{Tevatron} = [p_{LHC} / p_{Tevatron}]\ [r_{Tevatron} / r_{LHC}]}$$

$$\mathbf{B_{LHC} = [7/1]\ [1/4.3] = 1.63\ B_{Tevatron}}$$

Student Worksheet
Constant Acceleration/Force Problems

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1. The Fermilab accelerator has a circular shape, with radius of 1 km. It can take protons with an initial energy of 120 GeV and accelerate them to 980 GeV in 20 seconds. The acceleration actually only takes place via an electric force that is only 50 feet along the orbit. The remainder contains magnetic fields that only bring the protons back around in a circle for another acceleration phase.

   a. Calculate the average power added to the protons.

   Since the protons are relativistic (i.e., traveling at the speed of light at all energies), one can calculate the number of orbits per second.

   b. Calculate the number of orbits in 20 seconds.

   c. Calculate the increase in energy per orbit.

   d. Calculate the average strength of the electric field in the acceleration region. Assume the electric field is constant in the acceleration region.

---

2. The first accelerator in the Fermilab accelerator chain is the Cockcroft-Walton. A proton enters the accelerator with essentially zero energy and exits with a velocity of 4 percent of the speed of light (thus allowing you to ignore any relativistic effects). If the acceleration time is 0.16 μs,

   a. Calculate the average acceleration of the proton and compare it to the acceleration due to gravity.

b. Calculate the force on the proton.

c. If the electric field can be approximated as being constant and uniform, what is the length of the acceleration region?

---

1. The first accelerator in the Fermilab accelerator chain is the Cockcroft-Walton. A proton is accelerated from rest across an electric potential of 750 kV and exits the acceleration region in 0.16 μs. If the acceleration region is filled with a uniform and constant electric field, calculate the region's length.

Teacher's Key
Constant Acceleration/Force Problems

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1. The Fermilab accelerator has a circular shape, with radius of 1 km. It can take protons with an initial energy of 120 GeV and accelerate them to 980 GeV in 20 seconds. The acceleration actually only takes place via an electric force that is only 50 feet along the orbit. The remainder contains magnetic fields that only bring the protons back around in a circle for another acceleration phase.

   a. Calculate the average power added to the protons.

      $\langle P \rangle = (E_{final} - E_{initial})/\text{time} = (980 - 120)/20 = 43$ GeV/s $= 6.88 \times 10^{-9}$ W

   Since the protons are relativistic (i.e., traveling at the speed of light at all energies), one can calculate the number of orbits per second.

   b. Calculate the number of orbits in 20 seconds.

      $d = v\,t$, $v = c$, $\rightarrow d = (3 \times 10^{8}$ m/s$)(20$ s$) = 6 \times 10^{9}$ m
      Circumference $= 2\,\pi\,r = 6.28$ km
      (# orbits) = distance/circumference $= 9.6 \times 10^{5}$ orbits

   c. Calculate the increase in energy per orbit.

      $\Delta E/\Delta\text{orbit} = (980 - 120)/\ 9.6 \times 10^{5} = 9 \times 10^{-4}$ GeV/orbit = 900 keV/orbit

   d. Calculate the average strength of the electric field in the acceleration region. Assume the electric field is constant in the acceleration region.

      If the energy increase in each pass is 900 keV, and the particle is a proton, then the accelerating voltage is 900 kV.

      $V = Ed \rightarrow E = V/d = (900$ kV$)/(50$ ft$) = 60$ kV/m

---

1. The first accelerator in the Fermilab accelerator chain is the Cockcroft-Walton. A proton enters the accelerator with essentially zero energy and exits with a velocity of 4 percent of the speed of light (thus allowing you to ignore any relativistic effects). If the acceleration time is 0.16 μs,

   a. Calculate the average acceleration of the proton and compare it to the acceleration due to gravity.

$\langle a \rangle = (v_{final} - v_{initial})/time = (0.04)(3 \times 10^8)/(0.16 \times 10^{-6}) = 7.5 \times 10^{13}\ m/s^2$
(Much bigger than gravity's 9.8 m/s^2)

b. Calculate the force on the proton.

$F = m\ a = (1.67 \times 10^{-27}\ kg)\ (7.5 \times 10^{-13}\ m/s^2) = 1.25 \times 10^{-13}\ N$

c. If the electric field can be approximated as being constant and uniform, what is the length of the acceleration region?

$E = F/q = (1.25 \times 10^{-13}\ N)/(1.6 \times 10^{-19}\ q) = 7.82 \times 10^5\ N/C = 782\ kV/m$
Since E = V/d and consequently d = V/E, we need to find the accelerating potential. Since the particle starts at rest and has a final speed of 4 percent of the speed of light, we can calculate the change in kinetic energy, use energy conservation to calculate the initial potential energy and use the unit charge of the proton to determine the underlying electric potential.

$KE = 1/2m\ v^2 = 1/2(1.67 \times 10^{-27}\ kg)(\ 0.04 \times 3 \times 10^8)^2$
$PE = qV = KE \rightarrow V = KE/q = 750{,}000\ V$
So $d = V/E = (750\ kV)/(782\ kV) = 0.96\ m$

---

1. The first accelerator in the Fermilab accelerator chain is the Cockcroft-Walton. A proton is accelerated from rest across an electric potential of 750 kV and exits the acceleration region in 0.16 μs. If the acceleration region is filled with a uniform and constant electric field, calculate the region's length.

Calculate potential energy. Use energy conservation to calculate final velocity. Use velocity and time to calculate constant acceleration. Use acceleration and mass to find force. Use force and charge to calculate electric field. Finally, use electric potential and electric field to find distance.

$qV = 1/2m\ v^2 \rightarrow v = (2\ q\ V/m)^{1/2}$
$a = v/t$
$F = m\ a$
$E = F/q$
$d = V/E$
$d = t\ (Vq/(2m))^{1/2}$
$d = (0.16 \times 10^{-6})[(750000)(1.602 \times 10^{-19})/2/(1.67 \times 10^{-27})]^{1/2} = 0.96\ m$

The Electron

1. What is the value of e/m for a particle that moves in a circle of radius 8.0 mm in a 0.46 T magnetic field that is crossed by a 200 V/m electric field that makes the path straight?

2. Protons move in a circle of radius 5.20 cm in a 0.465 T magnetic field. What value of electric field could make their paths straight? In what direction must it point?

3. What is the velocity of a beam of electrons that go undeflected when passing through crossed electric and magnetic fields of magnitude 8.85×10^{3} V/m and 4.5×10^{-3} T respectively? What is the radius of the electron orbit if the electric field is turned off?

4. In an early set of experiments (1911), Millikan observed that the following measured charges, among others, appeared at different times on a single drop of oil. What value of elementary charge can be deduced from these data?

   a. 6.563×10^{-19} C
   b. 8.204×10^{-19} C
   c. 11.5×10^{-19} C
   d. 13.13×10^{-19} C
   e. 16.48×10^{-19} C
   f. 18.08×10^{-19} C
   g. 19.71×10^{-19} C
   h. 22.89×10^{-19} C
   i. 26.13×10^{-19} C

5. A negatively charged oil drop weighs 8.5×10^{-15} N. The drop is suspended in an electric field intensity of 5300 N/C.
   a. What is the charge on the drop?
   b. How many electrons does is carry?

The Electron
KEY

1. What is the value of e/m for a particle that moves in a circle of radius 8.0 mm in a 0.46 T magnetic field that is crossed by a 200 V/m electric field that makes the path straight?

   $$\frac{q}{m} = \frac{E}{B^2 r} \qquad \frac{q}{m} = \frac{200\ \text{V/m}}{(.46\text{T})^2(8 \times 10^{-3}\text{m})} = 118147\ \text{c/kg}$$

2. Protons move in a circle of radius 5.20 cm in a 0.465 T magnetic field. What value of electric field could make their paths straight? In what direction must it point?

   $$\frac{q}{m} = \frac{E}{B^2 r} \qquad \frac{q_p}{m_p} = \frac{200\ \text{V/m}}{(.465\text{T})^2(5.2 \times 10^{-2}\text{m})} \qquad E = 1.1 \times 10^6\ \text{V/m}$$

3. What is the velocity of a beam of electrons that go undeflected when passing through crossed electric and magnetic fields of magnitude 8.85 x 10^3 V/m and 4.5 x 10^{-3} T respectively?

   $$V = \frac{E}{B} = \frac{8.85 \times 10^3\ \text{V/m}}{4.5 \times 10^{-3}\ \text{T}} = 1.96 \times 10^6\text{m/s}$$

   What is the radius of the electron orbit if the electric field is turned off?

   $$\frac{mv^2}{r} = qvB \qquad \text{Solve for } r = 0.002\ \text{m}$$

4. In an early set of experiments (1911), Millikan observed that the following measured charges, among others, appeared at different times on a single drop of oil. What value of elementary charge can be deduced from these data?

   a.) 6.563 x 10^{-19} C
   b.) 8.204 x 10^{-19} C
   c.) 11.5 x 10^{-19} C
   d.) 13.13 x 10^{-19} C
   e.) 16.48 x 10^{-19} C
   f.) 18.08 x 10^{-19} C
   g.) 19.71 x 10^{-19} C
   h.) 22.89 x 10^{-19} C
   i.) 26.13 x 10^{-19} C

   First have the students notice the similar "ending" (x10^{-19}C).

   Second, find the greatest common factor of the numbers preceding the "similarity" by "2." You will soon notice another similarity . . . that each of these values is close to "1.6." Thus, the answer is "1.6x10^{-19}C" or the charge of a single electron.

5. A negatively charged oil drop weighs 8.5×10^{-15} N. The drop is suspended in an electric field intensity of 5300 N/C.
   a.) What is the charge on the drop?
   b.) How many electrons does is carry?

$F_E = mg$

a. **$E_q = mg$**
Solve for $q = \frac{8.5 \times 10^{-15}}{5300} = 1.6 \times 10^{-18}$

b. **Divide by q_e**
Answer = 10 e^{-1}

The History of the Electron Worksheet
Conceptual Physics

Directions: Please answer each question using a complete sentence.

1. Describe a cathode ray.

2. A fast moving electron enters a magnetic field. Describe what happens to the electron during this interaction. Use the words: *magnetic field, perpendicular, path and force*.

3. Explain Millikan's oil drop experiment. Use at least three sentences and include the words: *charge, force, gravity, electric*.

4. In an early set of experiments (1911), Millikan observed that the following measured charges, among others, appeared at different times on a single drop of oil. Each of these drops of oil had a different mass. What value of elementary charge can be deduced from these data?

   a. 6.563×10^{-19}C
   b. 11.5×10^{-19}C
   c. 13.13×10^{-19}C
   d. 22.89×10^{-19}C
   e. 26.13×10^{-19}C

   What does this elementary charge represent?

5. Draw a force diagram of an electron falling in the Millikan experiment.

6. What forces were applied on the cathode ray in J. J. Thompson's experiment?

   Draw a force diagram for the electron in Thompson's experiment when the electron is traveling in a straight path.

The History of the Electron Worksheet - Key
Conceptual Physics

<u>Directions</u>: *Please answer each question using a complete sentence.*

1. Describe a cathode ray.

   Look for the word "electron" or phrase "stream of charged particles."

2. A fast moving electron enters a magnetic field. Describe what happens to the electron during this interaction. Use the words: *magnetic field, perpendicular, path and force*.

   As the electron moves perpendicular to the constant magnetic field direction, a constant magnetic force causes the electron's path to bend.

3. Explain Millikan's oil drop experiment. Use at least three sentences and include the words: *charge, force, gravity, electric.*

   Charged oil drops are made to fall due to the force of gravity within a variable electric field. The force of gravity that varies with the mass of the oil drop is made to fall within an electric field. If the electric force acting on an oil drop is made to equal the gravitational force on the oil drop, then the charge mass ratio can be determined.

4. In an early set of experiments (1911), Millikan observed that the following measured charges, among others, appeared at different times on a single drop of oil. Each of these drops of oil had a different mass. What value of elementary charge can be deduced from these data?

   a. 6.563×10^{-19}C
   b. 11.5×10^{-19}C
   c. 13.13×10^{-19}C
   d. 22.89×10^{-19}C
   e. 26.13×10^{-19}C

   Divide each by 2 and 1.6×10^{-19}C should emerge.

   What does this elementary charge represent?

   The charge on an electron

5. Draw a force diagram of an electron falling in the Millikan experiment.

   Electric force vector up should equal gravitational force vector down.

6. What forces were applied on the cathode ray in J. J. Thompson's experiment?

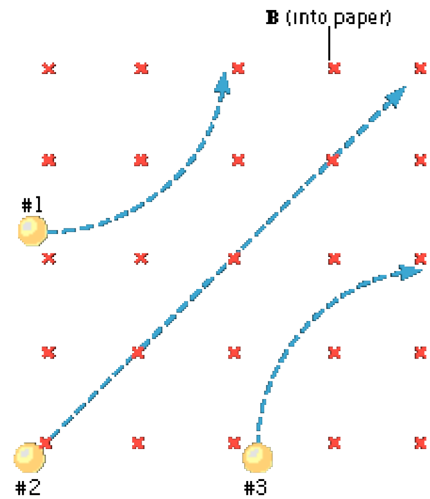
   Electric force, magnetic force, (gravitational force very weak)

   Draw a force diagram for the electron in Thompson's experiment when the electron is traveling in a straight path.

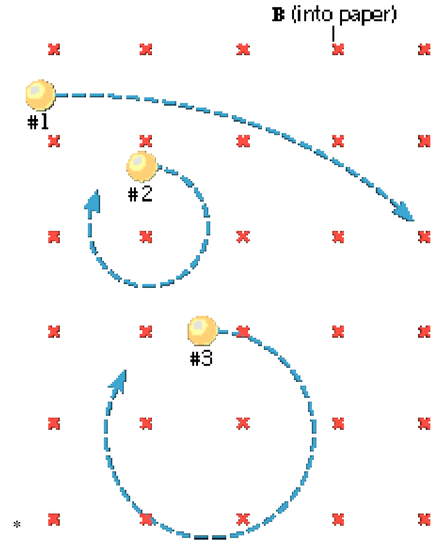
   Electric force on electron equal and opposite to magnetic force on electron

Student Worksheet
Motion of Charged Particles in a Magnetic Field

1. Three particles move through a constant magnetic field and follow the paths shown in the drawing. Determine whether each particle is positively charged, negatively charged, or neutral. Give a reason for each answer.



2. Three particles have identical charges and masses. They enter a constant magnetic field and follow the paths shown in the picture. Which particle is moving the fastest, and which is moving the slowest? Justify your answers.



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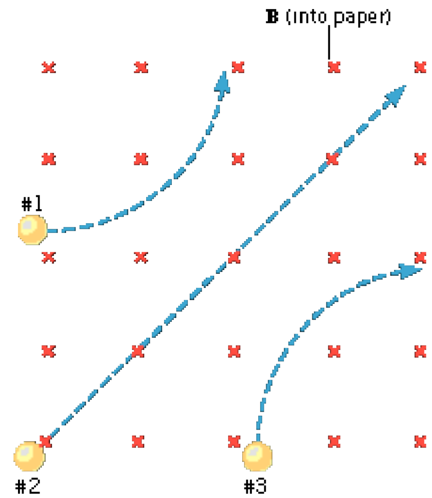
* Pictures are from Webassign.

Teacher's Key
Motion of Charged Particles in a Magnetic Field

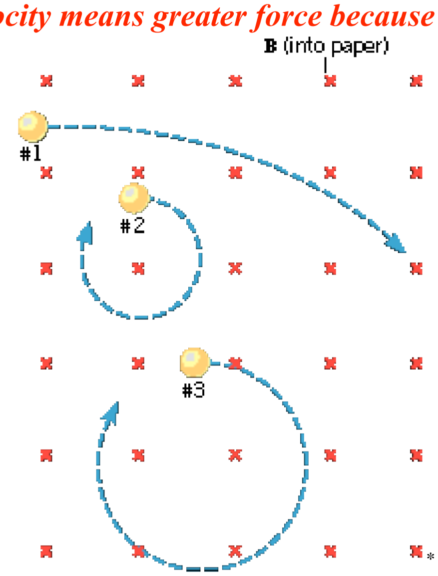
1. Three particles move through a constant magnetic field and follow the paths shown in the drawing. Determine whether each particle is positively charged, negatively charged, or neutral. Give a reason for each answer.

#1 is positive. ***#2 is neutral.*** ***#3 is negative.***



2. Three particles have identical charges and masses. They enter a constant magnetic field and follow the paths shown in the picture. Which particle is moving the fastest, and which is moving the slowest? Justify your answers.

Fast → Slow, the order is 2 – 3 – 1
Greater velocity means greater force because q & B are the same.



* Pictures are from Webassign.

Particle Quiz 2

Answer each question on a separate sheet of paper showing as much work as possible. When you are finished, add an extra question at the end of the quiz. If you ask about this at all, you will not receive credit for this question.

1. A uniform electric field exists in a region between two oppositely charged plates. An electron is released from rest at the surface of the negatively charged plate and strikes the surface of the opposite plate 2 cm away, 1.5×10^{-8} seconds later.

    a. Knowing that the electron will accelerate in the field, choose an equation from the board that will determine the acceleration of the electron and find it.

    b. Calculate the net force on the electron.

    c. Determine the weight of an electron.

    d. Determine the electric force on the electron and then calculate the electric field strength.

    e. Determine the electric potential difference between the plates.

2. An electron moving westward with a speed of 10000 m/s enters a uniform magnetic field of strength of 3T directed north.

    a. What is the magnetic force felt by the electron?

    b. What is the direction of the magnetic force?

    c. What electric field strength is needed to balance the magnetic force felt by the electron?

Particle Quiz 2
Key

Answer each question on a separate sheet of paper showing as much work as possible. When you are finished, add an extra question at the end of the quiz. If you ask about this at all, you will not receive credit for this question.

1. A uniform electric field exists in a region between two oppositely charged plates. An electron is released from rest at the surface of the negatively charged plate and strikes the surface of the opposite plate 2 cm away, 1.5×10^{-8} seconds later.

   a. Knowing that the electron will accelerate in the field, choose an equation from the board that will determine the final velocity of the electron.

   $v_i = 0$
   $v_f = ?$
   $d = 0.02m$
   $a = ?$
   $t = 1.5 \times 10^{-8}s$

   $d = v_it + 1/2at^2$
   $0.02m = 0 + 1/2a\ (1.5 \times 10^{-8}s)^2$
   $a = 1.8 \times 10^{14} m/s^2$

   b. Calculate the net force on the electron.

   $F = ma = (9.11 \times 10^{-31}kg)\ (1.8 \times 10^{14}m/s^2) = 1.6 \times 10^{-16}\ N$

   c. Determine the weight of an electron.

   $W = mg = (9.11 \times 10^{-31}kg)\ (9.8\ m/s^2) = 8.9 \times 10^{-30}\ N$

   d. Determine the electric force on the electron and then calculate the electric field strength.

   $F = E\text{-}W \rightarrow E = F+W = 1.6 \times 10^{-16}\ N$

   e. Determine the electric potential difference between the plates.

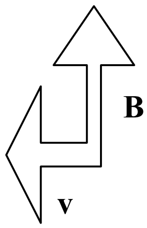
   $V = Ed = 1000\ N/C\ (.02m) = 20\ V$

2. An electron moving westward with a speed of 10000 m/s enters a uniform magnetic field of strength of 3T directed north.

   a. What is the magnetic force felt by the electron?

   $F_B = qvB = -1.6x19^{-19}C\ (10000\ m/s)\ (3T) = -4.8 \times 10^{-15}\ N$

b. What is the direction of the magnetic force?



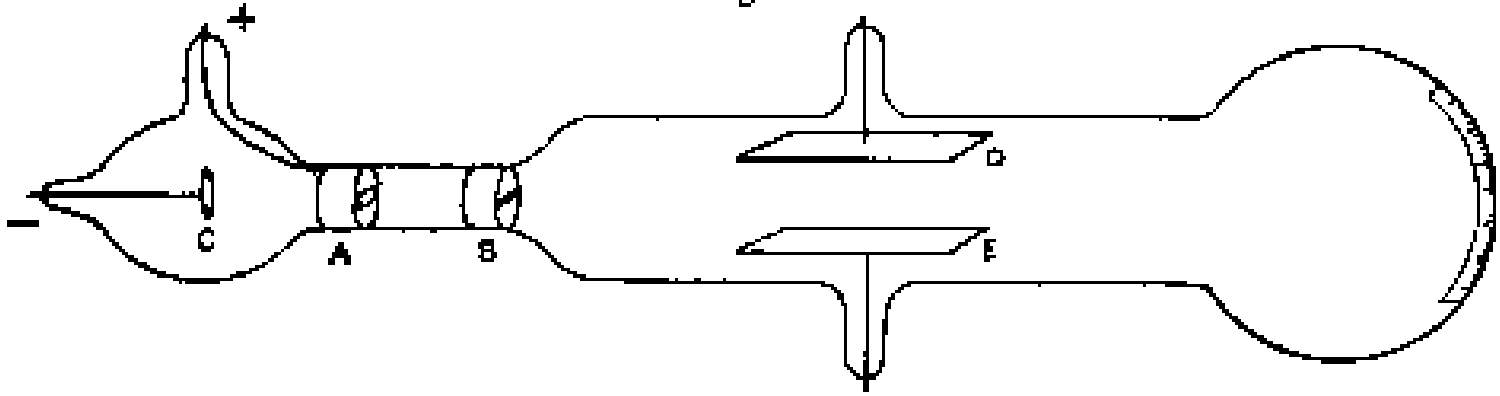
Out of the page

c. What electric field strength is needed to balance the magnetic force felt by the electron?

$\mathbf{E = F_E / q = F_B / q = 30000\ N/C}$

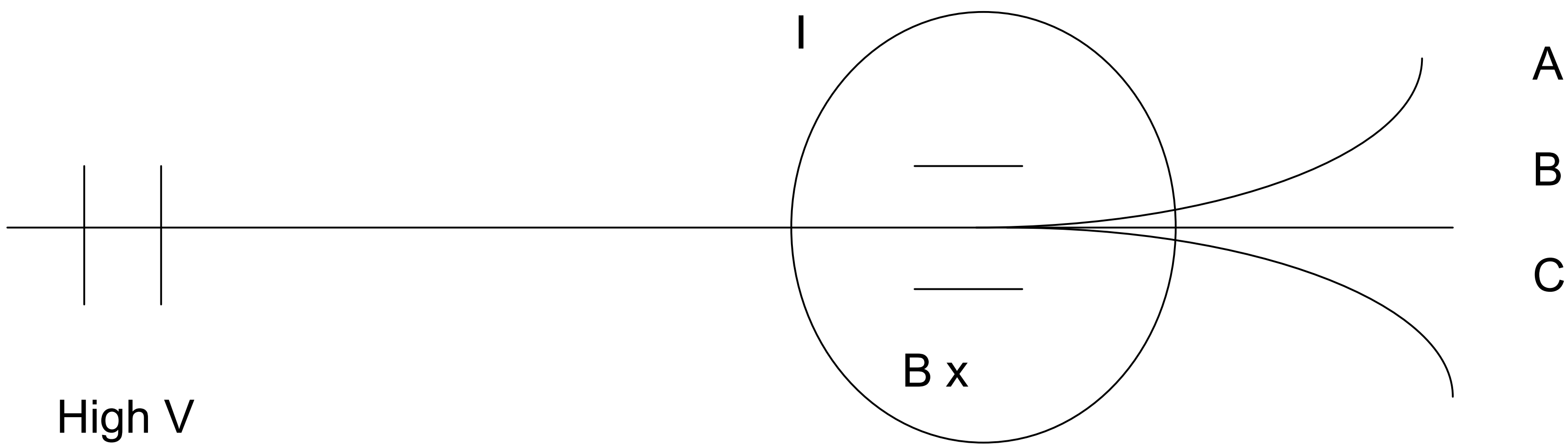
The Electron
<u>Discovery by J. J. Thompson (1897)</u>
Used idea that cathode rays (produced by cathode and anode at high electric potential) can be bent by interaction of electric fields and magnetic fields.

Fig. 2.



The Three Experiments in One…

A cathode ray sent into a variable magnetic field and through an electric field, which is also variable.



For path A…

The cathode ray only interacts with the electric field so:

$$F_c = F_E$$

$$(mv^2)/r = qE$$

For path C…

The cathode ray only interacts with the magnetic field so:

$$F_c = F_B$$

$$(mv^2)/r = qvB$$

$$q/m = v/(Br)$$

For path B…

The cathode ray interacts with both the electric field and the magnetic field simultaneously.

$F_E = F_B$

$qE = qvB$

$v = E/B$

Using v = E/B and q/m = v/(Br)…

$q/m = (E/B)/(Br)$ or

$q/m = E/(B^2r)$ since $V = Ed$

$q/m = V/(B^2rd)$

(Thompson could determine the charge-to-mass ratio of the "cathode ray" by measuring V, I (magnetic field), radius of curvature and the distance between the plates.)

Millikan’s Oil Drop Experiment

The electrical charge carried on an electron is a fundamental constant in physics. The accepted value for e = 1.602 E-19 C. R. A. Millikan was the first to measure the constant. He did so in his oil drop experiment (1909-1913). Millikan also showed the discreteness of the charge, meaning only integral multiples of the charge exists.

http://webphysics.davidson.edu/Alumni/ToHaynie/OilDrop/oilappa.htm
(the apparatus)

In his experiment, Millikan tried to suspend an oil drop within an electric field so that:

$Fe = mg$

$qE = mg$ and since $V = Ed$

$(qV)/d = mg$ or

$q/m = (gd)/V$

Millikan always seemed to get a certain multiple of a small amount of charge. Based upon this result and the known value of g, the distance between the plates and the electric potential between them, he could mass the electron!

http://www.aip.org/history/electron/jj1897.htm
(animated image of cathode ray bent by electric field)

http://webserver.lemoyne.edu/faculty/giunta/thomson1897.html
(copy of Thompson's paper published in 1897)

http://webphysics.davidson.edu/Alumni/ToHaynie/OilDrop/oiltable.htm
(Millikan's work)

Notes on the Electron PowerPoint Presentation

<u>What is a Cathode Ray?</u>

Streams of electrons issuing from the cathode of an evacuated tube.

Demos for <u>Three Experiments in One</u>

For Path A*

Equipment: Scotch® Magic™ Tape

To do:
1. Remove a 10 cm tape from the roll. Fold over a tab to make a handle. Secure the tape to the table.

2. Create a second tape of equal length with a handle. Place the tape on top of the first piece so that it covers the length of the first piece of tape. Remove both pieces of tape from the table simultaneously. Rip the pieces apart CAREFULLY!

3. Repeat the first two steps so that now you have four tapes.

4. Bring each of these tapes together and discover the interactions. *(Similar tapes should be repelled and opposite tapes should attract.)*

5. Record your observations.

*Similar to AAPT's "String and Sticky Tape Labs" by Ron Edge

For Path C

Equipment: Strong U-shaped magnet; direct current in a wire produced by the application of an electric potential.

To do:
1. Connect approximately 1 m of wire to a DC outlet.

2. Place the wire through the arms of the magnet so that the current flows in one direction perpendicular to the magnetic field produced by the poles of the magnet.

3. Apply an electric potential to the wire and observe the behavior of the wire. *(The wire should be pushed up or down.)*

Millikan's Experiment

Draw on the student's experimentation with the sticky tapes. . . .
What would happen to an electron if it were near a negatively charged tape?
(Repel)

What would happen if an electron were placed near a positively charged tape?
(Attract)

If the electron has mass, what would the electron do under the influence of Earth's gravitational field?
(Fall down . . .)

How could you design an experiment to make an electron stop falling to the Earth?
You get to use an electron, Earth's gravity, a negatively charged plate and a positively charged plate.

(The experiment designed should always have the force of gravity (weight) of the electron balanced by the electric force of the field created by the charged plates. See diagram on website listed below.)

This website has an excellent discussion with a link which simulates the experiment. The student needs to cause the electron to stop falling in the electric field.

http://www68.pair.com/willisb/millikan/experiment.html

(This site is nice, but the Java application/demo of Millikan's Experiment freezes the computer eventually. . . .)

Student Worksheet
Index of Refraction Problems

1. Assume that you have a long optical fiber with core index of refraction $n_{core} = 1.59$ and cladding $n_{clad} = 1.49$. The fiber is 2 m long with an inner-core diameter of 1 mm. Light is generated on the axis of the fiber at one end and bounces along it to the other end. Due to small imperfections in manufacturing, the light is not quite perfectly reflected at each bounce. Calculate what fraction of light is reflected at each bounce so that 50 percent of the light makes it out of the far end of the fiber. Assume that the reflection fraction is identical for each bounce and consider only light transmitted at the critical angle.

---

2. Standard materials used in scintillating fiber in particle physics experiments are polystyrene (n = 1.59), acrylic (PMMA, n = 1.49) and fluorinated acrylic (fPMMA, n = 1.42).

   Calculate the critical angle (i.e., the angle at the core-cladding interface) for light trapped:

   a. In a fiber with a polystyrene core and a PMMA cladding.

   b. In a fiber with a polystyrene core and an fPMMA cladding.

   c. In a fiber with a polystyrene core and two claddings, an inner one of PMMA, followed by an outer one of fPMMA.

---

3. A large particle detector uses optical fiber technology. The fiber consists of a core with index of refraction = 1.59, surrounded by a cladding with index of refraction 1.49. The fiber is 14 m long. If light is injected so that it bounces at the critical angle in the fiber, how long does it take to travel the length of the fiber and exit?

---

4. A common particle detector technique involves optical scintillating fiber, which emits light when crossed by a charged particle. If the fiber consists of a core with index of refraction 1.59 and a cladding of index of refraction 1.49, what fraction of the light is trapped in the fiber and transported to an end? Assume all light is emitted at the center of the fiber (i.e., on the fiber axis) and that the light emission is isotropic.

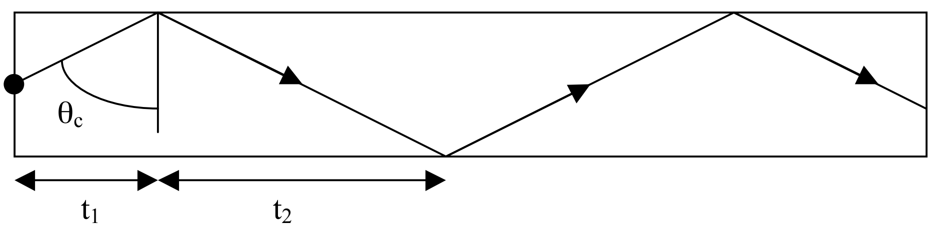
---

5. Cerenkov light is a form of light emitted when a charged particle travels in a transparent medium faster than light travels in the same medium. Calculate the minimum velocity an electron must have to emit Cerenkov light in water.

6. Cerenkov light is a form of light emitted when a charged particle travels in a transparent medium faster than light travels in the same medium. An imaginative experiment called ICE-CUBE plans to use a cubic kilometer of ice (which becomes clear at great depths) in Antarctica to detect charged particles from outer space called muons. Calculate the minimum velocity a muon must have to emit Cerenkov light in the ICE-CUBE experiment.

Teacher's Key
Index of Refraction Problems

1. Assume that you have a long optical fiber with core index of refraction $n_{core} = 1.59$ and cladding $n_{clad} = 1.49$. The fiber is 2 m long with an inner-core diameter of 1 mm. Light is generated on the axis of the fiber at one end and bounces along it to the other end. Due to small imperfections in manufacturing, the light is not quite perfectly reflected at each bounce. Calculate what fraction of light is reflected at each bounce so that 50 percent of the light makes it out of the far end of the fiber. Assume that the reflection fraction is identical for each bounce and consider only light transmitted at the critical angle.



First calculate the critical angle, then the amount of distance traveled by the light (along the fiber-axis direction) for each bounce. From that, you can calculate the number of bounces (n). Since each bounce reflects a factor r of the light, the light transmitted will be r^n.

$\sin \theta_c = 1.49/1.59 \rightarrow \theta_c = 69.6°$
$\tan \theta_c = t_1/(1\text{ mm}) \rightarrow t_1 = 2.69\text{ mm}$
$\tan \theta_c = t_2/(2\text{ mm}) \rightarrow t_1 = 5.38\text{ mm}$
How many bounces?
$t_1 + n\, t_2 = 2000\text{ mm} \rightarrow n = 371$ bounces.
Since each reflection reflects r fraction of the light,
$0.5 = r^n$,
which means that **r = 0.998 or 99.8%.**

---

2. Standard materials used in scintillating fiber in particle physics experiments are polystyrene (n = 1.59), acrylic (PMMA, n = 1.49) and fluorinated acrylic (fPMMA, n = 1.42).

   Calculate the critical angle (i.e., the angle at the core-cladding interface) for light trapped:

   a. In a fiber with a polystyrene core and a PMMA cladding.

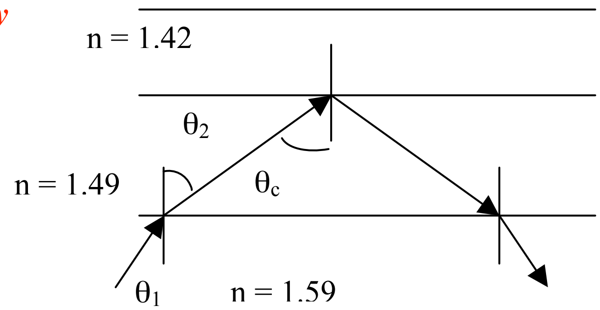
      $\sin \theta_c = 1.49/1.59 \rightarrow \theta_c = 69.6°$

b. In a fiber with a polystyrene core and an fPMMA cladding.

sin θ_c = 1.42/1.59 → θ_c = 63.3°

c. In a fiber with a polystyrene core and two claddings, an inner one of PMMA, followed by an outer one of fPMMA.

First find θ_c, then use symmetry to determine θ_2. Finally use Snell's law to determine θ_1.



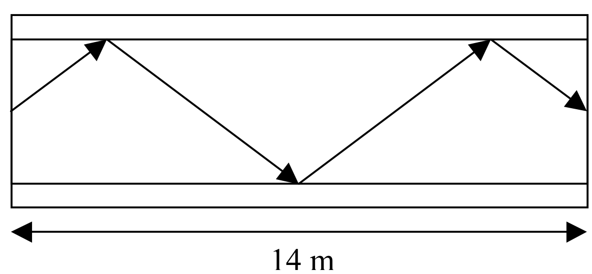
sin θ_c = 1.42/1.49
$\theta_2 = \theta_c$,

1.59 sin θ_1 = 1.49 sin θ_2
so
sin θ_1 = 1.42/1.59
θ_1 = 63.3°

---

3. A large particle detector uses optical fiber technology. The fiber consists of a core with index of refraction = 1.59, surrounded by a cladding with index of refraction 1.49. The fiber is 14 m long. If light is injected so that it bounces at the critical angle in the fiber, how long does it take to travel the length of the fiber and exit?

Need to calculate θ_c, from which you can calculate the actual path length taken by the light ray. Then you need to calculate the speed of light in the fiber. Finally, calculate time from distance and velocity.



sin θ_c = 1.49/1.59 → θ_c = 69.6°

The actual light path (l) is given by simple trigonometry.

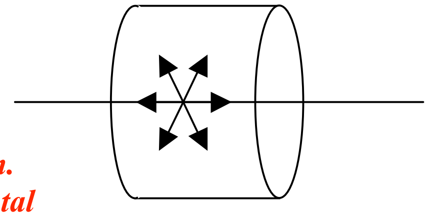
sin θ_c = (14 m)/(*l*) → *l* = 14.93 m

The velocity comes from definition of index of refraction **(v = c/n)**
v = (3 × 10^8 m/s)/(1.59) = 1.9 × 10^8 m/s

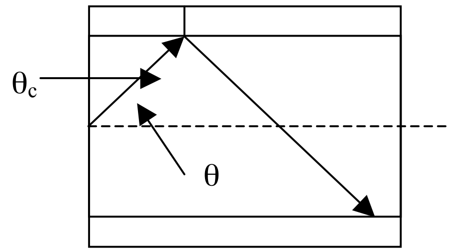
Finally, **t = d/v = (14.93 m)/(1.9 × 10^8 m/s) = 79 ns.**

---

4. A common particle detector technique involves optical scintillating fiber, which emits light when crossed by a charged particle. If the fiber consists of a core with index of refraction 1.59 and a cladding of index of refraction 1.49, what fraction of the light is trapped in the fiber and transported to an end? Assume all light is emitted at the center of the fiber (i.e., on the fiber axis) and that the light emission is isotropic.



This problem is fairly tricky, as it involves light emission into three dimensions. Thus, one must use calculus and solid-angle calculations. First, one must find the critical angle of reflection, then convert that to limits of integration. Finally, the integrated solid angle must be divided by the total solid angle.



$\sin\theta_c = 1.49/1.59 \rightarrow \theta_c = 69.6°$
$\theta = 90° - \theta_c = 20.43°$

Light is emitted into all solid angles.

$$\Omega = \int_0^{2\pi}\int_0^{\pi} \sin\theta \, d\theta \, d\phi = 4\pi$$

Only the light emitted with angle smaller than 20.43° (= 0.36 radians) will be trapped. Thus,

$$\Omega_{trapped} = \int_0^{2\pi}\int_0^{0.36} \sin\theta \, d\theta \, d\phi = 0.396$$

***The fraction trapped is* $\Omega_{trapped}/\Omega$ = 3.15%.**

A common error is to ignore the azimuthal angle and use a simple proportion. This error yields 11.3%.

---

5. Cerenkov light is a form of light emitted when a charged particle travels in a transparent medium faster than light travels in the same medium. Calculate the minimum velocity an electron must have to emit Cerenkov light in water.

   This is a simple problem. Use* $n = c/v$. *The index of refraction of water is 1.33.
   ***So* $v = 2.26 \times 10^8$ m/s.**

---

6. Cerenkov light is a form of light emitted when a charged particle travels in a transparent medium faster than light travels in the same medium. An imaginative experiment called ICE-CUBE plans to use a cubic kilometer of ice (which becomes clear at great depths) in Antarctica to detect charged particles from outer space called muons. Calculate the minimum velocity a muon must have to emit Cerenkov light in the ICE-CUBE experiment.

   This is a simple problem. Use* $n = c/v$. *The index of refraction of ice is 1.31.
   ***So* $v = 2.29 \times 10^8$ m/s.**

Student Worksheet
WARP SPEED

Step 1. Open up to http://www-ed.fnal.gov/projects/labyrinth/index.shtml

Step 2. Select *Warp Speed.*

Step 3. Select *Warp Speed* and enter your name.

Step 4. Read the story and hit *Warp Speed*, then select *Push the Particle*.

Step 5. Select *Go to Game.*

Step 6. Read the next few screens.

Step 7. Turn the light bulb on in the mission.

Step 8. Select *Show Data* button and reset until you have the best score.

Step 9. Try to double score.

Step 10. Attempt to double your score after reading the passage and answering the following question:

Before the particle enters the linac, it has an energy of 750 keV, or 750 kilo-electron volts. (Kilo is a prefix that means 1000.) By the time it leaves the linac, physicists must accelerate it to an energy of 116 MeV, or mega-electron volts. (Mega is a prefix for a million.) How many times greater is the energy the particle has when it leaves the linac than the amount of energy it has when it enters the linac?

About _ 1.5 _ 15 _ 150 _ 1500 _15000

Step 11. Select one of the above and hit *All Done* to see if you doubled your score.

Step 12. Print your Einstein bucks and hit *Go Back.*

Teacher's Key
WARP SPEED

Step 1. Open up to http://www-ed.fnal.gov/projects/labyrinth/index.shtml

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About _ 1.5 _ 15 _ ***150*** _ 1500 _15000

Step 11. Select one of the above and hit *All Done* to see if you doubled your score.

Step 12. Print your Einstein bucks and hit *Go Back.*

Student Worksheet
RACE FOR ENERGY

Step 1. Select Race for Energy and *Go to Game.*

Step 2. Select an angle (Default is 12°.)

Step 3. Select *Show Data* when ready to observe trials.

Step 4. Answer following question:

Study the graphs from a trial and answer this question correctly for 100 Einstein bucks.

Acceleration is: _ enormous speed _ change in speed

Step 5. If you are all done and want to double your score, then select the buttons and answer the following question after reading the material presented:

What force accelerates particles in the Fermilab accelerator?

_ Electric force _ Gravity _ Magnetism

Step 6. Select done to see if you doubled your score.

Step 7. Print your Einstein bucks.

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Student Worksheet
FERMILABYRINTH LAW & ORDER

Step 1. Select *Law 'n Order.*

Step 2. Read the story.

Step 3. Go through *Baryon Bonanza* and accumulate "bucks."

Step 4. Then select *Particle Families* and select a level, such as *Physics*. At the conclusion of "What is a Particle Family?," answer the following question:

1. Does the electron belong to the family of quarks or leptons?
   a. Quarks
   b. Leptons

At the conclusion of *Nature's Scale*, answer the following question:

2. If an atom's size is 10^{-7} mm, how many times smaller would a quark be?
   a. 4 X
   b. 5 X
   c. 8 X

At the conclusion of *Four Forces*, answer the following question:

3. The four forces do not include:
   a. Strong.
   b. Weak.
   c. Gravity.
   d. Electromagnetic.
   e. Centrifugal.

Fill out the following chart to indicate which forces affect the particles listed. Shade in the box if YES and leave the box empty if NO.

	FOUR FORCES			
PARTICLES	**GRAVITY**	**ELECTROMAGNETIC**	**WEAK**	**STRONG**
Neutron				
Neutrino				
Quark				
Proton				
Photon				
Electron				

Teacher's Key
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Neutrino				
Quark				
Proton				
Photon				
Electron				

Teacher's Notes
The Half-Life of Donkey Kong Dice

This lab uses a bag of Donkey Kong dice from an old game. Two sides of the dice say Donkey Kong rests. Any dice may be used by making some mark on two sides of the dice to represent the Donkey Kong sides.

The Half-Life of Donkey Kong Dice

Half-life is the amount of time it takes for half of a radioactive sample to decay. Our Donkey Kong dice are "radioactive." They have decayed when the Donkey Kong "rests" side comes up. The purpose of this lab is to investigate the nature of half-life and to determine the half-life of the Donkey Kong Dice.

Materials:

Baggie of dice
Shaker
Data table
Graph paper

Procedure:

1. Count your dice and record as Number of Dice Remaining at time = 0.
2. Shake and roll your dice, being careful that they do not fall on the floor.
3. Count and remove the decayed dice, return to baggie. Record the number as Number of Dice Decayed for time = 1 (Trial #1).
4. Count and record the Number of Dice Remaining for time = 1 (Trial #1). Return these dice to the shaker.
5. Shake and roll, etc. (steps 2 – 4), increasing time by 1 each time, until all the dice have decayed.
6. Place you data on the board to get class totals.

Analysis:

1. Plot Number of Dice Remaining vs. Time (Trial #)
   Plot Number of Dice Decayed vs. Time (Trial #)

   a. What do your two graphs look like?

   b. Do your graphs resemble each other?

   c. What kind of relationship is indicated by your graphs?

2. Using the combined class totals:
   Plot Class Total Number of Dice Remaining vs. Time (Trial #)
   Plot Class Total Number of Dice Decayed vs. Time (Trial #)

a. What do the graphs of the class data look like?

b. How are the class data graphs like or different from your graphs?

3. Use the graph of Class Total Number of Dice Remaining vs. Time to determine the Half-life of the Donkey Kong dice. Explain how you used the graph to determine the half-life.

<u>Conclusion</u>:

What can you conclude?

Real Radioactive Measurements & The Half-Life of Cesium-137

I. Background

Use the Geiger counter to measure the counts in the room for three one-minute intervals. Find the average. Use this count for normal background radiation.

			Average =

II. Rocks

Use the Geiger counter to measure the counts of the radiation for several different rock samples. For each sample time three one-minute intervals, find the average, and calculate the net count for that sample by subtracting the background radiation.

Rock Name				Average Count	Net Count

Which of these rock samples appear to be radioactive?

III. Fiesta Ware

Use the Geiger counter to measure the counts of the radiation for Fiesta Ware. Time three one-minute intervals, find the average, and calculate the net count.

Fiesta Ware				Average Count	Net Count

Is the Fiesta Ware more or less radioactive than the rocks? How can you tell?

IV. Cesium-137

We will time a sample of Cesium-137 for twelve minutes. We will record the count for each one-minute time interval for the twelve minutes, then calculate net count.

Time (min)	1	2	3	4	5	6	7	8	9	10	11	12
Count												
Net Count												

While we're collecting data, prepare a piece of graph paper to graph Net Count Decayed vs. Time and start plotting points.

Analysis:

What does the graph of Net Count Decayed vs. Time look like?

Does it look like the Donkey Kong dice graph?

What was the original net count? __________

What is half of the original net count? __________

How much time elapsed between the original and half of the original? __________

This is the half-life of Cesiun-137.

What is 1/4 of the original net count? _________

How much time elapsed between the original and 1/4 the original? __________

How many half-lives is this time interval? __________

Look up the half-life of uranium. __________

Fiesta Ware contains uranium. If we timed the Fiesta Ware for twelve minutes and graphed the Net Count vs. Time, how would you expect the graph look? Explain your reasoning.

Conclusion:

Half-Life Activity

Procedure

1. Put your M&M's in a shoebox with a lid on it and shake the box. Remove the M&M's that have the M-side up and record these in a data chart.

2. Repeat step one until one or no M&M's remain.

3. Total the number of candies that you recorded in each iteration of step 1. Use this number to calculate the number of candies that remained in the box each time.

4. Create a plot of your data of the number of candies remaining vs. the number of shakes you had.

Questions

1. What is the meaning of your graph?

2. Approximately what percent of the remaining candies were removed on each shake? Why?

3. Each shake represents a half-life for the candies. What is meant by a half-life?

Half-Life Practice

1. What is half-life?

2. If you have 100 g of a radioactive isotope with a half-life of 10 years:

   a. How much of the isotope will you have left after 10 years?

   b. How much of the isotope will you have left after 20 years?

   c. How many half-lives will occur in 20 years?

3. The half-life of plutonium-239 is 24,300 years. If a nuclear bomb released 8 kg of this isotope, how many years would pass before the amount is reduced to 1 kg?

4. The half-life of radon-222 is 3.8 days. How much of a 100-g sample is left after 15.2 days?

5. Carbon-14 has a half-life of 5,730 years. If a sample contained 70 mg originally, how much is left after 17,190 years?

6. How much of a 500-g sample of potassium-42 is left after 62 hours if its half-life of 12.4 hours?

7. The half-life of cobalt-60 is 5.26 years. If 50 g are left after 15.8 years, how many grams were in the original sample?

8. The half-life of I-131 is 8.07 days. If 25 g are left after 40.35 days, how many grams were in the original sample?

9. If 100 g of Au-198 decays to 6.25 g in 10.8 days, what is the half-life of Au-198?

10. Graph the following data on the graph paper, then use the graph to determine the half-life of this isotope.

Time (years)	0	1	2	3	4	5	6	7	8	9	10
Mass Remaining (grams)	100	75	56	42	32	24	18	13	10	8	6

half-life = ________________

Radioactivity

The emission of alpha or beta particles, or gamma rays from the nucleus of an unstable atom. Unstable atoms are considered radioactive.

Alpha Particle

- **The nucleus of a helium atom**
- **Made up of two protons and two neutrons**

$$ {}^{2}_{2}\mathrm{He} \qquad \alpha $$

Beta Particle

- **An electron emitted from the nucleus at very high speed**

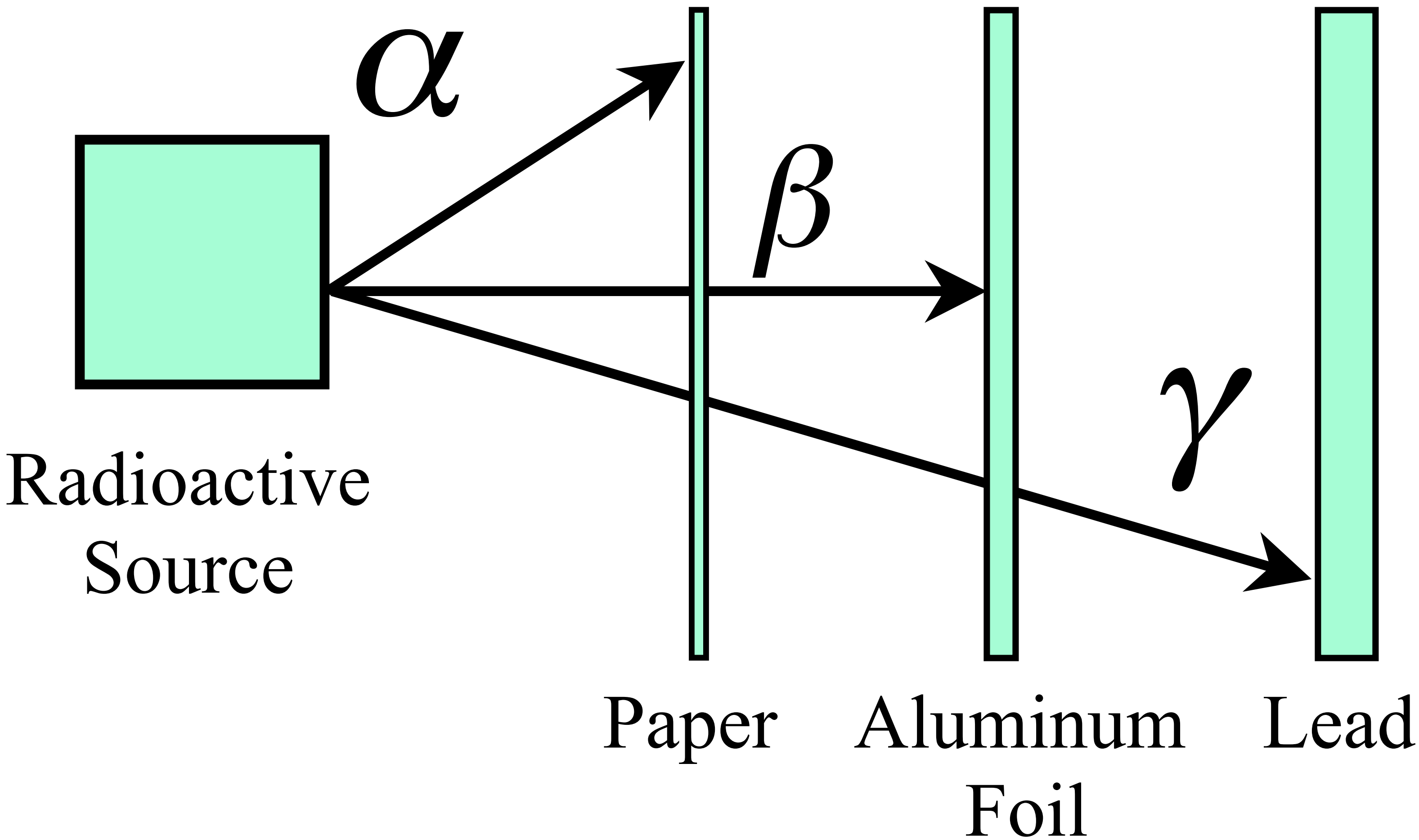
$$\beta$$

Gamma Radiation

- Electromagnetic waves with very high frequency and energy
- Has no mass and no charge
- Travels at the speed of light

$$\gamma$$

Penetrating Power



Modern Physics
Relativity Set #1

1. You are on a speedboat on a lake. You see ahead of you a wavefront, caused by the previous passage of another boat, moving away from you. You accelerate, catch up with, and pass the wavefront. Is this scenario possible if you are in a rocket and you detect a wavefront of light ahead of you? Explain.

2. You are packing for a trip to another star, to which you will be traveling at 0.99 c. Should you buy smaller sizes of clothing, because you will be skinnier on the trip? Can you sleep in a smaller cabin than usual, because you will be shorter when you lie down? Explain.

3. Two identically constructed clocks are synchronized. One is put in orbit around the Earth and the other remains on Earth. Which clock runs more slowly? When the moving clock returns to Earth, will the two clocks still be synchronized? Explain.

4. A muon formed high in the earth's atmosphere travels at speed v = 0.99 c for a distance of 4.6 km before it decays into an electron, a neutrino, and an antineutrino: $\mu^- \rightarrow e^- + \upsilon_\mu + \overline{\upsilon_e}$
   a. How long does the muon live, as measured in its reference frame?

b. How far does the muon travel, as measured in its frame?

5. Manisha is in a spaceship and travels past you at a high speed. She tells you that her ship is 20 m long and that the identical ship you are sitting in is 19 m long. According to your observations:

   a. How long is your ship?

   b. How long is her ship?

   c. What is the speed of Manisha's ship?

Modern Physics
Relativity Homework Set #2

1. Imagine an astronaut on a trip to Sirius, which is eight light-years from Earth. On arrival at Sirius, the astronaut finds that the trip lasted six years. If the trip was made at a constant speed of 0.8 c, how can the eight light-year distance be reconciled with the six-year duration?

2. Some distant star-like objects, called quasars, are receding from us at half the speed of light or greater. What is the speed of light we receive from these quasars? Explain.

3a. An unstable high-energy particle enters a detector and leaves a track 1.05 mm long before it decays. Its speed relative to the detector was 0.992 c. What is its proper lifetime? That is, how long would the particle have lasted before its decay in its own reference frame (at rest relative to the detector)?

   b. A pi-meson has an average lifetime in its own frame of reference of 2.6×10^{-8} seconds. (This is the proper lifetime.) If the meson moves with a speed of 0.95 c, what is its mean lifetime as measured by an outside observer,

   c. And the average distance it travels before decaying?

4a. Can a person, in principle, travel from Earth to the Galactic Center (about 23,000 light-year distance) in a normal lifetime? Explain using either time-dilation or length-contraction arguments. (1 light-year is the distance light travels in one year.)

b. What constant speed would be necessary to make the trip in 30 years of proper time?

5. A space traveler takes off from Earth and moves at speed 0.99 c toward the star Vega, which is 26 light-year distant. How much time will have elapsed by Earth clocks:

a. When the traveler reaches Vega?

b. When Earth observers receive word from the traveler that she has arrived?

d. How much older will Earth observers calculate the traveler to be (measured from her frame) when she reaches Vega than she was when she started the trip?

Modern Physics
Relativity Set #2

1. Sneha and Anjali are at it again. Sneha's battle cruiser moves directly toward Anjali's super secret scout ship when Sneha fires a decoy toward the scout ship. Relative to the scout ship, the speed of the decoy is 0.980c and the speed of Sneha's cruiser is 0.900 c. What is the speed of the decoy relative to the cruiser?

2a. In terms of c, what is the speed of an electron whose kinetic energy is 100 MeV?

b. Find the speed and the Lorentz factor γ for a proton whose kinetic energy is 1.00 keV.

c. For the protons at Fermilab, whose energies are > 500 GeV?

3. Quasars are thought to be the nuclei of active galaxies in the early stages of their formation. A typical quasar radiates energy at the rate of 10^41 Joules/second. At what rate is the mass of this quasar being reduced to supply this energy? Express your answer in solar mass units per year, where the solar mass is 2.0 x 10^30 kg.

4. In a high-energy collision between a cosmic ray particle and a particle near the top of the earth's atmosphere, 120 km above sea level, a pion is created. The pion has a total energy of 1.35 X 10^5 MeV and is traveling vertically downward. In the pion's rest frame, the pion decays 35.0 ns after its creation. At what altitude above sea level, as measured from the earth's reference frame, does the decay occur? The rest energy of a pion is 139.6 MeV.

5. Gabe, who as we all know, is in his own galaxy, Galaxy A, recedes from us in our Milky Way at 0.35 c. Oleg is in Galaxy B and is located in precisely the opposite direction and is also found to be receding from us at 0.35 c. What recessional speed would Gabe compute for us? And what speed would he compute for Oleg?

TNT vs. Fission Worksheet

1. How much energy is released in the explosion of a fission bomb (like the ones dropped on Hiroshima and Nagasaki) containing 3.0 kg of fissionable material? Assume that 0.10 percent of the mass is converted into released energy.

2. What mass of TNT would have to explode to provide the same energy release? Assume that each mole of TNT liberates 3.4 MJ of energy on exploding. The molecular mass of TNT is 0.227 kg/mol.

3. For the same mass of explosive, how much more effective is the nuclear explosion than the TNT explosion? That is, compare the amounts of energy released in explosions involving, say, 1 kg of fissionable material and 1 kg of TNT.

Modern Physics
The Ultraviolet Catastrophe!

1. As Ms. Nicks turns up and down the lamp, how does the spectrum change? Describe what happens.

2. Go to the website http://skyserver.sdss.org/. The Sloan Digital Sky Survey is an attempt to make a scientific map of the night sky in the Northern Hemisphere. One thing they have done is to take spectra of several stars and galaxies. To locate these, we will use their Navigate tool. Under Skyserver Tools, click Visual Tools, then Navigate. A pretty picture of some galaxies should come up in a new window. To see which objects the Sloan scientists have actually taken spectra of, click "SpecObjs" under Drawing options. Now those galaxies and stars for which they have spectra will have a red box around them. The galaxy in the center is such a galaxy.

   Click on the red box, and a small picture of the galaxy and some numbers will come up on the right-hand side of the screen. If you click on Explore over on the right, the data about this galaxy will come up in a new window, called the Object Explorer window. You can look at the spectrum if you scroll down a bit. If you click on the spectrum, it will open up to a picture you can actually see. Sketch this spectrum, and indicate what overall wavelength you think the peak of this spectrum is (the peak of the overall trend, not the tiny little peaks and valleys).

If you like this galaxy, you can “Save in Notes” over on the left side. You can do this with any galaxy.

3. Now, go back to the Navigate window and zoom way out (click the bar next to the minus) so that you can go to another part of the sky. The red boxes, again, mean that SDSS has a spectrum for that object. Click on a part of the sky with lots of red boxes, and then click Recenter over on the right. Then zoom back in not quite halfway. (If you zoom in too much, you may lose the objects with the red boxes.) You can click N/S/E/W to find more objects. Sketch five spectra and indicate the overall peak wavelength. Save them in your Notes. You can see your notes at any time by clicking Show Notes in the Explorer window.

   Your five spectra: (Estimate the overall peak of each one.)

By the way, the y-axis of these graphs is called the energy density. It's a measure of how many incoming waves have that particular wavelength. If the peak of the spectrum is in the red, there are more red waves coming in than any other type of wave. A spectrum, then, is a graphical way to represent the demo in #1.

4. Now we'd like to figure out what all this means, but we don't want to go through an astronomy tutorial. (You're welcome to on your own if you'd like.) Close the Navigate and Explorer windows. Go to Projects, and click Advanced; these are the high school and introductory college projects. Then click Color. The tutorial here goes into great depth about star color, which is certainly interesting, but we'd like a bigger picture. Scroll down the page, and on the left, click Light from Stars.

   a. Now, think carefully about what you saw in the demo. What color do you think these two stars would be? (This is **Question 2** of the tutorial.)

   b. **Question 3**. Some stars have peak wavelengths in the infrared part of the spectrum, longer than red light. Can you still see these stars? Why or why not? What color do they appear? What about stars whose peak wavelengths are in the ultraviolet?

   c. Click Next, and click on the Animation to play it. Then answer **Question 5**. If you continued heating the plate, you would no longer be able to see its glow . . . but it would give you a sunburn! Why?

   d. Click Next. These are actual radiation (light) curves from stars of different temperatures. Click on the words **Interactive Java Applet** and try different temperatures. You'll see the color of the star on the left.
   Sum up what you just saw:

This is the end of our journey with the SDSS website.

5. OK, so that's real data from real stars and galaxies. In the early 1900's, the best theory that our physicists could come up with was that the overall curve of the spectra (what you were sketching before) should look like the following equation, called Rayleigh-Jean's law:

$$\text{energy density} = \frac{8\pi kT}{\lambda^4}$$

where k = 1.38 x 10^{-23} J/K, and T is the temperature of the object. For a star, 2500 K is a cool star, 15000 K is a hot star.

   a. Sketch a graph of this equation for an average star. Remember λ should be on the x-axis. It's your independent variable.

   b. Hmm. . . . Why, do you think, was this disagreement between theory (Rayleigh-Jean's law) and experiment (your galaxy notes) called the Ultraviolet Catastrophe?

6. Wien was an experimental physicist and tried to come up with a best-fit equation for his data. (Sound familiar?) He thought this equation best fit the data:

$$\text{energy density} = \frac{C_1}{\lambda^3} e^{-C_2/\lambda T}$$

k and T have the same values as above, $C_1 = 7.01 \times 10^{-14}$, and $C_2 = 0.00819$.
Sketch the graph of this equation for the same temperature star as before (again, λ should be on the x-axis).

Here's the catch! Wien had no idea why it worked. (Ever have that trouble in a science lab?!) There was no theory to support his pretty equation that fit the data so well. To be honest, Wien's law didn't fit the data all that well; it did fit the ultraviolet end of the spectra, but not the infrared; go figure. Now, a theory isn't such a good theory if you have to switch it for different stellar temperatures (or any hot object).

7. Max Planck was a theoretical physicist working in Wien's lab and was good friends with Wien. To try to help out his friend, Planck added a bit to the theory of physics. (He FUDGED the PHYSICS to FIT the data; ever do that?) What he added was this:

$$E = nhf$$

where $h = 6.626 \times 10^{-34}$ J s, called Planck's constant (or Planck's fudge factor); n was an integer: 1, 2, 3, …; and f was the frequency of the light.

a. What's the relationship between frequency and wavelength for light?

He called E the energy of an "oscillator," or the source of the light. With this little fudge, he came up with an equation sort of like Wien's:

$$\text{energy density} = \frac{8\pi ch}{\lambda^5}\left(\frac{1}{e^{hc/k\lambda T} - 1}\right)$$

k and T are the same as before, h is Planck's new fudge factor, and c is the speed of light, our old friend.

b. Sketch a graph of this equation:

The thing is, this equation fit ALL of the experimental data perfectly—the ultraviolet, the infrared, the visible, . . .
There was only one small problem:

What does **E = nhf** mean?

Well, we'll need a better data-fudger than Planck for that.

Modern Physics
Bohr Theory Problems

1. How do Bohr's assumptions contradict classical physics?

2a. What is the energy of the photon that could cause an electron's transition from the $n = 4$ state to the $n = 5$ state of hydrogen?

b. What energy would be released by an electron making the transition from the $n = 5$ state to the $n = 4$ state?

3a. Calculate the radii of the first, second and third Bohr orbits of hydrogen.

b. Calculate the radius of the first Bohr orbit in b: He^{+}, Li^{2+}, and Be^{3+}

4. Calculate the wavelength of the photon that is released when the electron in a hydrogen atom initially in the n = 3 state drops back down to the ground state.

   What type of light is this?

5. A muon is a particle with a charge of –e and a mass equal to 207 times the mass of an electron. Muonic lead is formed when ionized ^{208}Pb captures a muon. According to the Bohr theory, what are the radius and energy of the ground state of muonic lead?

Modern Physics
de Broglie Problems

1. What was de Broglie's assumption and why is it so weird?

2. Calculate the de Broglie wavelength of a 74-kg person running at a speed of 5 m/s.

3. An electron and a photon each have energy equal to 50 keV. What are their de Broglie wavelengths?

4. A hydrogen atom initially in the $n = 3$ state emits a photon and drops back down to the ground state.
   a. What is the energy and wavelength of the photon?

   b. What type of light is this?

5. An air rifle is used to shoot 1-g particles at speeds of 100 m/s through a hole of diameter 2 mm. How far from the rifle must an observer be in order to see the beam spread by 1 cm? Compare this to the diameter of the universe ($\sim 10^{26}$m).

Modern Physics
Introduction to Quantum Mechanics

*Please **attempt** every problem.*

1. Who was Planck and why was he important?

2. Calculate the energy in Joules and electron volts of a photon whose frequency is:

   a. 5×10^{14} Hz

   b. 10 GHz

   Calculate the energy in Joules of a photon whose wavelength is 632.8 nm.

3. An electron is stopped by two plates connected to a 1.5 V AA battery.
   a. What does the previous statement mean in terms of the electron's energy?

   b. What is the electron's potential energy in this electric field? Give your answer both in electron volts and in Joules.

   c. What was the electron's initial kinetic energy?

   d. If the mass of an electron is 9.11×10^{-31} kg (which it is, and also an important number to remember; it is stored in your calculator under the constants menu—see M_e), what was the electron's initial velocity when it entered the electric field region?

4. The work function for potassium is 2.24 eV. If potassium metal is illuminated with light of wavelength 350 nm, find:
   a. The maximum kinetic energy of the photoelectrons at this wavelength.

   b. The cutoff wavelength for potassium.

   If the outgoing electrons are stopped with a 550 mV stopping potential, what wavelength of photon was absorbed by those electrons?

5a. Why is the photon model of light more appropriate for describing the photoelectric effect experiment?

   b. When is the wave model of light more appropriate for describing the behavior of light?

Modern Physics
Photoelectric Effect Write-up

Your lab write-up should be somewhat formal, be typed, and stand on its own and not rely on someone else's work; include printouts of all graphs and data tables. If you would like to organize it into sections (i.e., Purpose, Procedure, Data . . .), you may, but you are not required to. Either way, you need to provide detailed answers to the following questions in addition to providing your data in tables and your graphs. Another reasonably intelligent person (i.e., your roommate) should be able to pick up the report and be able to replicate your particular experiment and get the same kinds of data you did.

1. What was Planck's assumption and why was Planck important?

2. Provide a sketch and short description of the experimental setup. Why is it necessary to do this experiment in the dark?

3. Give a short description of what is happening inside the "Photoelectric Effect" box. Include what happens when you twiddle the two knobs.

4. Describe what you do to get a graph of current vs. voltage and why these graphs are important.

5. What is the final goal of the experiment? What calculations do you need to do to get there? Provide at least a sample of each calculation that you did.

6. What is your final graphical model of kinetic energy vs. frequency? Explain the graph and the mathematical model you use to fit the data. Explain what the slope and y-intercept mean and the units of such numbers.

Planck vs. The Macroscopic Oscillator

Planck derived a correct explanation for the spectrum of a blackbody radiator. In his case, the oscillator was a light wave, but we can extend his thought here. He insisted that the energy of any oscillator had to be an integer multiple of h (Planck's constant) times the frequency (f) of oscillation of the oscillator. In other words,

$$E = nhf$$

In this problem we will explore the implications for a macroscopic oscillator.

We have already analyzed the behavior of an oscillating mass on a spring. Another macroscopic oscillator is the simple pendulum. Suppose a pendulum is constructed as shown below with a string of length L and a mass of m near the surface of the earth where $g = 9.8\ m/s^2$. We start the mass swinging by holding it at some angle θ and releasing it from rest. The period of oscillation is then:

$$T = 2\pi\sqrt{\frac{l}{g}}$$

a. What is the total energy of the pendulum in terms of θ and the other parameters in this problem (L, m, g)? Remember that potential energy = mgh and that kinetic energy = $1/2\ mv^2$.

b. Now suppose that the energy of the system could only come in integer multiples of H times frequency, i.e., E = nHf, where H just happens to be 0.66 J-s. (Perhaps we could call H Nickerson's constant!) What values of θ are allowed? Use m = 1.0 kg and L = 1.0 m.

c. Now apply the real value of Planck's constant to this system, so that the real allowed energies are E = nhf. (This is really what Planck is saying!!) What values are allowed for θ? Could we detect these quantum behaviors?

Modern Physics
Quantum Mechanics Questions

1. Is light a wave or a particle? Explain. What about an electron?

2. How would de Broglie account for the fact that in the Bohr model (which remember was highly successful in predicting the spectral lines of hydrogen), the electrons are always found at certain distinct distances from the nucleus?

3. Why is the wave nature of matter not more apparent to us in our everyday lives?

4. In classical physics, the accuracy of measurements has always been limited by the measuring instruments used, and no instrument is perfect. How is this limitation different from that formulated by Heisenberg in the uncertainty principle?

5. What is the physical significance of the square of the Schroedinger wave function, $|\Psi|^2$?

6. Describe the quantum-mechanical model of the atom. How is this similar to Bohr's model? How are the two different?

7. Sum up quantum mechanics and our current interpretations of quantum mechanics. Use Feynmann's notes if you find them helpful.

Modern Physics
Quantum I Turn-in Problems

1. Molybdenum has a work function of 4.2 eV.
   a. Find the cutoff wavelength and the threshold (cutoff) frequency for the photoelectric effect.

   b. Calculate the stopping potential if the incident light has a wavelength of 200 nm.

2. A light source of wavelength λ illuminates a metal and ejects electrons with a maximum kinetic energy of 1 eV. A second light source with half the wavelength of the first ejects electrons in the same metal with a maximum kinetic energy of 4 eV. What is the work function of the metal?

Modern Physics
Quantum Mechanics Catches on—and Gives a New Atomic Model

Electrons were discovered in 1898 by J. J. Thomson. It had been known before that that the atom was composed of positive and negative charges, but that most atoms were indeed neutral overall. J. J. Thomson found the source of the negative charge—the electron. He constructed a model of the atom called the "Plum Pudding" model of the atom in which the majority of the "stuff" that composed the atom was positive, and the electrons were stuck inside like chocolate chips in a chocolate chip cookie (or like plums in a plum pudding). Draw a picture of this model of the atom.

Check out the regular (incandescent) light bulb with the specs on. Describe what you see.

Now check out the three lamps with the specs on. Describe what you see.

What's the difference between the lamps and the bulb?

Why do you think this difference occurs?

What was Balmer's formula, what did it describe, and how did he come up with it? (We'll put it in Rydbergh's notation to make it less complicated.)

Draw Geiger, Marsden, and Rutherford's experiment here:

Explain briefly the experiment:

Now explain why Rutherford is quoted as saying, "It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." Use J. J.Thomson's model of the atom (which is what Rutherford was operating under) and the current model of the atom to explain why Geiger and Marsden saw what they saw.

What were Bohr's four assumptions?

What was Bohr's formula for the radius of a hydrogen atom?

Plug in numbers for the n = 1 state: (This is called the Bohr radius.)

What was Bohr's formula for the energy in each state? Plug in numbers for the n = 1 (called the **ground** state). This is the ground state energy for the hydrogen atom (otherwise known as the *ionization* energy).

How would you calculate the transition energy for an electron from one state to another?

Could you find the wavelength of photon that is required for such a transition? Describe how:

Explain why Balmer/Rydbergh’s formula worked:

Fermilab Questions

Directions: ***Find the answers to these questions at http://www.fnal.gov/ and submit them in complete sentences by the end of class today.***

1. How far is it from _______________?

2. What is it? Who created it? Why?

3. What two methods do scientists use to study particles?

4. What is the Standard Model? Give examples.

   (What are quarks? What are leptons? What are mediating particles?)

5. List in order the devices used to accelerate the particles.

6. How is the linear accelerator different from the Tevatron?

7. What is DØ?

8. What is CDF?

9. What two ways do detectors identify particles?

10. Describe how particle physics assists cosmology.

11. List thee new questions as a result of completing this assignment.

Fermilab Questions - Solutions

1. How far is it from ________________?
   Variable answer; can design for your town.

2. What is it? Who created it? Why?
   Particle physics laboratory created by _________ to discover the smallest building blocks of nature.

3. What two methods do scientists use to study particles?
   Scientists collide protons into targets of either moving antiprotons or of fixed targets of different materials.

4. What is the Standard Model? Give examples.
   The "periodic table" of physics. It is a comparative list of the smallest building blocks of matter and its interactions.

   What are quarks?
   Common quarks u and d

   What are leptons?
   Common leptons electrons and neutrinos

   What are mediating particles?
   A common mediating particle is the photon.

5. List in order the devices used to accelerate the particles.
   Cockcroft-Walton, Linac, Booster Ring, Main Injector, Tevatron

6. How is the linear accelerator different from the Tevatron?
   Linear accelerators do not use magnets to accelerate protons. The Tevatron does.

7. What is DØ?
   A detector of collisions on the Main Ring of the Tevatron at Fermilab. It specializes in the energy measurements of the particle collisions.

8. What is CDF?
   A detector of collisions on the Main Ring of the Tevatron at Fermilab. It specializes in the momentum measurements of the particle collisions.

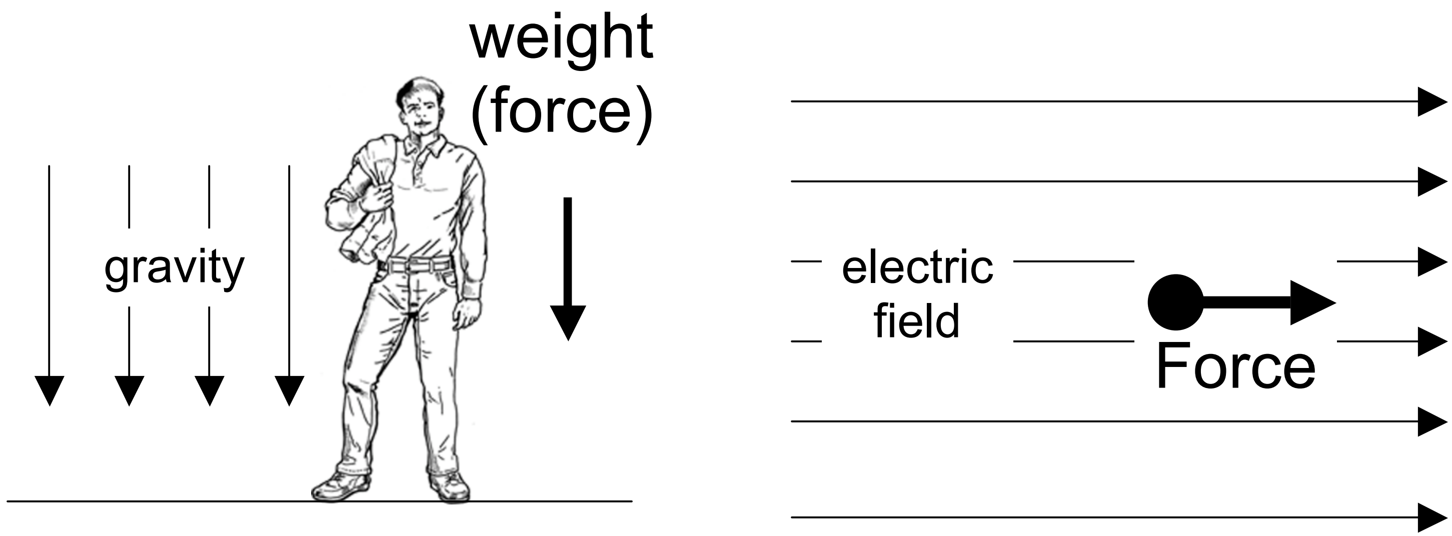
9. What two ways do detectors identify particles?
   Calorimeters (energy detectors) and the scintillating tracking chamber, which when teamed with magnets, can give a momentum measurement.

10. Describe how particle physics assists cosmology.
    Each collision creates a mini Big Bang simulation. The higher the energy of a Fermilab collision, the farther back in time an astrophysicist sees. The Big Bang theory says that at one time very early in the universe, the universe was very hot. It is only with a particle collider that this "hotness" can be replicated. Fermilab helps us see what particles existed in the early universe.

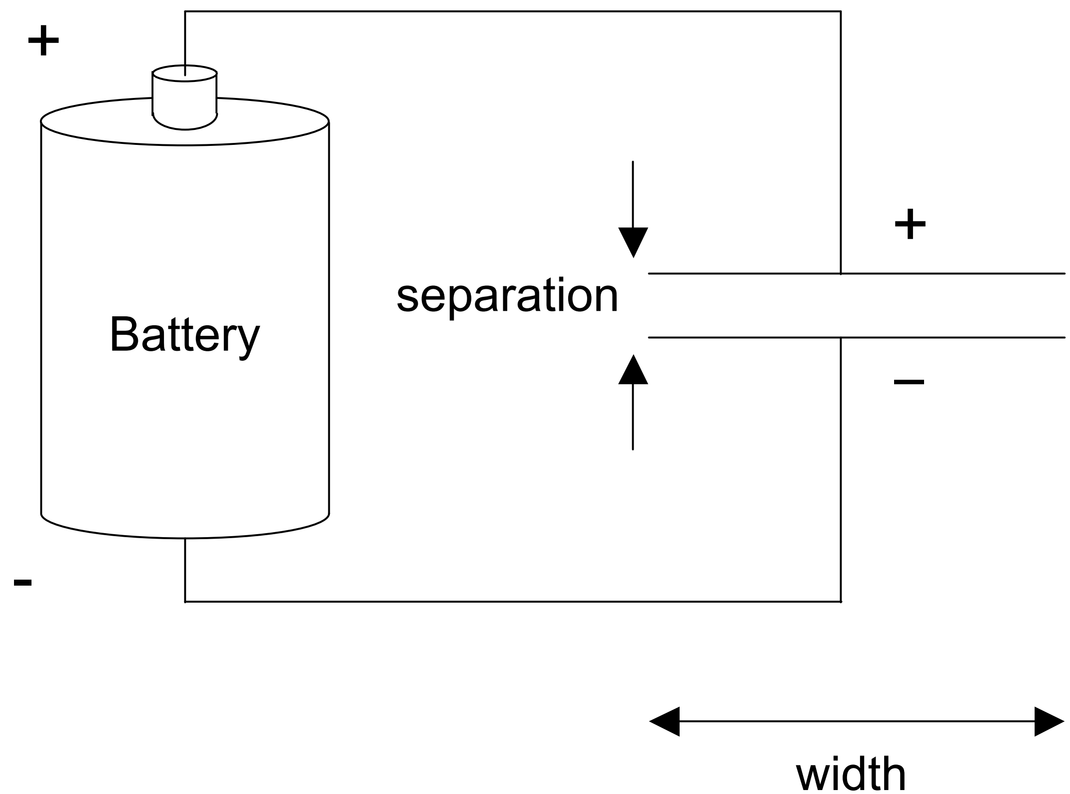
11. List three new questions as a result of completing this assignment.
    Answers will vary.

Particle Accelerators
(Basic Principles)

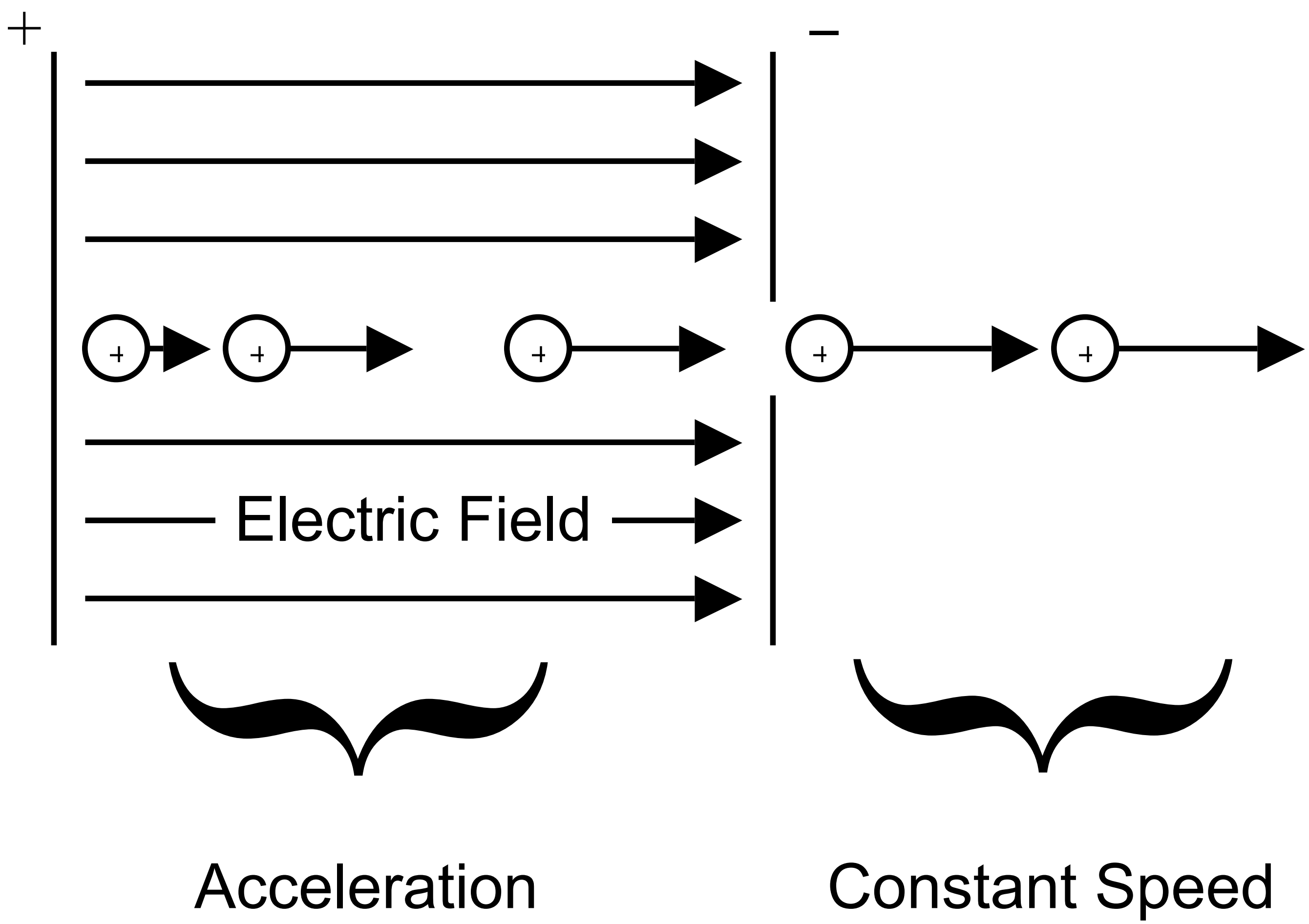
Particle Acceleration (Principles)



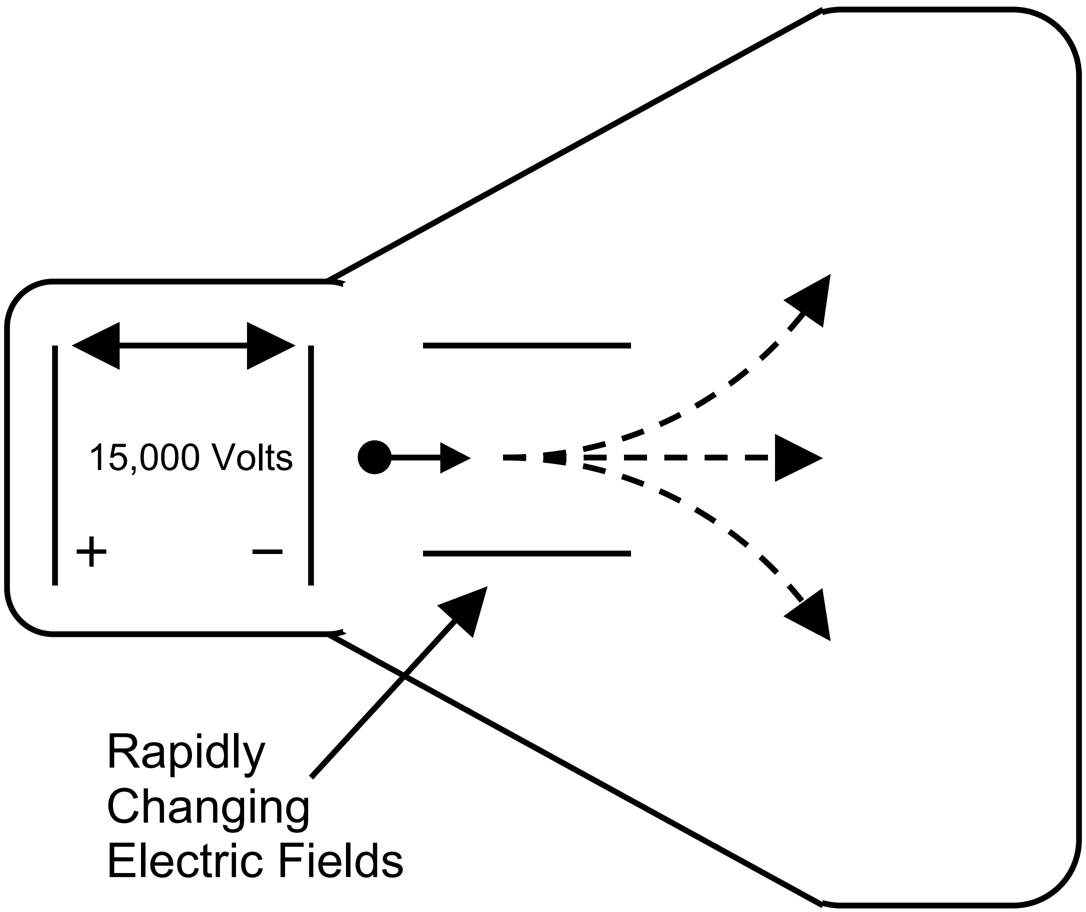
Electric Field (Reminder)



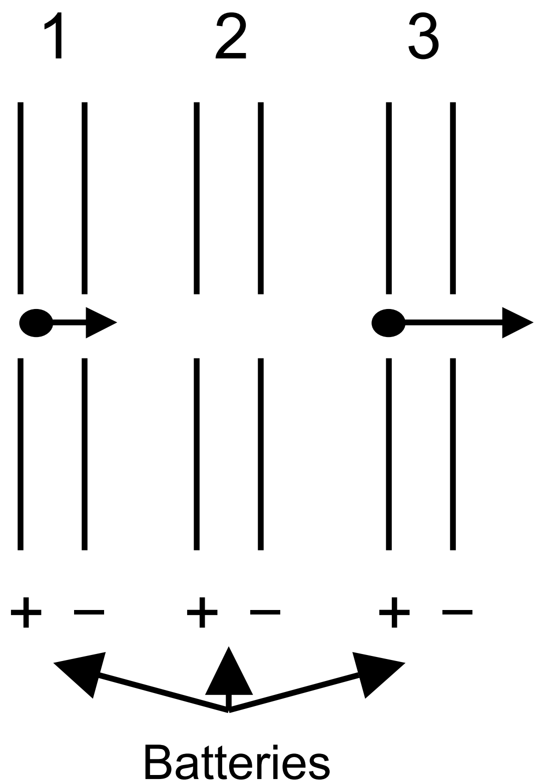
Electric Field and Acceleration

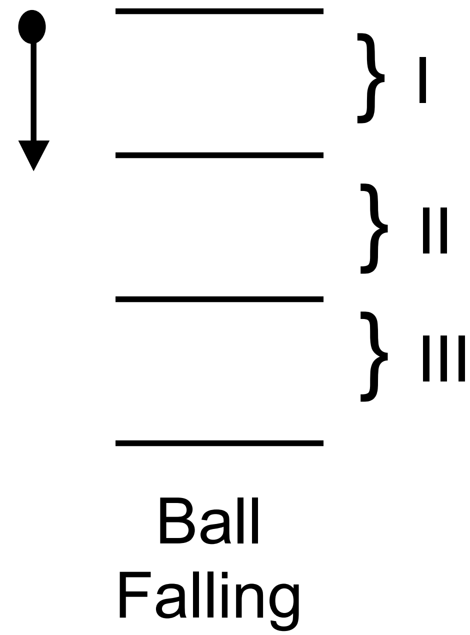


TV: A Familiar Accelerator

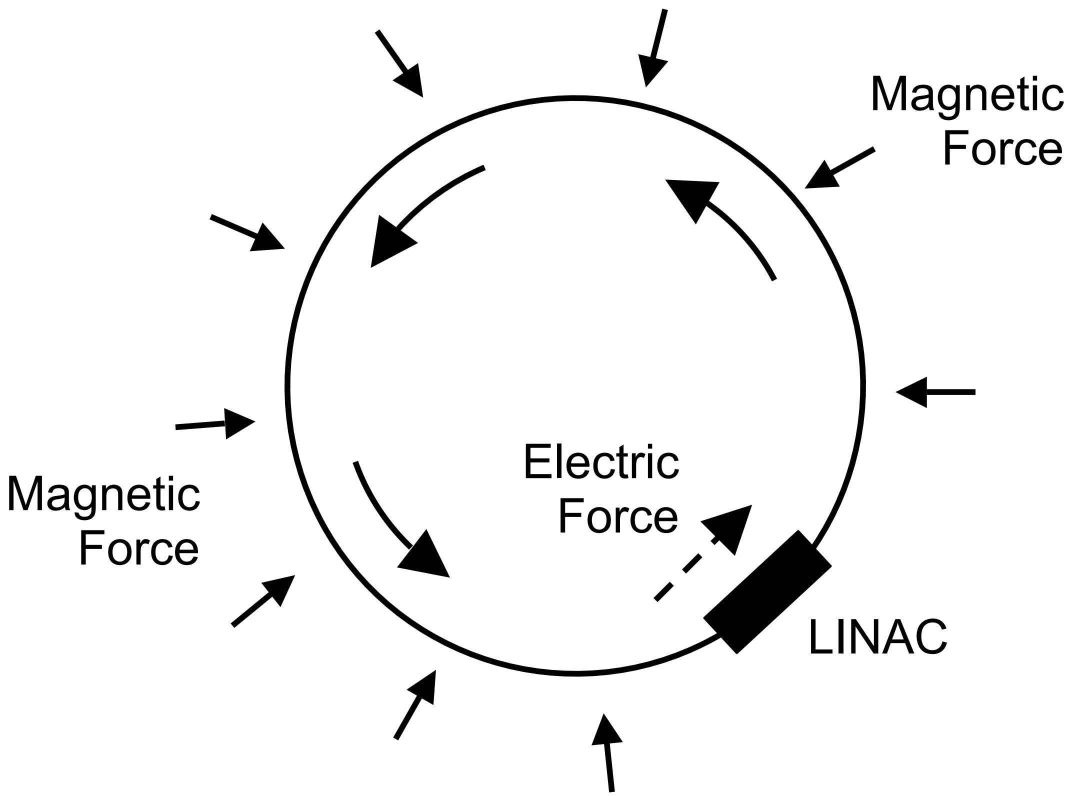


Multistage Accelerators (LINAC)





The Role of Magnetism



Particle Accelerators

<u>Why were they created?</u>

A. The greater the energy in the collision, the greater the mass of the particle being created. ($E = mc^2$)

B. A good way to “see” the small. de Broglie theorized that particles can behave like waves. Just as light can behave like a particle (Einstein’s photoelectric effect – Nobel Prize) or a wave (Young’s diffraction experiment), so can an electron beam be diffracted in a crystal lattice (Davisson and Germer).

The greater their speed, the smaller the wavelength; thus, the smaller the object that can be “seen.”

$E = hf$ with $c = \lambda f$. Thus, $\lambda = hc/E$.
E is the sum of the particle’s rest energy (mc^2) and its KE.

How is the speed increased?

A. By varying the electric field from positive to negative

1. Van de Graff or Cockcroft-Walton

2. Linear

B. The use of magnetic fields in cyclotrons and synchrotron

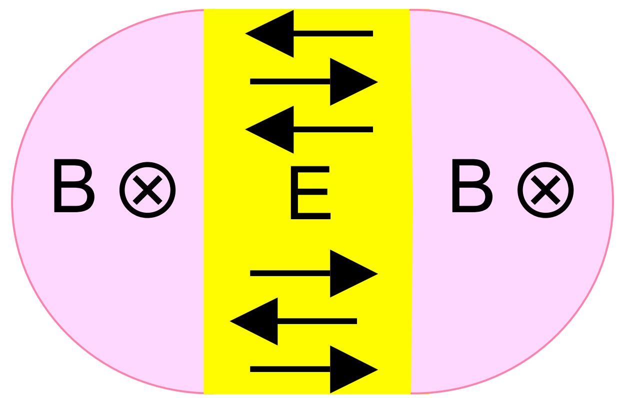
$F_c = F_b$ (using $F_c = (mv^2)/r$ and $F_b = qvB$…)

$v = (qrB)/m$ (so as v increases, B needs to increase.)

Now, if $v = 2\pi r/T$ or $v = 2\pi rf$, then:

$f = qB/2\pi m$

Cyclotrons are constructed as two “D” magnets with a gap in between through which a particle is accelerated further by a reversing electric potential (field).



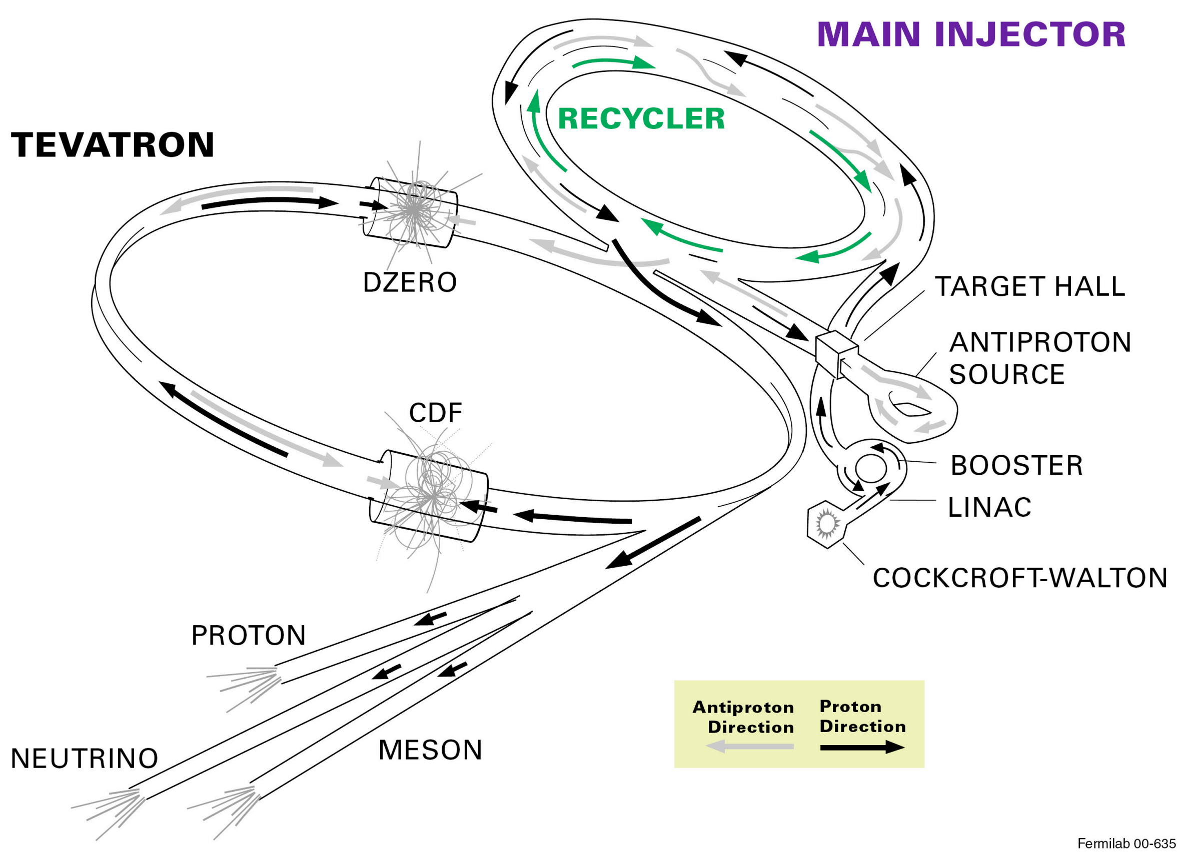
So as to visualize this structure, if the gap in a certain cyclotron has an electric potential difference of 10 MeV and the particle gains 200 MeV in the cyclotron, what is the frequency of the cyclotron?

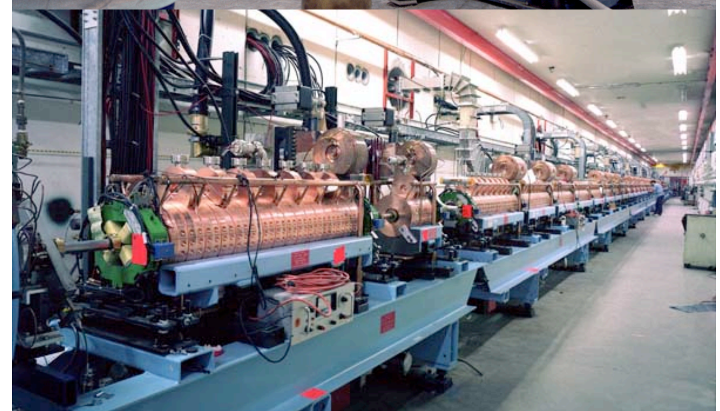
Sample Problems

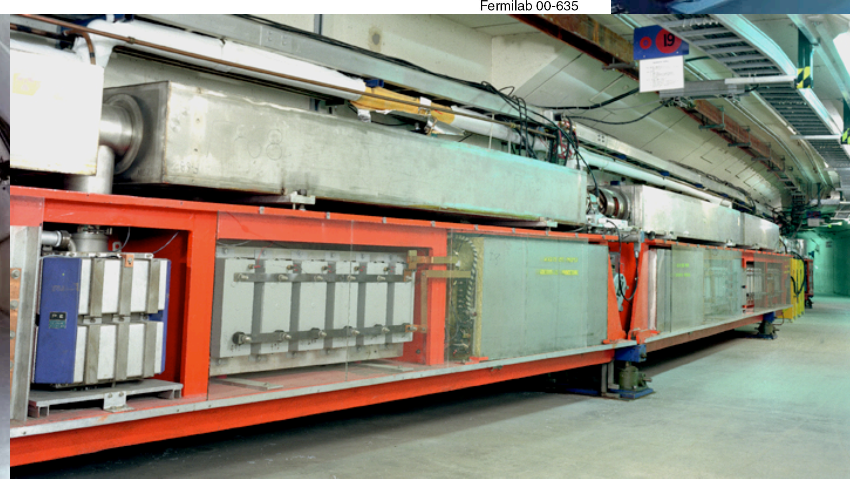
1. Calculate the wavelength of 30 GeV electrons. (1eV = 1.6×10^{-19}J)

2. What strength of the magnetic field is used in a cyclotron in which protons make 1.9×10^{7} revolutions per second?

FERMILAB'S ACCELERATOR CHAIN







Fermilab Accelerators

Name	Year Turned On	Initial Energy	Final Energy	Maximum Velocity (% speed of light)	Acceleration Time (seconds)
Cockcroft-Walton	1971	0	750 keV	4	1.6×10^{-7}
Linac	1971	750 keV	401 MeV	71	8×10^{-7}
Booster	1971	401 MeV	8 GeV	99.45	10^{-5}
Main Injector	1999	8 GeV	120 GeV	99.998	2.5
Tevatron	1983	120 GeV	1 TeV	99.99996	20

QUIZ ON PARTICLE ACCELERATORS

1. Determine the wavelength of a 40 GeV proton beam.

2. Determine how long it takes for an electron to travel around a cyclotron with a magnetic field strength of 2T.

Particle Accelerators Quiz

(Solutions for PowerPoint Presentation Quiz)

1. Determine the wavelength of a 40 GeV proton beam.

$$\lambda = hc / E$$

$$\frac{hc}{(m_o c^2 - KE)}$$

$$\frac{1.98 \times 10^{-25}}{1.5 \times 10^{-10} + 6.4 \times 10^{-9}}$$

$$3 \times 10^{-19}\ \mathrm{m}$$

2. Determine how long it takes for an electron to travel around a cyclotron with a magnetic field strength of 2T.

$$F = \frac{qB}{2\pi m}$$

$$F = \frac{1.6 \times 10^{-19} c\ (2T)}{2\pi(9.11 \times 10^{-31})}$$

$$F = 5.6 \times 10^{10}\ \mathrm{Hz}$$

$$T = 18 \times 10^{-11}\ \mathrm{sec}$$

Particle Zoo

Bosons and Fermions

Bosons: Do not obey Pauli/have integer spin.

Fermions: Obey Pauli/have 1/2 spin.

Fermions

Leptons (6): Weak nuclear force guides them.

Quarks (6): Strong force guides them.

mesons (q-anti q)

baryons (qqq or 3 anti q)

(Collectively, these are hadrons.)

There are 12 elementary particles that make up most of the Standard Model:

Quarks: u, d, c, s, t, b

Leptons: e, μ, τ, n_e, n_μ, n_τ

The quarks combine into 2 groups:

Mesons

Baryons

They combine via four conservation rules:

1. Conservation of charge (Q)

2. Conservation of Baryon Number (B)

   Why? Because certain reactions are not observed.

3. Conservation of Strangeness (S)

   Why? Because some reactions are not observed and because some particles have longer lifetimes.

4. Conservation of Mass (E/p)

Particle Accelerator Problems

1. What is the total energy of a proton whose kinetic energy is 15 GeV? What is its wavelength?

2. The voltage across the dees of a cyclotron is 50 kV. How many revolutions do protons make to reach a kinetic energy of 15 MeV?

3. What is the time for one complete revolution for a very high-energy proton ($v = c$) in the 1-km radius Fermilab accelerator?

4. What is the wavelength attainable using 400 GeV protons at Fermilab?

5. Protons are injected into the 1-km radius Fermilab synchrotron with an energy of 8 GeV. If they are accelerated by 2.5 q each revolution, how far do they travel and approximately how long does it take for them to reach 400 GeV?

6. What magnetic field intensity is needed at the 1-km radius Fermilab synchrotron for 400 GeV protons? Use the relativistic mass.

Particle Accelerator Problems
KEY

1. What is the total energy of a proton whose kinetic energy is 15 GeV? What is its wavelength?

   $$\boldsymbol{\lambda = (hc) / \varepsilon = (hc) / (\varepsilon_o + KE) = 1.98 \times 10^{-25} / (1.5 \times 10^{-10}\ J + 2.4 \times 10^{-9}\ J) = 7.76 \times 10^{-17}\ m}$$

   $$\boldsymbol{\varepsilon = \varepsilon_o + KE = 2.55 \times 10^{-9}\ J}$$

2. The voltage across the dees of a cyclotron is 50 kV. How many revolutions do protons make to reach a kinetic energy of 15 MeV?

   15 MeV / n (10 kV) = 1

   n = 150

3. What is the time for one complete revolution for a very high-energy proton ($v = c$) in the 1-km radius Fermilab accelerator?

   $$\boldsymbol{v = 2\pi r / T}$$

   $$\boldsymbol{T = 2\pi r / v = 2\pi\ (100\ m) / 3 \times 10^8 = 2.1 \times 10^{-5}\ sec}$$

4. What is the wavelength attainable using 400 GeV protons at Fermilab?

   $$\boldsymbol{\lambda = (hc) / (\varepsilon_o + KE) = 1.98 \times 10^{-25} / (1.5 \times 10^{-10}\ J + 6.4 \times 10^{-8}\ J) = 3.1 \times 10^{-18}\ m}$$

5. Protons are injected into the 1-km radius Fermilab synchrotron with an energy of 8 GeV. If they are accelerated by 2.5 MeV each revolution, how far do they travel and approximately how long does it take for them to reach 400 GeV? (Assume the protons are moving at the speed of light.)

   Knowing Ei = 8 GeV and Ef = 400 GeV, then Ef - Ei = 392 GeV difference. Since on each pass around the ring the proton gains 2.5 MeV, then the proton will move around the ring 1.57 x 10^5 times. Since the radius of the ring is 1000 m, the circumference is 2π(1000 m). If the proton moves around the ring 1.57 x 10^5 times, then the total distance the proton moves is 9.85 x 10^8 m. Further, since the particle is moving at the speed of light (3 x 10^8 m/s), the time to move a distance of 9.85 x 10^8 m at this speed would be 3.3 sec.

6. What magnetic field intensity is needed at the 1-km radius Fermilab synchrotron for 400 GeV protons? Use the relativistic mass.

$$\varepsilon = mc^2$$

$$\varepsilon_o + KE = mc^2$$

$$m = (\varepsilon_o + KE) / c^2 = (1.5 \text{ x } 10^{-10} \text{ J} + 6.4 \text{ x } 10^{-8} \text{ J}) / (3 \text{ x } 10^8)^2 = 7.13 \text{ x } 10^{-25} \text{ kg}$$

$$f = qB / 2\pi m = 2\pi mf / q = B = 2\pi m / qT = 2\pi(7.13 \text{ x } 10^{-25} \text{ kg}) / (1.6 \text{ x } 10^{-19})(2.1 \text{ x } 10^{-5} \text{ s})$$

$$B = 1.33 \text{ T}$$

Calculate the Mass of the Z^o Boson Questions

The Z^o boson is a particle that is involved in radioactive decay. It was discovered in Europe in 1983. Because it decays in 10^{-23} seconds, it is impossible to observe it directly. It can only be observed by its decay products which, among others, can be a muon and an antimatter muon. We say $Z^o \rightarrow \mu^+\mu^-$. In this exercise, we use the energy and momentum of the muons to infer the Z^o boson's mass.

This packet contains first the mathematics for determining the mass of the Z^o boson from the given material and two worked examples. It then contains student worksheets (six variants) and separate answers sheets. The six variants of the worksheet are separated into 2D and 3D cases. Within each case, version 1 is a simple calculation, version 2 requires the students to measure the ϕ angle with a protractor and version 3 is the most difficult, requiring the students to calculate the not-given momentum using the given mass.

To determine the mass of a particle, we need to use the extended version of Einstein's famous equation $E = mc^2$. This extended equation is:

$$E^2 = m^2c^4 + p^2c^2$$

where *E, m* and *p* are the energy, mass and momentum of the Z^o respectively. *c* is the speed of light. Since we cannot directly observe the Z^o boson, we need to use our familiar concepts of conservation of energy and momentum. If the Z^o boson decays into a muon (μ^-) and an antimatter muon (μ^+), then conservation of energy and momentum can be expressed as:

$$E_{Z^o} = E_{\mu^+} + E_{\mu^-}$$

$$\vec{p}_{Z^o} = \vec{p}_{\mu^+} + \vec{p}_{\mu^-}$$

For the sake of simplicity, we can treat the muons as massless and this means (for muons) $E = |pc|$. Substituting these equations into the first one, we find the final interesting equation:

$$m_{Z^o} = \frac{1}{c^2}\sqrt{(E_{\mu^+} + E_{\mu^+})^2 - (\vec{p}_{\mu^+} + \vec{p}_{\mu^+})^2 c^2}$$

Thus we see that the mass of the Z^o boson can be expressed simply as a combination of the energy and momenta of the two muons. We must remember what the last part of this equation means.

The square of a sum of momentum means:

$$(\vec{p}_{\mu^+} + \vec{p}_{\mu^+})^2 = (p_{\mu^+} + p_{\mu^+})_x^{\;2} + (p_{\mu^+} + p_{\mu^+})_y^{\;2} + (p_{\mu^+} + p_{\mu^+})_z^{\;2}$$

And finally, we need to remember spherical coordinates. Given a specific momentum, polar and azimuthal angle (p, θ, ϕ) (and assuming the particle is massless), we can write:

$$p_x = p\sin\theta\cos\phi$$
$$p_y = p\sin\theta\sin\phi$$
$$p_z = p\cos\theta$$
$$E = pc$$

So let's do an example.

Event #1	μ_1	μ_2	Sum	Sum^2
φ	108°	336°		
θ	54°	107°		
P Gev/c	42.3	56.0		
Px Gev/c	-10.575	48.923	38.348	1470.581 (GeV/c)^2
Py Gev/c	32.547	-21.782	10.765	115.875 (GeV/c)^2
Pz Gev/c	24.86	-16.373	8.491	72.089 (GeV/c)^2
E Gev	42.3	56.0	98.3	9662.89 (GeV)^2

And doing:

$$\begin{aligned} m &= \frac{1}{c^2}\sqrt{E^2 - c^2 p_x^2 - c^2 p_y^2 - c^2 p_z^2} \\ &= \frac{1}{c^2}\sqrt{9662.89 - 1470.58 - 115.88 - 72.09} \\ &= 89.5\ \mathrm{GeV/c^2} \end{aligned}$$

One can do a 2D example, which basically is equivalent to setting θ = 90°.

We need to remember 2D polar coordinates. Given a specific momentum and azimuthal angle (*p*, φ) (and assuming the particle is massless), we can write:

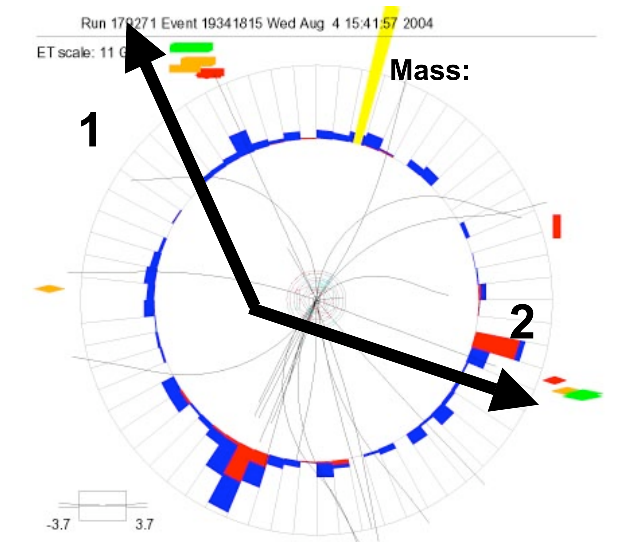
$$p_x = p\cos\phi$$
$$p_y = p\sin\phi$$
$$E = pc$$

So let's do an example.

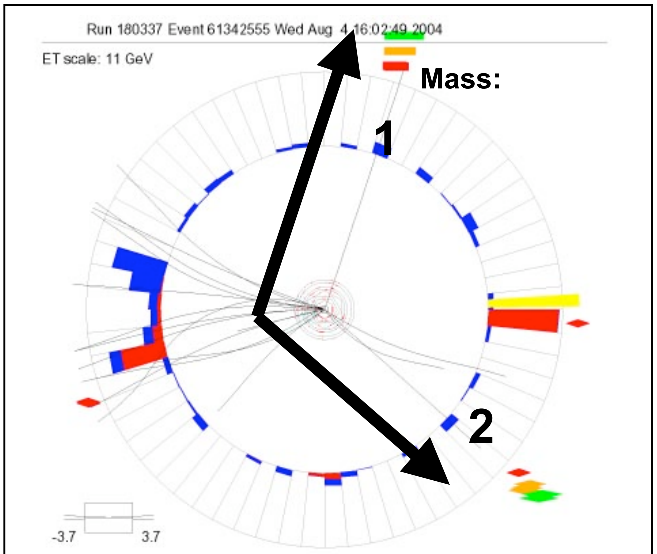
Event #1	μ_1	μ_2	Sum	Sum^2
φ	108°	336°		
P Gev/c	65.4	38.2		
Px Gev/c	-20.21	34.90	14.69	215.74 (GeV/c)^2
Py Gev/c	62.20	-15.54	46.67	2177.32 (GeV/c)^2
E Gev	65.4	38.20	103.60	10733.01 (GeV)^2

$$\begin{aligned} m &= \frac{1}{c^2}\sqrt{E^2 - c^2 p_x^2 - c^2 p_y^2} \\ &= \frac{1}{c^2}\sqrt{10733.01 - 215.74 - 2177.32} \\ &= 91.3\ \mathrm{GeV/c^2} \end{aligned}$$

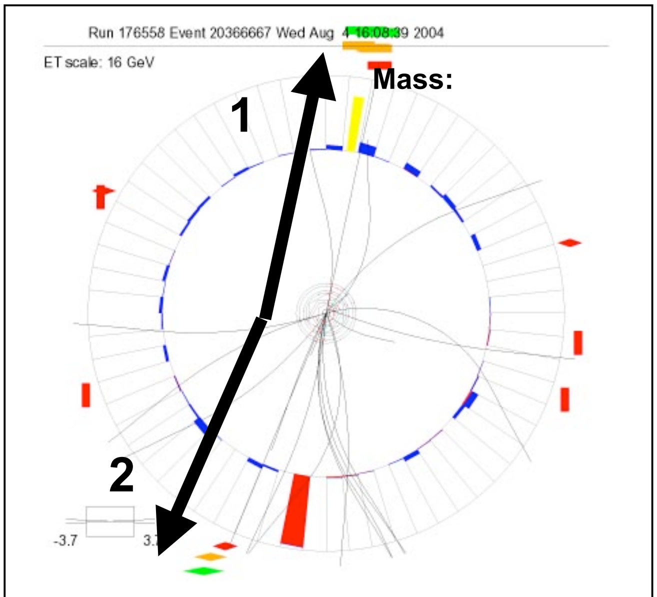
Z Boson Mass Reconstruction for DØ Events
Student 3D-Version 1



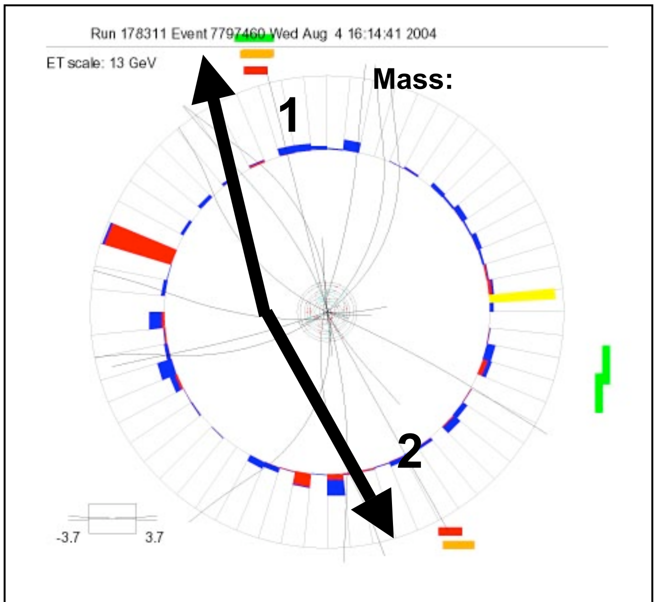
Event #1	μ_1	μ_2
φ	108°	336°
θ	54°	107°
P	42.3 GeV	56.0 GeV



Event #2	μ_1	μ_2
φ	70°	315°
θ	40°	80°
P	70.1 GeV	53.6 GeV

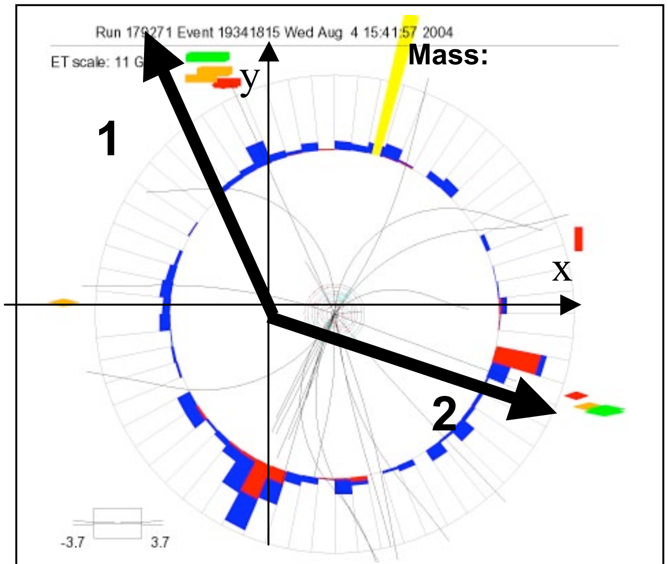


Event #3	μ_1	μ_2
φ	78°	249°
θ	42°	137°
P	33.3 GeV	56.5 GeV

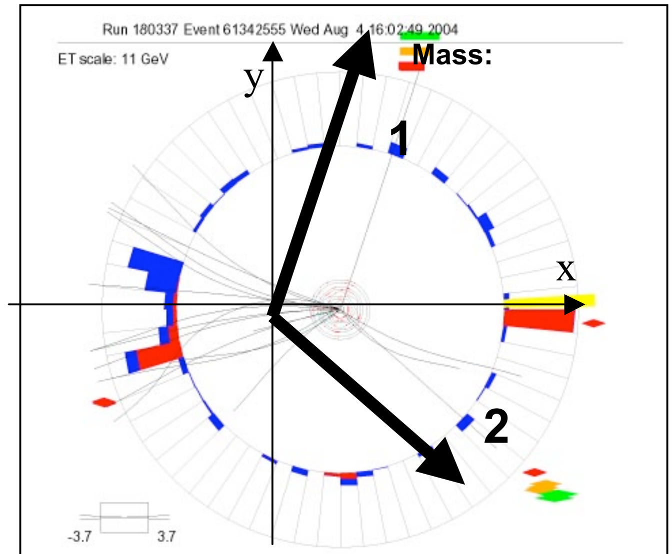


Event #4	μ_1	μ_2
φ	103°	296°
θ	78°	112°
P	31.6 GeV	65.3 GeV

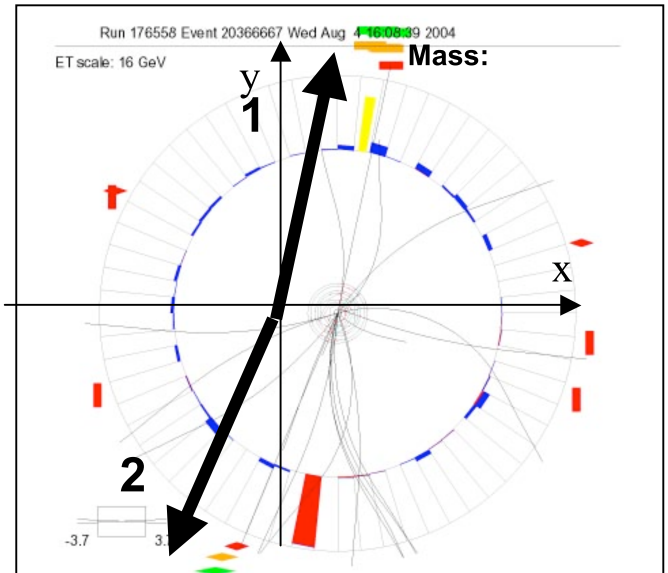
Z Boson Mass Reconstruction for DØ Events
Student 3D-Version 2



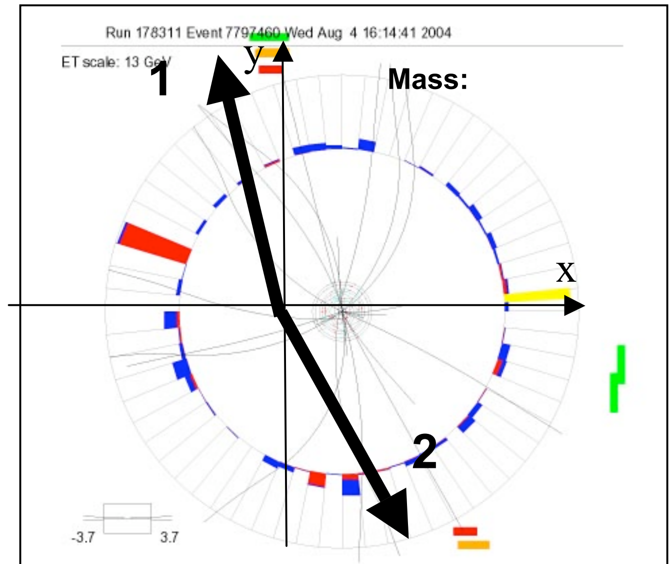
Event #1	μ_1	μ_2
φ		
θ	77°	64°
P	54.8 GeV	52.01 GeV



Event #2	μ_1	μ_2
φ		
θ	55°	88°
P	62.8 GeV	50.08 GeV

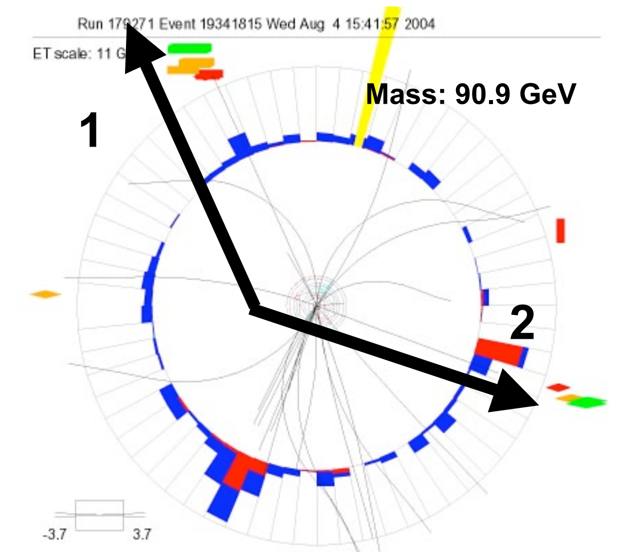


Event #3	μ_1	μ_2
φ		
θ	60°	99°
P	37.9 GeV	51.53 GeV

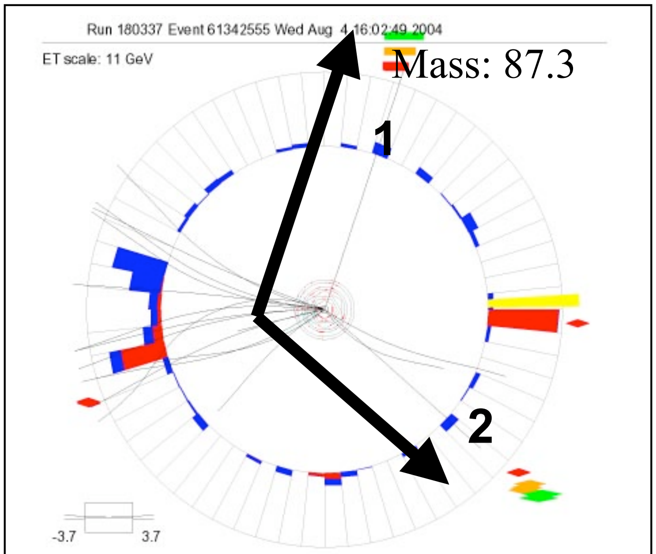


Event #4	μ_1	μ_2
φ		
θ	74°	76°
P	41.55 GeV	56.4 GeV

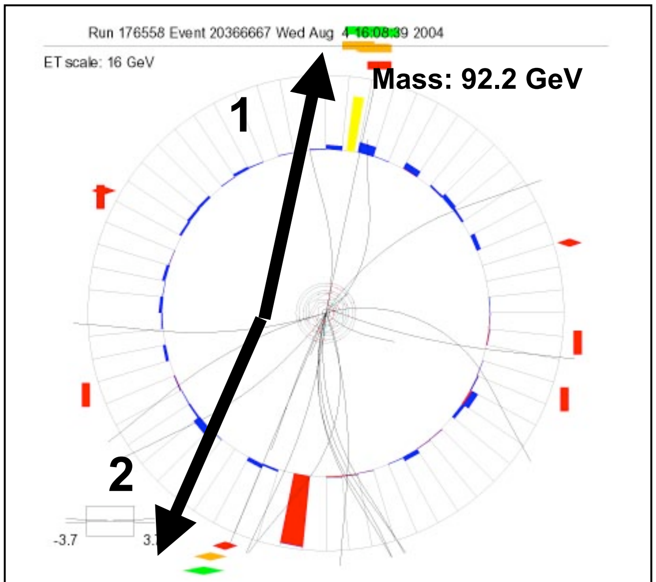
Z Boson Mass Reconstruction for DØ Events
Student 3D-Version 3



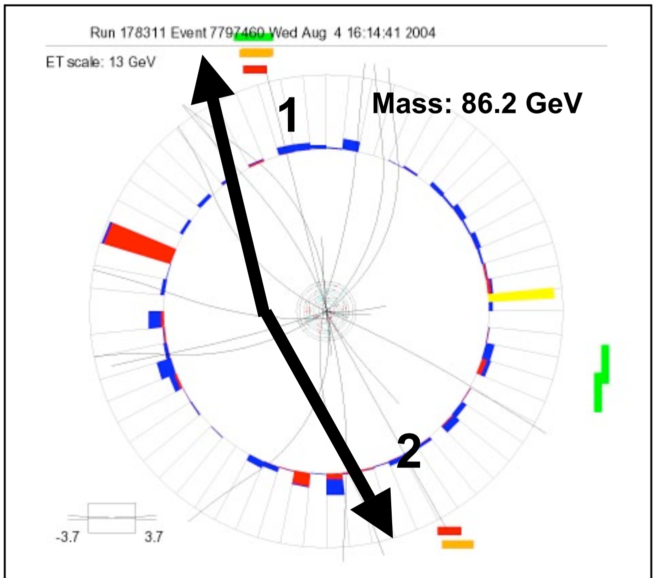
Event #1	μ_1	μ_2
φ	108°	336°
θ	74°	34°
P		48.49 GeV



Event #2	μ_1	μ_2
φ	70°	315°
θ	69°	98°
P	38.6 GeV	

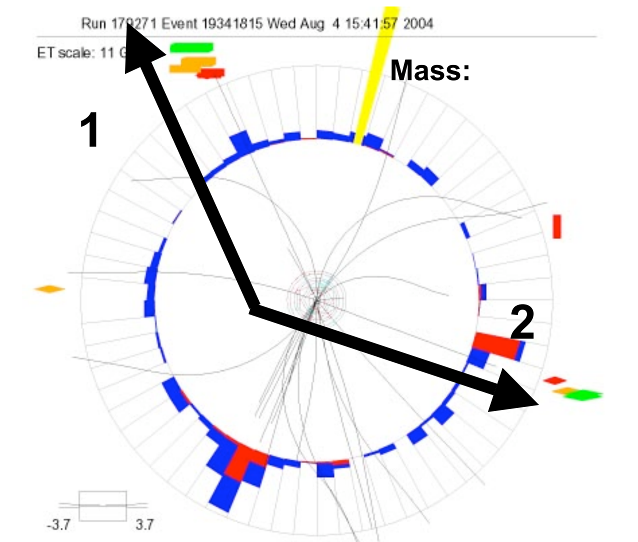


Event #3	μ_1	μ_2
φ	78°	249°
θ	84°	64°
P	31 GeV	

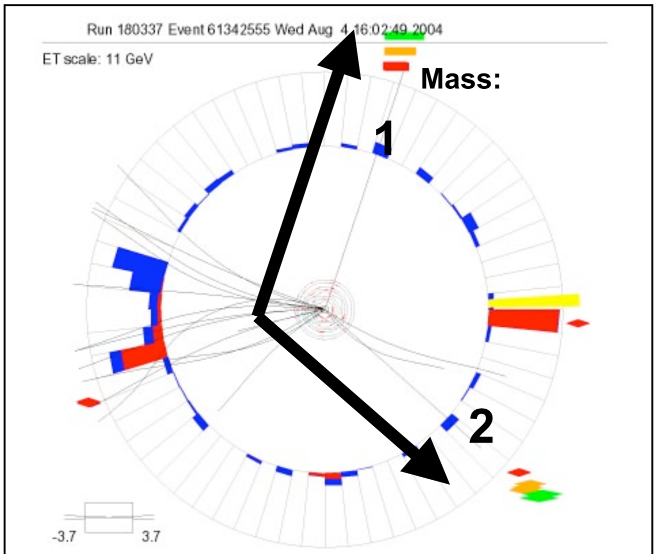


Event #4	μ_1	μ_2
φ	103°	296°
θ	47°	104°
P		37.06 GeV

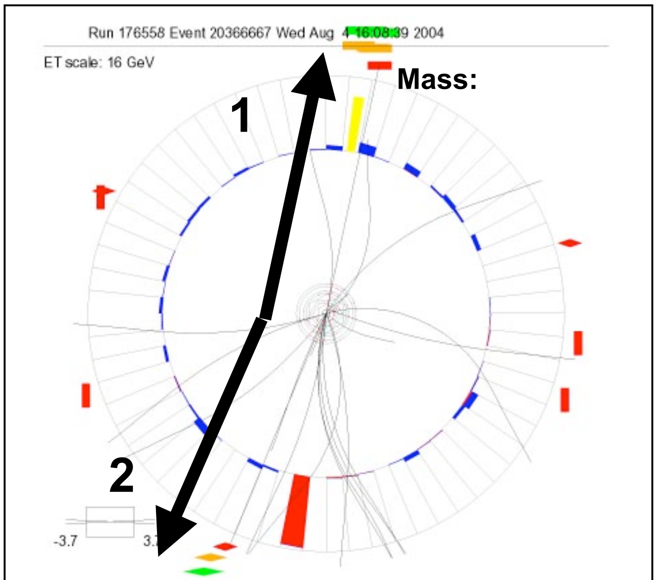
Z Boson Mass Reconstruction for DØ Events
Student 2D-Version 1



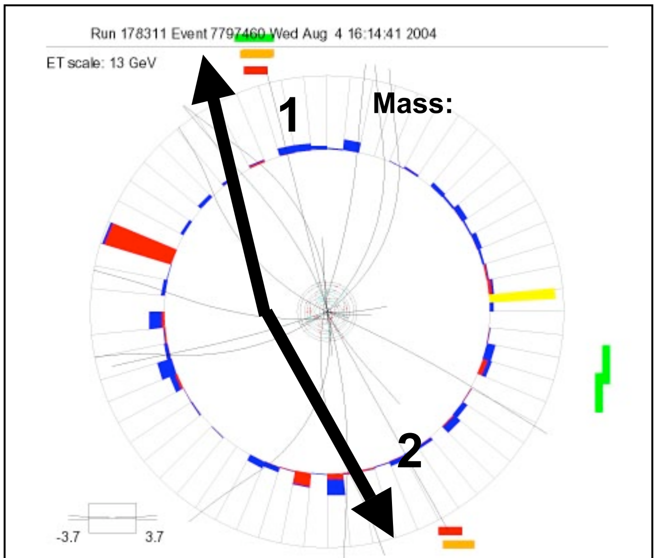
Event #1	μ_1	μ_2
φ	108°	336°
P	65.4 GeV	38.2 GeV



Event #2	μ_1	μ_2
φ	70°	315°
P	52.3GeV	56.7 GeV

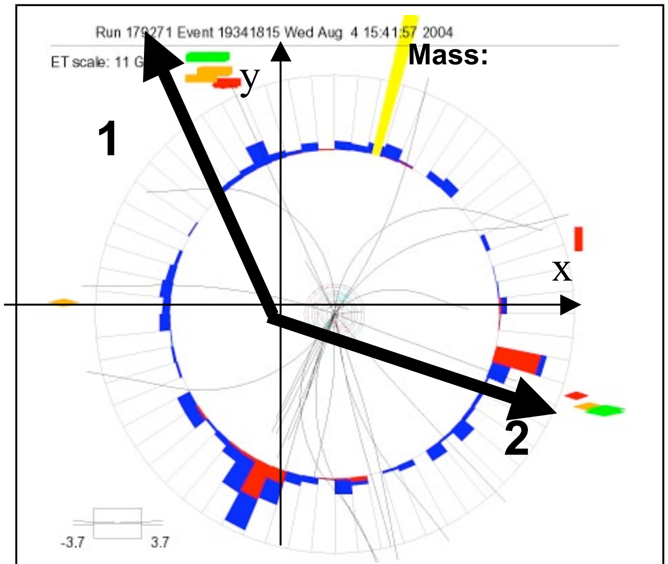


Event #3	μ_1	μ_2
φ	78°	249°
P	47.6 GeV	44.3 GeV

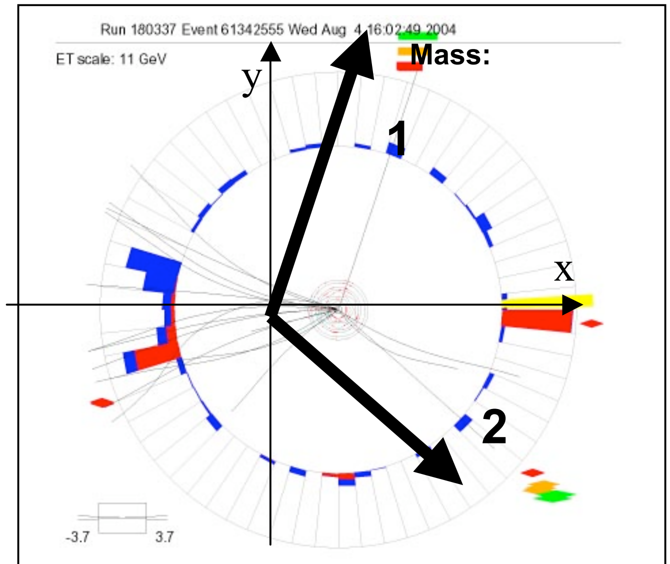


Event #4	μ_1	μ_2
φ	103°	296°
P	48.3 GeV	42.3 GeV

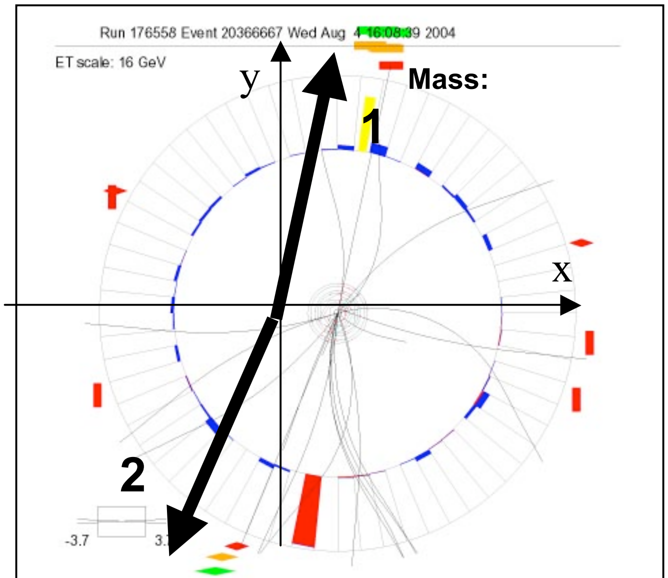
Z Boson Mass Reconstruction for DØ Events
Student 2D-Version 2



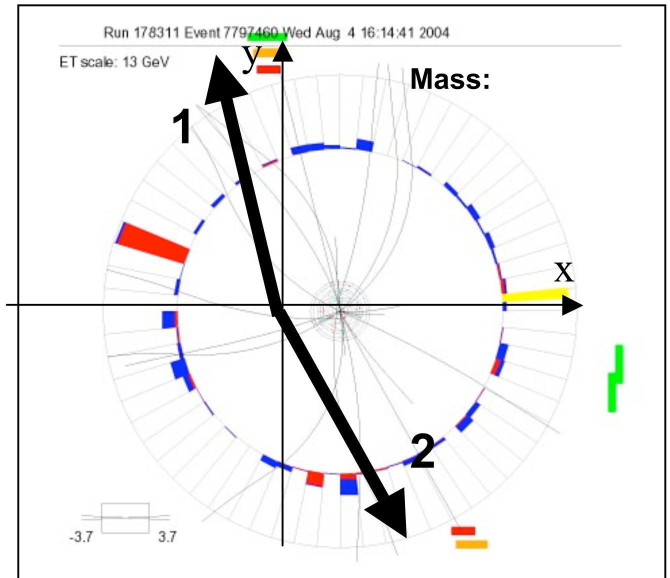
Event #1	μ_1	μ_2
φ		
P	51.9 GeV	48.7 GeV



Event #2	μ_1	μ_2
φ		
P	56.7 GeV	53.6 GeV

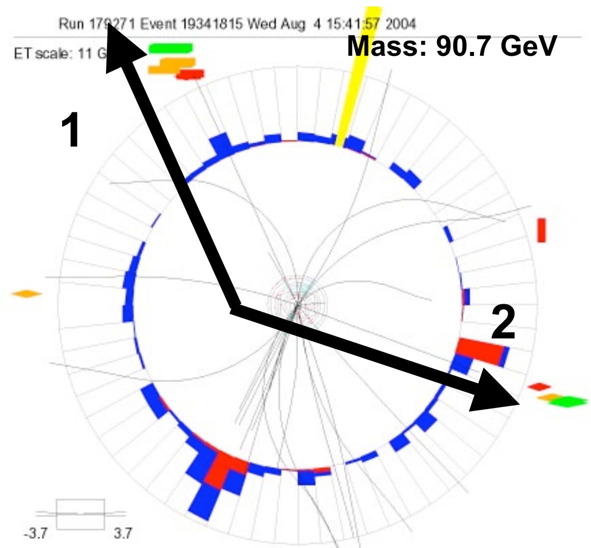


Event #3	μ_1	μ_2
φ		
P	45.6 GeV	45.3 GeV

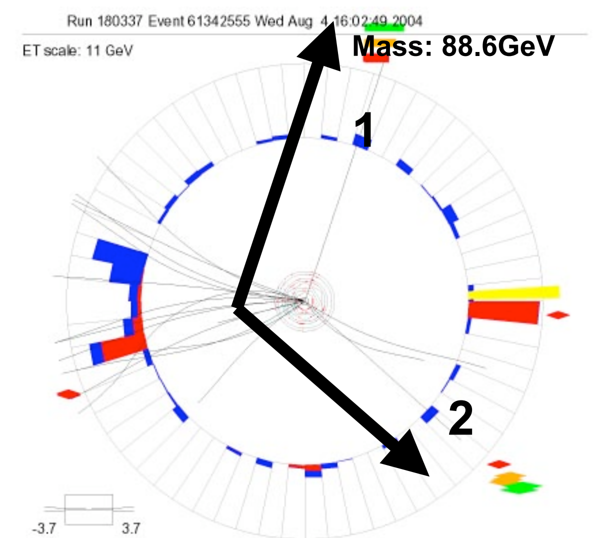


Event #4	μ_1	μ_2
φ		
P	47.2 GeV	42.3 GeV

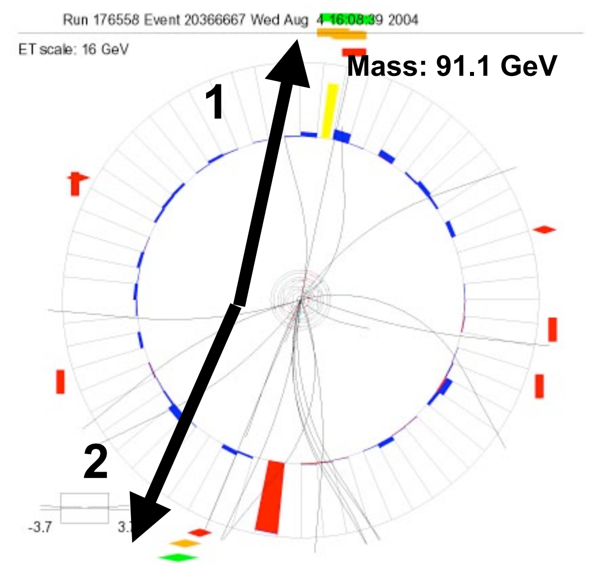
Z Boson Mass Reconstruction for DØ Events
Student 2D-Version 3



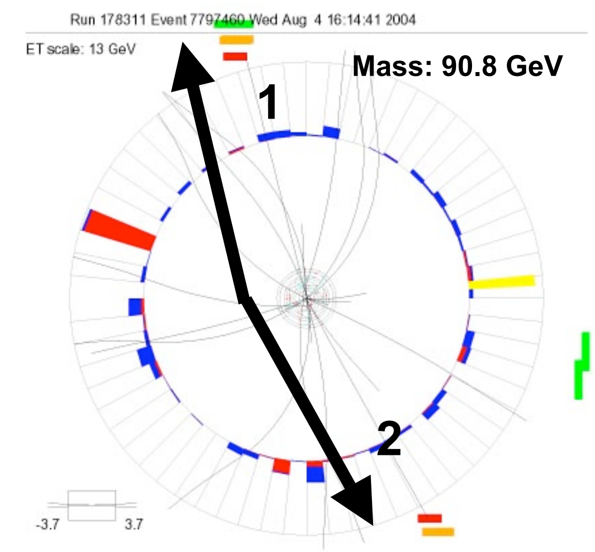
Event #1	μ_1	μ_2
φ	108°	336°
P		48.49 GeV



Event #2	μ_1	μ_2
φ	70°	315°
P	38.6 GeV	



Event #3	μ_1	μ_2
φ	78°	249°
P	31 GeV	



Event #4	μ_1	μ_2
φ	103°	296°
P		37.06 GeV

Z Boson Mass Reconstruction Answers

	Version 1						
Problem	Mass	$\phi 1$	$\theta 1$	p1	$\phi 2$	$\theta 2$	p2
1	89.5	108	54	42.30	336	107	56.00
2	92.3	70	40	70.10	315	80	53.60
3	86.6	78	42	33.30	249	137	56.50
4	90.0	103	78	31.60	296	112	65.30

	Version 2						
Problem	Mass	$\phi 1$	$\theta 1$	p1	$\phi 2$	$\theta 2$	p2
1	92.1	108	77	54.80	336	64	52.01
2	91.3	70	55	62.80	315	88	50.08
3	86.7	78	60	37.90	249	99	51.53
4	92.9	103	74	41.55	296	76	56.40

	Version 3						
Problem	Mass	$\phi 1$	$\theta 1$	p1	$\phi 2$	$\theta 2$	p2
1	90.9	108	74	75.30	336	34	48.49
2	87.3	70	69	38.60	315	98	68.61
3	92.2	78	84	31.00	249	64	74.60
4	86.2	103	47	54.00	296	104	37.06

Indicates information not given on worksheet

2D

Z Boson Mass Reconstruction Answers

	Version 1				
Problem	Mass	$\phi 1$	p1	$\phi 2$	p2
1	91.3	108	65.40	336	38.20
2	91.9	70	52.30	315	56.70
3	91.6	78	47.60	249	44.30
4	89.8	103	48.30	296	42.30

	Version 2				
Problem	Mass	$\phi 1$	p1	$\phi 2$	p2
1	91.9	108	51.90	336	48.70
2	93.0	70	56.70	315	53.60
3	90.6	78	45.60	249	45.30
4	88.8	103	47.20	296	42.30

	Version 3				
Problem	Mass	$\phi 1$	p1	$\phi 2$	p2
1	90.7	108	50.80	336	48.49
2	88.6	70	38.60	315	71.50
3	91.1	78	31.00	249	67.30
4	90.8	103	56.30	296	37.06

Indicates information not given on worksheet

Particle Test

1. Which combination of quarks is invalid?
   a.) d d
   b.) $d\ \bar{u}$
   c.) u u d
   d.) $\bar{u}\ \bar{d}\ \bar{d}$

2. What quarks exist in your body?
   a.) u
   b.) d
   c.) e-
   d.) answers a and b
   e.) answers a, b, and c

3. What particle groups are represented in your body?
   a.) mesons
   b.) baryons
   c.) leptons
   d.) answers a and b
   e.) answers b and c

4. What are the charge number, baryon number and strangeness of a usd (Λ^o) particle?
   a.) Q = 0, B = 0, S = 1
   b.) Q = 0, B = 1, S = -1
   c.) Q = 1, B = 0, S = 0
   d.) Q = 1, B = 1, S = -1

5. What forces act upon Millikan's oil drop when it is suspended?
   a.) electric force and magnetic force
   b.) electric force and gravitational force
   c.) magnetic force and gravitational force
   d.) electric force, magnetic force and gravitational force

6. Millikan's work measured the _________ of an electron?
   a.) charge
   b.) mass
   c.) charge/mass ratio
   d.) speed

7. J. J. Thompson applied a net force of zero on the cathode rays by applying both an electric and a magnetic field. As a result, Thompson measured the _______ of the cathode rays.

   a.) charge
   b.) mass
   c.) charge/mass ratio
   d.) speed

8. Fermilab accelerates_________.

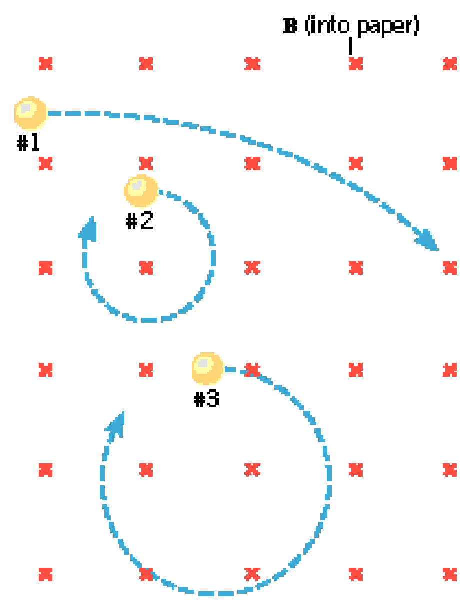
   a.) electrons
   b.) protons
   c.) neutrinos
   d.) neutrons

9. Determine the direction of the magnetic field required to cause the proton beam to move counterclockwise in a circular path as shown.

   a.) into the page
   b.) out of the page
   c.) toward the top of the page
   d.) toward the bottom of the page

10. Three particles have identical charges and speeds. They enter a constant magnetic field and follow the paths shown in the picture. Which particle is the most massive?

   a.) 1
   b.) 2
   c.) 3



11. A proton (u u d) and an antiproton ($\bar{u}\ \bar{u}\ \bar{d}$) collide and a u and a $\bar{u}$ annihilate to create a total of eight quarks (u $\bar{u}$ d $\bar{d}$ d $\bar{d}$ s $\bar{s}$). What three particles form?

a.) $\overline{\Sigma^-}\ \Lambda^o \pi^-$

b.) $K^+\ \pi^+$ p

c.) $\Lambda^o\ \pi^+$ p

12. What wavelength is produced by 20 MeV protons?

a.) 9.9×10^{-33} m

b.) 9.9×10^{-27} m

c.) 1.3×10^{-15} m

d.) 5×10^{-17} m

13. At what fraction of the speed of light are the protons moving along Fermilab's 1-km radius collider if its magnetic field directing the beam is 0.003 T?

a.) 0.96 c b.) 0.9 c c.) 0.85 c d.) 0.5 c

14. Name two particles or particle characteristics for which Fermilab is currently searching.

15. Fermilab's accelerator is currently operational and its particles move through the following sequence so as to collide with various targets:

a.) Linac, Cockcroft-Walton, Tevatron, Main Injector

b.) Cockcroft-Walton, Linac, Tevatron, Main Ring

c.) Cockcroft-Walton, Linac, Main Injector Tevatron

d.) Linac, Cockcroft-Walton, Main Ring, Tevatron

16. The Linac accelerates particles using:

a.) alternating electric fields

b.) magnetic quadruples

c.) magnetic dipoles

d.) electric and magnetic fields

17. CDF measures the __________ of particles using __________. DØ measures the __________ of particles using __________.

a.) energy / a calorimeter / momentum / a silicon detector and a magnet

b.) momentum / a calorimeter / energy / a silicon detector and a magnet

c.) momentum / a silicon detector and a magnet / energy / a calorimeter d.) energy / a silicon detector and a magnet / momentum / a calorimeter

18. When objects collide:

    a.) the initial velocity of the objects must equal the final velocity of the objects.

    b.) the initial momenta of the objects is greater than the final momenta of the objects.

    c.) the initial momenta of the objects is less than the final momenta of the objects.

    d.) the initial momenta of the objects must equal the final momenta of the objects.

19. A 0.5-kg puck moving with a speed of 3 m/s collides with a stationary 2-kg puck. After the collision, the 2-kg puck moves off in the same direction as the 0.5-kg puck was moving before the collision with a speed of 1 m/s. What is the final velocity of the 0.5-kg puck?

    a.) 0 m/s   b.) 1 m/s in the same direction   c.) 1 m/s in the opposite direction

A p^+ and a π^o were created from the decay of an unknown particle. Using this information and the questions below, identify the unknown particle.

20. What was the energy of that unknown particle if the p^+ has an energy of 0.973 GeV and the π^o has an energy of 0.325 GeV?

    a.) 0.32 GeV   c.) 1.30 GeV

    b.) 0.648 GeV   d.) 2.99 GeV

21. What was the momentum of the unknown particle that decayed if the p^+ has a momentum of 0.257 GeV/c and initially travels at an angle of 21.5 degrees and the π^o has a momentum of 0.295 GeV/c and initially travels at an angle of –18.7 degrees?

    a.) 0.257 GeV/c (cos 21.5^0) + 0.295 GeV/c (cos 18.7^0)

    b.) 0.257 GeV/c (sin 21.5^0) + 0.295 GeV/c (sin 18.7^0)

    c.) 0.257 GeV/c (cos 21.5^0) + 0.295 GeV/c (sin 18.7^0)

    d.) 0.257 GeV/c (sin 21.5^0) + 0.295 GeV/c (cos 18.7^0)

22. Using your results from questions 20 and 21, compute the rest mass and identify the particle that decayed.

Particle Test **Name:** ______________________________

1) ______

2) ______

3) ______

4) ______

5) ______

6) ______

7) ______

8) ______

9) ______

10) ______

11) ______

12) ______

13) ______

14) ____

15) ______

16) ______

17) ______

18) ______

19) ______

20) ______

21) ______

Answer 22 on the back and show your work.

Particle Test Answer Key

1) A

2) E

3) E

4) B

5) B

6) B

7) C

8) B

9) A

10) B

11) A

12) C

13) A

14) Top, Higgs, Neutrino Oscillations

15) C

16) A

17) C

18) D

19) C

20) C

21) A

Answer 22 on the back and show your work.

Answer should be m = 1.19 GeV/c^2 or Σ^+

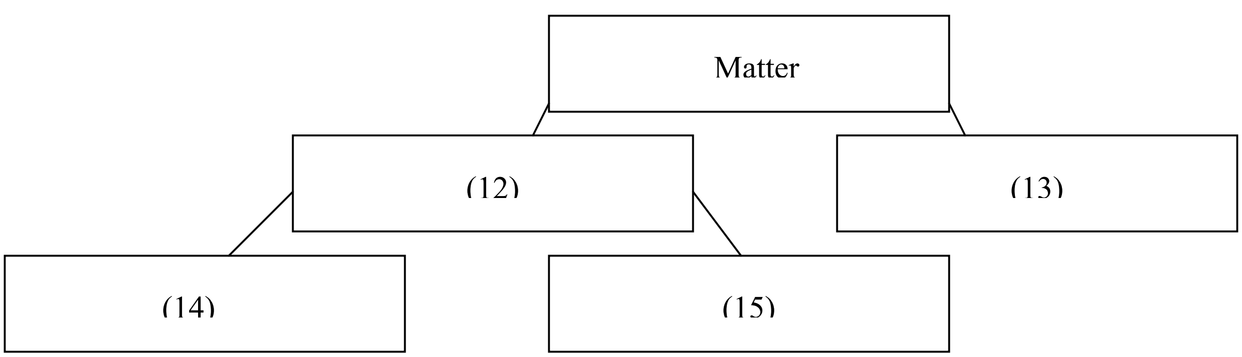
Using . . . $E^2 = p^2 + m^2$, solve for m using p (0.518 GeV/c) and E (1.3 GeV) in 21 and 20 respectively.

Conceptual Particle Physics Test

Directions: For problems #1-11, choose the best match for each definition. For #12-15, fill in the correct terms for the chart using the choices below. (1 pt. each.)

(A) Atomic mass number
(B) Atomic number
(C) Baryons
(D) Elements
(E) Gluons
(F) Gravitons
(G) Hadrons
(H) Isotope
(I) Leptons
(J) Mesons
(K) Nucleon
(L) Photons
(M) W & Z bosons
(N) None of the above

	1.	The force carrier for the gravitational force
	2.	An alternate version of an element
	3.	This describes the number of protons and neutrons in the nucleus.
	4.	Atoms of the same kind form _____________.
	5.	The force carrier for the weak force
	6.	This describes the number of protons in the nucleus.
	7.	The force carrier for the strong force
	8.	The force carrier for the electromagnetic force
	9.	This type of particle has three quarks.
	10.	This type of particle has two quarks. (1 quark & 1 antiquark)
	11.	Proton + Neutron



16. What are the three particles that make up an atom? (3 pts.)

_________________ _________________ _________________

17. Who discovered the electron? (1 pt.) _________________

18. What did Rutherford discover? Explain how he made this discovery. (Explain his lab.) (4 pts.)

19. What element is produced when a gold nucleus gains a proton? (1 pt.) _____________

20. How many protons are there in the nucleus of $^{82}_{38}Sr$? How many neutrons? How many electrons are there in the neutral atom? (3 pt.)

Protons: _______________ Neutrons: ________________ Electrons: _______________

21. What holds the nucleons in a nucleus together? (1 pt.) _________________

22. Name the six leptons (<u>not</u> the antileptons). (6 pts.)

_________________ _________________ _________________

_________________ _________________ _________________

23. Name the six quarks (<u>not</u> the antiquarks). (6 pts.)

_________________ _________________ _________________

_________________ _________________ _________________

BONUS

Name the two main detectors at Fermilab. _________________ _________________

Which quark did they discover at Fermilab? _________________

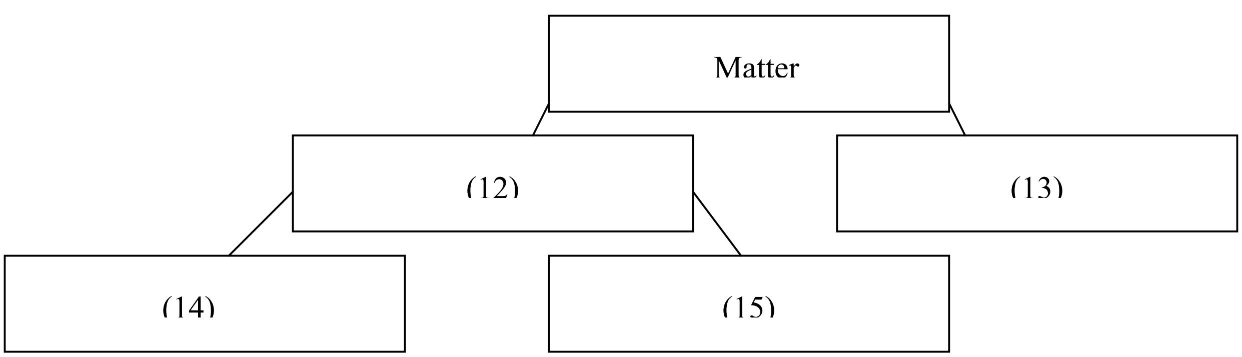
Who named the quark? _________________

Conceptual Particle Physics Test – Answer Key

Directions: For problems #1-11, choose the best match for each definition. For #12-15, fill in the correct terms for the chart using the choices below. (1 pt. each.)

(A) Atomic mass number
(B) Atomic number
(C) Baryons
(D) Elements
(E) Gluons
(F) Gravitons
(G) Hadrons
(H) Isotope
(I) Leptons
(J) Mesons
(K) Nucleon
(L) Photons
(M) W & Z bosons
(N) None of the above

F	12.	The force carrier for the gravitational force
H	13.	An alternate version of an element
A	14.	This describes the number of protons and neutrons in the nucleus.
D	15.	Atoms of the same kind form _____________.
M	16.	The force carrier for the weak force
B	17.	This describes the number of protons in the nucleus.
E	18.	The force carrier for the strong force
L	19.	The force carrier for the electromagnetic force
C	20.	This type of particle has three quarks.
J	21.	This type of particle has two quarks. (1 quark & 1 antiquark)
K	22.	Proton + Neutron



(12) **G** (13) **I** (14) **C** (15) **J**

16. What are the three particles that make up an atom? (3pts.)

Proton ***Neutron*** ***Electron***

17. Who discovered the electron? (1 pt.) *J. J. Thompson*

18. What did Rutherford discover? Explain how he made this discovery. (Explain his lab.) (4pts)

He discovered the positive nucleus. He shot alpha particles at the gold nucleus and they came back!

19. What element is produced when a gold nucleus gains a proton? (1 pt.) **Hg - Mercury**

20. How many protons are there in the nucleus of $^{82}_{38}Sr$? How many neutrons? How many electrons are there in the neutral atom? (3 pt.)

Protons: ***38*** Neutrons: ***44*** Electrons: ***38***

21. What holds the nucleons in a nucleus together? (1 pt.) **Strong force (or gluons)**

22. Name the six leptons (not the antileptons). (6 pts.)

Electron	**Muon**	**Tau**
Electron Neutrino	**Muon Neutrino**	**Tau Neutrino**

23. Name the six quarks (not the antiquarks). (6 pts.)

Top	**Up**	**Charm**
Bottom	**Down**	**Strange**

BONUS

Name the two main detectors at Fermilab. **DØ** **CDF**

Which quark did they discover at Fermilab? **Top**

Who named the quark? **Murray Gell-Mann**

<u>Up (u)</u> Matter Quark Charge = +2/3 Mass = 5 MeV/c ^{2}	<u>Down (d)</u> Matter Quark Charge = -1/3 Mass = 8 MeV/c ^{2}
<u>Charm (c)</u> Matter Quark Charge = +2/3 Mass = 1500 MeV/c ^{2}	<u>Strange (s)</u> Matter Quark Charge = -1/3 Mass =160 MeV/c ^{2}
<u>Top (t)</u> Matter Quark Charge = +2/3 Mass = 180,000 MeV/c ^{2}	<u>Bottom (b)</u> Matter Quark Charge = -1/3 Mass = 4250 MeV/c ^{2}
<u>Antiup ($\overline{u}$)</u> Antimatter Quark Charge = -2/3 Mass = 5 MeV/c ^{2}	<u>Antidown ($\overline{d}$)</u> Antimatter Quark Charge = +1/3 Mass = 8 MeV/c ^{2}

<u>Anticharm ($\overline{c}$)</u> Antimatter Quark Charge = -2/3 Mass = 1500 MeV/c^2	<u>Antistrange ($\overline{s}$)</u> Antimatter Quark Charge = +1/3 Mass = 160 MeV/c^2
<u>Antitop ($\overline{t}$)</u> Antimatter Quark Charge = -2/3 Mass = 180,000 MeV/c^2	<u>Antibottom ($\overline{b}$)</u> Antimatter Quark Charge = +1/3 Mass = 4250 MeV/c^2
<u>Electron (e)</u> Matter Lepton Charge = -1 Mass = 0.511 MeV/c^2	<u>Electron neutrino (ν_e)</u> Matter Lepton Charge = 0 Mass = ~0 MeV/c^2
<u>Muon (μ)</u> Matter Lepton Charge = -1 Mass = 105.7 MeV/c^2	<u>Muon neutrino (ν_μ)</u> Matter Lepton Charge = 0 Mass = ~0 MeV/c^2

Tau (τ) Matter Lepton Charge = -1 Mass = 1777 MeV/c ^{2}	Tau neutrino (ν_τ) Matter Lepton Charge = 0 Mass = <70 MeV/c ^{2}
Positron (e^+) Antimatter Lepton Charge = +1 Mass = 0.511 MeV/c ^{2}	Electron antineutrino ($\overline{\nu}_{e+}$) Antimatter Lepton Charge = 0 Mass = ~0 MeV/c ^{2}
Antimuon ($\overline{\mu}$) Antimatter Lepton Charge = +1 Mass = 105.7 MeV/c ^{2}	Muon antineutrino ($\overline{\nu}_\mu$) Antimatter Lepton Charge = 0 Mass = ~0 MeV/c ^{2}
Antitau ($\overline{\tau}$) Antimatter Lepton Charge = +1 Mass = 1777 MeV/c ^{2}	Tau antineutrino ($\overline{\nu}_\tau$) Antimatter Lepton Charge = 0 Mass = ~0 MeV/c ^{2}

Gluon Gauge boson Force carrier: Strong force Charge = 0 Mass = 0 MeV/c^2	**W^+** Gauge boson Force carrier: Weak force Charge = +1 Mass = 81,000 MeV/c^2
W^- Gauge boson Force carrier: Weak force Charge = -1 Mass = 81,000 MeV/c^2	**Z^0** Gauge boson Force carrier: Weak force Charge = 0 Mass = 93,000 MeV/c^2
Photon Gauge boson Force carrier: Electromagnetic force Charge = 0 Mass = 0 MeV/c^2	**Graviton** Gauge boson Force carrier: Gravitational force Charge = 0 Mass = 0 MeV/c^2

Standard Model Mixer

Some instructions regarding this "mixer"

1. It can be done whenever in the year. Perhaps this is a good introduction to a particle physics unit.
2. No prerequisite standard model knowledge is required.
3. This is a good critical thinking activity. That is, students need to classify, organize, sort, compare/contrast, etc.
4. Here is the general flow of thinking:
   --"Am I matter, antimatter or a gauge boson?"
   --"OK, now am I a quark, lepton, or a force carrier?"
   --"What is my net charge?"
   --"Finally, what is my rest mass?"
5. Students should be able to organize into the following hierarchy (with some guidance):
    1. Matter
        2. Quarks
            3. +2/3 charge
                4. Up
                4. Charm
                4. Top
            3. -1/3 charge
                4. Down
                4. Strange
                4. Bottom
        2. Leptons
            3. –1 charge
                4. Electron
                4. Muon
                4. Tau
            3. Zero charge
                4. Electron neutrino
                4. Muon neutrino
                4. Tau neutrino
    1. Antimatter
        2. Antiquarks
            3. +2/3 charge
                4. Antiup
                4. Anticharm
                4. Antitop
            3. -1/3 charge
                4. Antidown
                4. Antistrange
                4. Antibottom

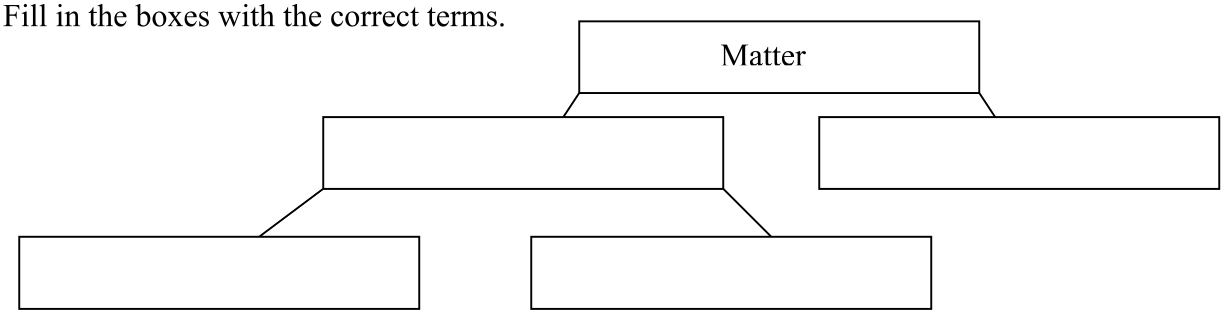
        2. Leptons

        3. –1 charge
            4. Positron
            4. Antimuon
            4. Antitau
        3. Zero charge
            4. Electron antineutrino
            4. Muon antineutrino
            4. Tau antineutrino
1. Gauge bosons
    2. Force carriers
        3. Strong
            4. Gluon
        3. Weak
            4. W+
            4. W-
            4. Zo
        3. Electromagnetism
            4. Photon
        3. Gravity
            4. Graviton

6. NOTE: The numbering on this hierarchy is from Project CRISS (Creating Independence through Student-Owned Strategies), third edition, Santa, Havens, and Valdes. This numbering strategy is called “power thinking.” At first it looks weird, but it makes sense after a short time.
7. The Standard Model used is from the Education Office publication, *Topics in Modern Physics*, Teacher Resource Materials, First Revision, August 1996. It is found on page 2 of this document.
8. The hierarchy suggested above is JUST A SUGGESTION. Students could organize themselves in other logical ways as well. In fact, various standard model tables organize the elements in physically different manners on the paper. This is unlike the Periodic Table—where no matter who publishes it, the format is always uniform.
9. There are 30 “items” to categorize. This is sufficient for a larger class. Smaller classes could eliminate some or all of the antiparticles.

Standard Model Review

1. Fill in the boxes with the correct terms.



2. List the four fundamental forces with the strongest on top down to the weakest. Then list the force carrier particles for each.

Force	**Force Carrier Particles**
a)	
b)	
c)	
d)	

3. List the six quarks (not antiquarks) and the six leptons (not antileptons).

Quarks	**Leptons**

4. Which type of particle has three quarks?________________________________

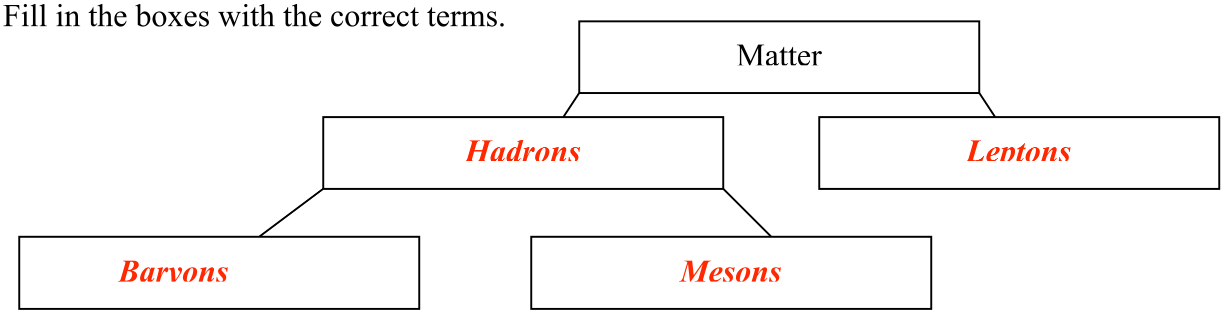
5. Which type of particle has two quarks (1 quark & antiquark)?_________________________

6. Who discovered the electron?________________________________

7. What is the difference between hadrons and leptons?________________________________

Standard Model Review – Answer Key

1. Fill in the boxes with the correct terms.



2. List the four fundamental forces with the strongest on top down to the weakest. Then list the force carrier particles for each.

Force	**Force Carrier Particles**
a) Strong	*Gluon*
b) Electromagnetic	*Photon*
c) Weak	*W & Z bosons*
d) Gravitational	*Graviton*

3. List the six quarks (not antiquarks) and the six leptons (not antileptons).

Quarks	**Leptons**
Up	*Electron*
Down	*e^- neutrino*
Charm	*Muon*
Strange	*μ neutrino*
Top	*Tau*
Bottom	*τ neutrino*

4. Which type of particle has three quarks? ***Baryons***

5. Which type of particle has two quarks (1 quark & 1 antiquark)? ***Mesons***

6. Who discovered the electron? ***J. J. Thompson***

7. What is the difference between hadrons and leptons? ***Hadrons participate in all four force interactions and leptons do not participate in the strong force.***

Analyzing Bubble Chamber Decays Lab

<u>Goal</u>: Find the mass of Λ^o using the equation $E^2 = m^2+p^2$.

<u>Note</u>: Do not forget to draw the appropriate work on the graph clearly and neatly.

<u>Procedure</u>:

1. Draw two chords on the curve, bisect, and find the radius of the curve for each resulting particle. Using this radius (R), and the knowledge that a charged particle (q) with a known mass (m) is moving in a uniform magnetic field (B) at a given velocity (v), write a relationship that will relate q, v , B, m, and R in the space below.

2. Given the above relationship and considering that we will ultimately need to find the momentum (p), solve the above relationship for the momentum. (HINT: Think back to the original formula for momentum and manipulate the above to solve for momentum.) Write your answer below.

3. You should be able to see that R is proportional to p; this means that if you know R you "know" p.

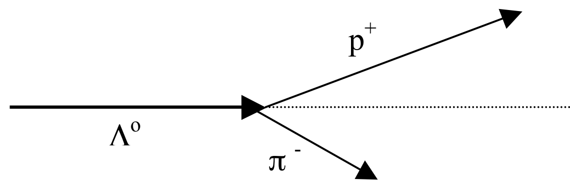
$$R_{p+} \sim p_{p+} \qquad\qquad R_{\pi-} \sim p_{\pi-}$$

4. For this experiment, the momentum = 2 x radius (in meters).

p_{p+}: ______________________

$p_{\pi-}$: ______________________

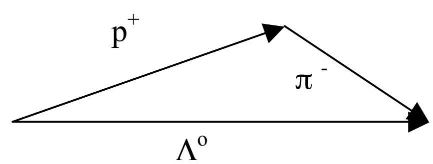
5. Now draw the p vectors of p^+ and π^- before they curved. With these vectors you can now get the angle at which they are traveling in.



Angle of p^+: ______________________

Angle of π^-: _______________________

6. Draw these to scale recalling that R~p so the radius value is the magnitude of the momentum vectors of p^+ and π^+ . Add these two vectors to get the resultant, which will be the initial p of Λ^o. (Recall the idea of conservation!) Show your work below.



7. Now we can move on to the masses of these particles. I have listed them here for you.

$M_{p+} = 0.938\ GeV/c^2$ $M_{\pi-} = 0.140\ GeV/c^2$

8. Now that you know the masses and the momenta, find the energy with the formula given in the goal. Show your work below.

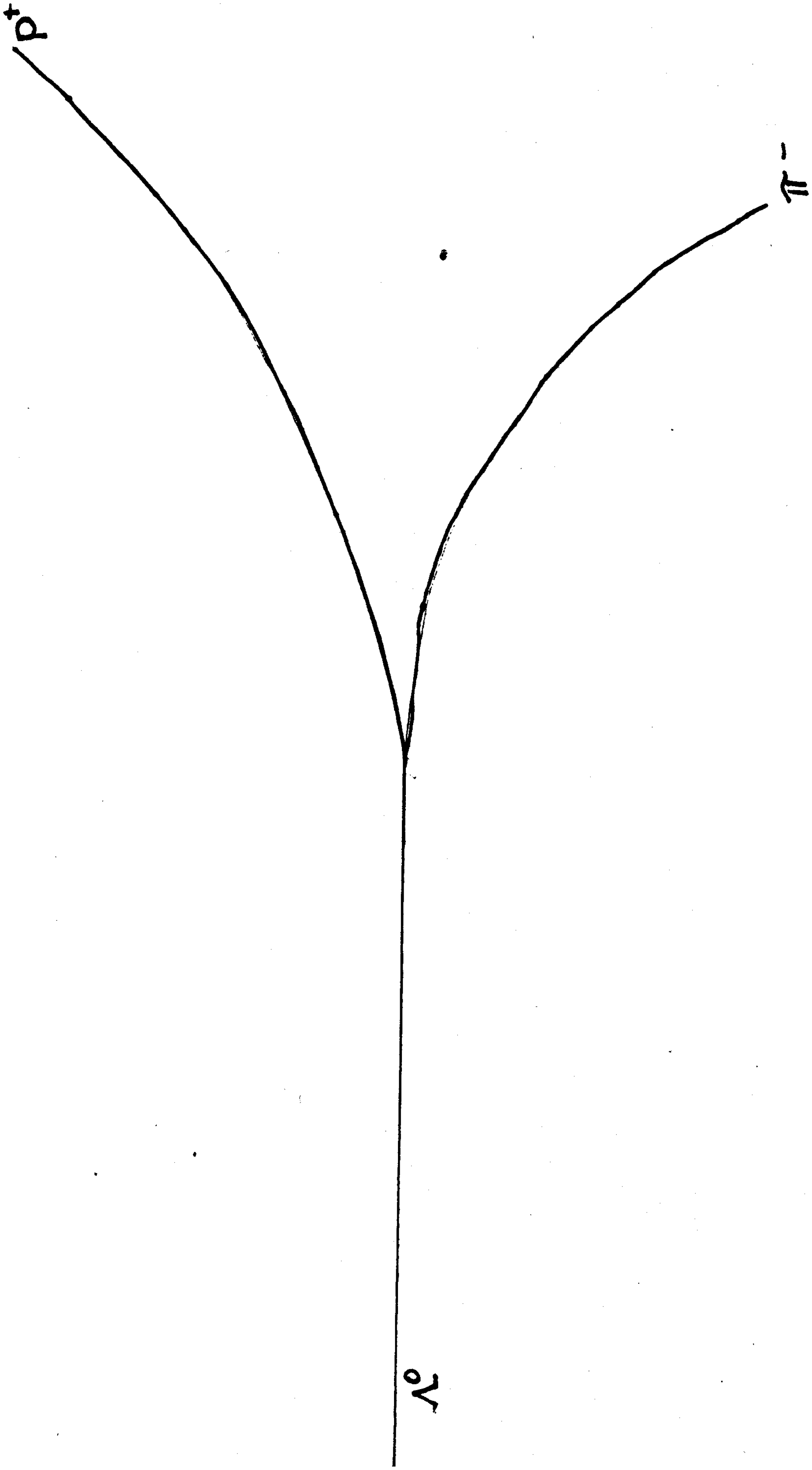
E_{p+}: ________________ $E_{\pi-}$: ________________

9. Using the idea of the conservation of energy, find the energy of the Λ^o. Remember to relate the energy before the decay to the energy after the decay. Show your work below.

$E_{\Lambda}{}^{o}$: ________________________

10. Now we can finally move on to solving for the mass of Λ^o because we now know the energy and the momentum of Λ^o. Show your work below:

$Mass_{\Lambda}$: __________________________


p^+
π^-
Λ^0

Analyzing Bubble Chamber Decays Lab – Teacher's Key

Goal: Find the mass of Λ^o using the equation $E^2 = m^2+p^2$.

Note: Do not forget to draw the appropriate work on the graph clearly and neatly.

Procedure:

1. Draw two chords on the curve, bisect, and find the radius of the curve for each resulting particle. Using this radius (R), and the knowledge that a charged particle (q) with a known mass (m) is moving in a uniform magnetic field (B) at a given velocity (v), write a relationship that will relate q, v , B, m, and R in the space below.

$$F_B=F_{centr.}$$

$$q\ v\ B = m\ \frac{v^2}{R}$$

$$q\ B = \frac{m\ v}{R}$$

2. Given the above relationship and considering that we will ultimately need to find the momentum (p), solve the above relationship for the momentum. (HINT: Think back to the original formula for momentum and manipulate the above to solve for momentum.) Write your answer below.

$$q\ B = \frac{m\ v}{R}$$

$$q\ B\ R = m\ v$$

$$q\ B\ R = p$$

3. You should be able to see that R is proportional to p; this means that if you know R you "know" p.

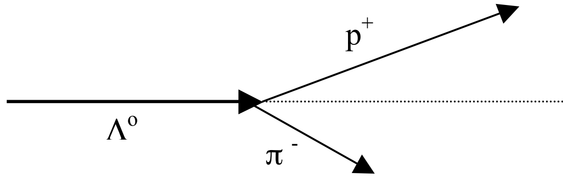
$R_{p+} \sim p_{p+}$ $\qquad$ $R_{\pi-} \sim p_{\pi-}$

4. For this experiment, the momentum = 2 x radius (in meters).

p_{p+}: **0.320**

$p_{\pi-}$: **0.214**

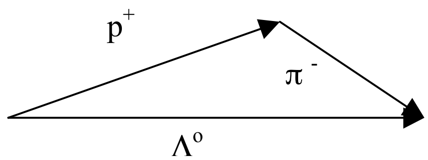
5. Now draw the p vectors of p^+ and π^- before they curved. With these vectors you can now get the angle at which they are traveling in.



Angle of p^+: ________**10°**__________

Angle of π^-: _____**-8° or 352°**_______

6. Draw these to scale recalling that R~p so the radius value is the magnitude of the momentum vectors of p^+ and π^+ . Add these two vectors to get the resultant, which will be the initial p of Λ^o. (Recall the idea of conservation!) Show your work below.



	Momentum	**Angle**	**x → mag(cos Θ)**	**y → mag(sin Θ)**
$\mathbf{p^+}$	.325	10°	.315	.056
$\boldsymbol{\pi^-}$	.214	-352°	.212	-.030
$\boldsymbol{\Lambda^o}$	.528 GeV/c		.527	.026

7. Now we can move on to the masses of these particles. I have listed them here for you.

$M_{p+} = 0.938$ GeV/c^2 $\qquad$ $M_{\pi-} = 0.140$ GeV/c^2

8. Now that you know the masses and the momenta, find the energy with the formula given in the goal. Show your work below.

E_{p+}: **0.991 GeV** $\qquad$ $E_{\pi-}$: **0.256 GeV**

$E_{p+} = \text{sqrt}\ (p_{p+}{}^2 + m_{p+}{}^2)$ $\qquad$ $E_{\pi-} = \text{sqrt}\ (p_{\pi-}{}^2 + m_{\pi-}{}^2)$

$E_{p+} = \text{sqrt}\ [(0.320)^2 + (0.938)^2]$ $\qquad$ $E_{\pi-} = \text{sqrt}\ [(0.214)^2 + (0.140)^2]$

$E_{p+} = 0.991$ eV $\qquad$ $E_{\pi-} = 0.256$ eV

9. Using the idea of the conservation of energy, find the energy of the Λ^o. Remember to relate the energy before the decay to the energy after the decay. Show your work below.

$E_{\Lambda}{}^o$: **1.247 GeV**

$E_{\Lambda}{}^o = E_{\pi+} + E_{\pi-}$

$E_{\Lambda}{}^o = 0.991$ GeV $+ 0.256$ GeV

10. Now we can finally move on to solving for the mass of Λ^o because we now know the energy and the momentum of Λ^o. Show your work below:

Mass_{Λ}: **1.130 eV/c^2** ***note: actual $m_{\Lambda}{}^o$ is about 1.115 GeV/c^2***

$E_{\Lambda}{}^o = 1.247$ GeV
$p_{\Lambda}{}^o = 0.528$ GeV/c

$m_{\Lambda}{}^o = \text{sqrt}\ (E_{\Lambda}{}^{o\,2} - p_{\Lambda}{}^{o\,2})$

$m_{\Lambda}{}^o = \text{sqrt}\ [(1.247\text{GeV})^2 - (0.528\ \text{GeV/c}^2)2]$

Sloan Digital Sky Survey SkyServer Project
http://skyserver.sdss.org/dr1/en/

I. Brief Description

A. Designed for Honors to Advanced Placement level student
B. For AP course, project completed following the AP exam
C. For honors course, project completed following "Astronomy" unit:
   1. Kepler's Laws
   2. Universal Gravitation
   3. Einstein's General Relativity
   4. SDSS SkyServer Project (new component of the Astronomy unit)

A complete unit outline of the AP Physics/Astronomy unit, in its current form, can be found on the following two pages. The Honors Physics outline would be similar, but would also include general relativity. Note that no additional astronomy and/or astrophysics content would necessarily follow the SkyServer activities. SkyServer activities would act as a culminating event for the unit, and can easily be appended to the existing unit.

This instructor has found that some students are left "wanting more" following a study of Kepler's Law's, universal gravitation, and the physical systems governed by these laws. SkyServer activities satisfy this niche, offering students an opportunity to explore asteroids, star makeup, galaxies, as well as other astrophysics topics. Additionally, the process is structured such that students must apply the scientific method as they face sometimes difficult categorization, data organization, and data analysis tasks.

Newton's Universal Law of Gravitation
and Kepler's Laws of Planetary Motion
(Chapter 7b)

I. Teacher's Notes:
These two topics fall under the larger topic we've been working through recently, which is Simple Harmonic Motion (SHM). Just like an oscillating pendulum, a mass oscillating on the end of a spring, or an object moving in a circle, planets orbiting the sun or satellites orbiting the Earth have a measurable period of oscillation. This group of topics together make up a sizable 6 percent of the AP exam, so work to become comfortable with these ideas.

II. Student Objectives:
Students should:
A. Know Newton's Law of Universal Gravitation so they can:
   1. Determine the force that one spherically symmetrical mass exerts on another.
   2. Determine the strength of the gravitational field at a specified point outside a spherically symmetrical mass.

B. Understand the motion of a body in orbit under the influence of gravitational forces so they can, for a circular orbit:
   1. Recognize that the motion does NOT depend on the body's mass.
   2. Describe qualitatively how the velocity, period of revolution, and centripetal acceleration depend upon the radius of the orbit.
   3. Derive expressions for the velocity and period of revolution in such an orbit.

C. Understand the motion of a body in orbit under the influence of gravitational forces so they can, for a general (not necessarily circular) orbit:
   1. Apply conservation of angular momentum to determine the velocity and radial distance at any point in the orbit.
   2. Apply angular momentum conservation and energy conservation to relate the speeds of a body at the two extremes of an elliptical orbit.

III. Activities and Assignments:
A. READ CHAPTER 7, sections 7.7 - 7.8 (a very nice intro. to the topics)

B. Gravitational interactions activity
   1. Brainstorm, "What CAUSES gravity?"
   2. Worksheet, "Gravitational Interactions"
   3. Where does "g" = 9.8 m/s^2 come from??

C. Interactive Physics Simulation 32, "Solar System"

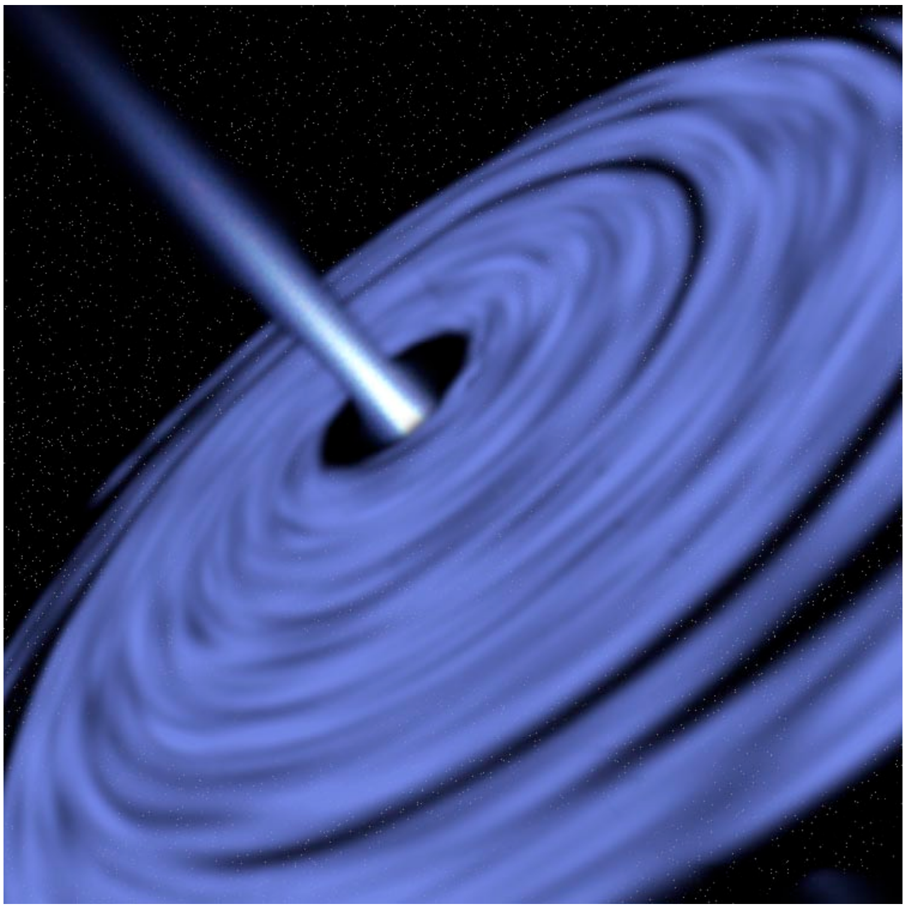
D. **Problem Set #1, Chapter 7, pages 202-211**
   1. CQ: 14, 19
   2. P: 8a, 41, 42, 47, 49

E. Kepler's Laws of Planetary Motion
   1. Lecture/Demo
      a. First Law—elliptical orbits
      b. Second Law—equal areas in equal times
      c. Third Law—mathematically relates orbital periods and radii
      d. Seasons and speeds w/planet dance

2. Geosynchronous orbit example (w/globe, also address home dishes)
3. Other examples using EASY units such as AUs and YEARS

F. **Problem Set #2, Chapter 7, pages 202-207**
1. CQ: 13 (Sketch & explain how sketch shows this.)
2. P: 43, 50, 71
3. wkst circled problems

G. Black hole space race



II. Intended Activities and Approximate Timeline

A. Introduce project to students (< 1 period).

1. Teacher introduces SkyServer website.
2. Teacher shows students (via projection) the types of projects available.
3. While quickly advancing through possible projects, teacher identifies physics already studied including: spectral lines, stars, galaxies, rotations, Doppler shift, etc.
4. Explain final product to students:
    a. Work in groups of two.
    b. Select project topic:
        1. Looking for project on the order of 4-5 hours of "estimated time" to complete.
        2. Show students how they can find estimated time by looking to the teacher information.
        B. Show students suggestions for shortening longer projects to the 4-5 hour time frame, also found within teacher information.
5. Students form groups of two.

B. Explain expectations for student product (< 1 period).

1. Students will document all work in a scientific lab book. Lab book entries will include:
    a. Notes from introductory materials.
    b. Work from all exercises completed in lab book including:
        1. Data tables
        2. Sketches
        3. Calculations
        4. All questions from project written in lab book
        5. Student responses to each question
        6. Printouts of all Excel spreadsheets and graphs glued into lab book
    c. List of items still confusing to student following completion of activity.
2. Grading rubric: See Section III.

C. Student groups work in computer lab to complete project (~3-4 periods).

D. Groups prepare to share ONE interesting item from their project (< 1 period).

E. Groups share their item with the class (~1 period).

III. Grading Rubric

Project appropriate for time frame (4-5 hours) _____ / 5

5 Yes

0 No

Work documented in lab book ______ / 5

5 Yes

2 Some

0 No lab book used

Notes from introductory materials _____ / 5

5 Organized, confusing things noted

2 Few things jotted down, little organization

0 None

Work from all exercises completed in lab book including:

Data tables _____ / 10

10 Organized, units shown when appropriate, if columns show calculated values, equation used shown

5 Somewhat confusing organization, some necessary units missing

0 Data tables missing

Sketches _____ / 5

5 Clear, add to understanding of project

2 Hastily done appearance

0 None

Calculations _____ / 5

5 Equations written, appropriate amount of algebra shown

3 Shown work leaves reader somewhat unclear

0 Calculations absent

All questions from project written in lab book _____ / 8

8 Yes

0 No

Student responses to each question _____ / 7

7 Though evident, done with care, reasonable conclusions

3 Some thought evident; some parts appear done just to get done.

0 Few, if any, responses present

Printouts of all Excel spreadsheets and graphs from project glued into lab book _____ / 5

5 All present, follow appropriate scientific style, few errors (axes & columns labeled, BEST FITS present)

3 All present; errors in scientific style detract from overall quality.

0 Required tables and/or plots missing

List of questions that students still have _____ / 5

5 Shows evidence of thought and effort

3 Typical questions; show some but not extensive thought

Presentation to class:

Scope _____ / 5

5 Appropriate for ~5-minute time frame

3 Too short or too long

0 Little, if any, preparation evident

Quality_____ / 5

5 Component of project presented became clear to audience. Projection/other AV items used offered clear/organized/relevant information.

3 Some problems/lack of smoothness in utilization of AV

0 Little, if anything, shown to class

OVERALL SCORE: / 70

What the Fermilab Website Has to Offer for Particle Physics Activities

If you go to the Education Office link from Fermilab's home page (*ed.fnal.gov*), you'll find the bold titles listed below on that page, giving you an easy way to find these activities. This commentary focuses on resources that will help teach particle physics. There are some other resources listed on this website that Fermilab offers yet are not addressed below.

Lederman Science Center

This gives you information about the center including details about exhibits, times, the Teacher Resource Center and ongoing programs for students. Also included in this website are learning activities under the categories of "physics games" and "prairies exhibits."

QuarkNet

QuarkNet is a program that joins high school teachers with scientist mentors from across the country at locations that offer research in high-energy physics. The goal is to make high-energy physics more accessible to high school students. This is the home page for QuarkNet. From this link you can find out more information about:

- Joining a QuarkNet program near you.
- Educators will find classroom activities you can use and a list of other online resources.
- Students will find links to activities they can use and webcasts to watch.

LInC Online

This link describes the Fermilab Leadership Institute Integrating Internet, Instruction, and Curriculum. "The new Fermilab LInC ACT course facilitates teachers through the process of evaluating, selecting and customizing an inquiry-based online project to teach content in their existing curriculum. Then participants exchange ideas and feedback with colleagues and experienced engaged learning mentors each step of the way as they field-test their project with students."

Teacher Workshops

This links you to a calendar of workshops for teachers of varying grades.

Teacher Resource Center

The Teacher Resource Center is located in the Lederman Center. "The Teacher Resource Center provides a preview collection of K-12 instructional materials. Educators have access to curriculum materials, books, multimedia, educational supply catalogs, periodicals and newsletters. The collection also includes reports on science and mathematics education, standards, assessment, equity and other topics. Visitors also have access to Internet resources. TRC services include professional development workshops, consultation assistance available upon request, a periodical holding list, bibliographies and telephone reference. A U.S. Department of Education Eisenhower National Clearinghouse Demonstration Site is located in the TRC. . . . Staff is available to assist science, mathematics and technology educators with curriculum and instruction issues."

Physics Data

Investigate Special Relativity

"This Website provides resources for secondary and post-secondary teachers of physical science. These resources include data reduction projects and particle physics data files. The data reduction projects guide student investigation of a dataset to a particular end result. The data files are written in a format that allows for rapid Web file transfer and ease of import into commonly available applications such as Microsoft Excel. Students download and reduce these data in an open-ended environment in which they investigate their own questions. The first of these resources is a data reduction project that guides students to an understanding of special relativity." (Description taken from Fermilab website)

Calculate the Top Quark Mass

"This classroom activity is available online or as part of the Topics in Modern Physics revised teachers guide. Students use data from a special top quark event and conservation of momentum to calculate the mass of the top quark. The activity builds on an understanding of vector addition, and the instruction needs to add only a short explanation of particle physics." (Description taken from Fermilab website)

Study Cosmic Rays with Student-Collected Data

The cosmic ray e-Lab allows users to search for data from more than 120 cosmic ray detectors located in high schools across the world. These small detectors observe the ground-level signature of particles that constantly bombard Earth's upper atmosphere. Analyzing the data can answer such questions as "Where do these things come from?" or "How often do they arrive?" or "How long do they last? Students can share the results of their analysis by publishing an e-Lab poster. The web document also allows other students to ask questions or leave comments on the poster.

Search for the Higgs Activity

These web pages invite visitors to join in the hunt for evidence of the Higgs particle. This boson will allow us to understand the process by which particles attain their mass. Accelerators are approaching the energy needed to create these. The detector teams must create plans for what signature a Higgs will leave behind. The web pages offer data in Excel spreadsheets suitable for downloading. Visitors can analyze these data and look for patterns that might indicate evidence for the Higgs.

Fermilabyrinth

This is a computer game that offers the student the opportunity to learn about accelerators, tracking particles and identifying particles. They play the game to earn Einstein bucks. You could have them turn in the bucks for credit for the day's work. The computer game is self-sufficient.

Online Instructional Material

This area has a number of different online resources for both students and teachers. Students can find a link to photographs and videos, and a variety of articles about high-energy physics. Included in these articles are a comic about accelerating science, a newspaper about particle physics for middle school students and a *FermiNews* series called "High-Energy Physics Made Painless." Teachers can find classroom units and individual activities. The list of these related to particle physics is:

- Fermilabyrinth
- Special Relativity
- Top Quark Mass
- Physics Activities
- Handbook for Engaged Learning Projects
- Index of All LInC Projects - Project Exemplars
- NTEP Projects

Educators

This section of the website holds a wealth of information for educators. You can find information about workshop schedules, school physics presentations, the Teacher Resource Center and the Lederman Science Center. This section also includes the following topics that have many subcategories with more information: (1) Field Trips, Study Units & Workshops, (2) Web-based Classroom Projects, (3) Fermilab Physics Resources, (4) Fermilab Prairie Resources, (5) Special Programs, (6) URL Lists, and (7) Interesting Publications.

Outlined below are some of the specifics under the category of "Fermilab Physics Resources." While the other categories hold much information that may be useful, some of it is outlined already in this paper, and others are not directly related to the study of particle physics.

Accelerator Kiosk

"The video for this project was developed for the Accelerator Kiosk exhibit at the Lederman Science Center." You may request a DVD or play it at this link in real video.

Anatomy of a Detector

"Joe Boudreau, a physicist in the CDF collaboration, uses a virtual reality tool to show the different parts of the detector and how they are used to display the debris from a collision."

Fermilab's Accelerators

This is a short video that goes through the path the particle takes through the detector. It also has links to other pages to learn more about each aspect of the run.

Searching for the Building Blocks of Matter

This is the exhibit on the 15th floor of Wilson Hall that is for the public. This website takes you through the pieces of the exhibit online.

Fermilab Stories

This is a link to a series of streaming videos describing a variety of aspects of Fermilab. Topics include "Work Ethic," "The Early Years," "Hardware and Solutions," and "Outreach."

Top Quark Discovery

This is a link that takes you to pages explaining what it took to discover the top quark. It has pages explaining CDF, DØ, affiliates of both, and background information on what it took to discover the top quark.

Inquiring Minds

There are links to more information on the science behind Fermilab. It includes the following with descriptions taken directly from the website:

- **The Science of Matter, Space and Time -** An introduction to elementary particles and forces in our universe.
- **Physics at Fermilab** - Particle physics at the energy frontier.
- **Questions about Physics** - Physics questions from real people and physics answers from Fermilab scientists.
- **Other High-Energy Physics Sites** - Links to physics labs around the world.
- **More About Particle Physics** - A glossary and other online resources for those who would like to know more.
- **Library** - Information is given about Fermilab's onsite library.
- **Visual Media Services -** A link to Fermilab's visual media services and its resources.
- **Particles Matter—Physics at High Energy** - An interactive timeline illustrating the history of high-energy physics.
- **Accelerator Science in Action** - A website of Fermilab's "Pulse" exhibit.

Research at Fermilab

This link offers an overview of the research going on at Fermilab and links to each home page of particular groups. It is a wealth of information of details about every aspect of research at the facility.

Pulse

This is an online exhibit explaining accelerator science in medicine.

Interactive Timeline

This interactive timeline describes high-energy particle physics over the past century.

1996 Revised Topics in Modern Physics Resource Book including Three-Day and Five-Day High School Physics Lesson Plans

This link takes you to a sample of the *TMP Resource Book* and the two units that can be downloaded for your use. It is important to note that this book can be ordered at no cost to you at Fermilab.

Catching the Sun

This is a unit that was developed to go along with the New Explorers *Catching the Sun* videotape concerning the Davis Experiment where he studied neutrinos. Included in this link is a sample of that curriculum.

Study Cosmic Rays

In conjunction with the QuarkNet program, this page allows you to investigate cosmic rays. Not only does it outline some information about cosmic rays themselves, there is actual data and instructions about the analysis of this data that you or your students can use.

Leo's Log Book

Here you can download a sample of a scientific logbook. You can then use this as an example in your own classroom.

Students

This would be the place to send your students to do more research on what is happening here at Fermilab. Included are student-friendly resources such as videos, articles, and online activities. It is divided into two sections, one for students K-12 and the other for post-secondary students.

Programs

This is a search engine to help you locate particular programs on this website. You simply check the appropriate descriptions for subject, audience and level and you will be directed to the findings.

Calendar

Here you will find the calendar of events for educational opportunities offered at Fermilab.

Visitors

This link will give visitors information about visiting Fermilab.

Applets & Other Web Resources

Electron:

Millikan's oil-drop experiment:
http://www68.pair.com/willisb/millikan/experiment.html

Thompson's e/m experiment:
http://www.sciencemuseum.org.uk/on-line/electron/section2/shockwave.asp

Nucleus/protons:

Rutherford scattering:
History (good initial reading):
http://www.physlink.com/Education/AskExperts/ae46.cfm

http://galileo.phys.virginia.edu/classes/252/Rutherford_Scattering/Rutherford_Scattering.html

Applet:
http://galileo.phys.virginia.edu/classes/109N/more_stuff/Applets/rutherford/rutherford.html

Applet, with reference to Cinema Classics clip
http://www.physics.brown.edu/physics/demopages/Demo/modern/demo/7d5010.htm

Miscellaneous:

Simple and elegant Kepler's law/elliptical orbit applet:
http://home.att.ne.jp/gold/kamikawa/physics/motion/motion_e.htm

Excellent clip showing powers of 10. Start way outside of the Milky Way and end up near a proton in Florida!
http://micro.magnet.fsu.edu/primer/java/scienceopticsu/powersof10/

Nice applet of a light clock; you alter the velocity (up to 0.8c). Simple, but shows length contraction rather well.
http://webphysics.davidson.edu/Applets/TaiwanUniv/relativity/relativity.html

Web, Magazine, Book Resources for Particle Physics Unit

Bubble Chambers

http://teachers.web.cern.ch/teachers/archiv/HST2000/teaching/resource/bubble/bubble.htm

Anatomy of a Detector (CDF detector overview)

http://quarknet.fnal.gov/run2/boudreau.shtml

Virtual Tour of Fermilab

http://www.fnal.gov/pub/about/tour/index.html

Click on accelerators and components: Photos of Fermi Accelerators

http://www-visualmedia.fnal.gov/VMS_Site_2/gallery/photography.shtml

CERN Centric

http://info.web.cern.ch/Press/PhotoDatabase/welcome.html

General Information for Particle Physics, Accelerators, and Detectors

http://www.interactions.org/imagebank/

http://www.particleadventure.org
good source of background information and quiz information

http://www-bd.fnal.gov/public/index.html
"How big is an electron volt?" is particularly good.
There are also some good descriptions of the basics of Fermilab's accelerators and accelerators in general.

http://www.slac.stanford.edu/quarknet/links.html

http://www-ed.fnal.gov/projects/exhibits/searching/

An Interactive Simple Demo to Accelerate a Charged Particle by Flipping a Battery

http://microcosm.web.cern.ch/Microcosm/RF_cavity/ex.html

Encyclopedia

http://www.absoluteastronomy.com/encyclopedia/P/Pa/Particle_detector.htm

A Game for Building a Detector

http://ed.fnal.gov/projects/labyrinth/games/ghostbustin/index.html?name=

more specific

http://ed.fnal.gov/projects/labyrinth/games/ghostbustin/calorimeter/activity.html?name=

Accelerator Games

http://ed.fnal.gov/projects/labyrinth/teachers/game_descript/game_descript.html

Building Accelerator Analogs

http://quarknet.fnal.gov/toolkits/ati/accelerators.html

Building "Ruler" Accelerator

- "The Gauss Rifle & Magnetic Energy" by James A. Rabchuck, *The Physics Teacher*, Volume 41, March 2003, pp. 158-160.

- C Physics Lecture Demo: Gauss Rifle
http://demo.physics.uiuc.edu/LectDemo/scripts/demo_descript.idc?DemoID=1098

- "Energy and Momentum in the Gauss Accelerator" by David Kagan, *The Physics Teacher*, Volume 42, January 2004, pp. 24-26.

- Get magnets from: http://www.wondermagnet.com
Forcefield
614 South Mason Street
Fort Collins, CO 80521
1-877-944-6247

- Get bearings from: http://www.bocabearings.com
Boca Bearing
755 NW 17th Ave. #107
Delray Beach, FL 33445
1-800-332-3256

- Articles:
  - http://scitation.aip.org/journals/doc/PHTEAH-ft/vol_41/iss_3/158_1.html
  - http://scitoys.com/scitoys/scitoys/magnets/gauss.html or go to http://scitoys.com and click on "The Gauss Rifle: A Magnetic Linear Accelerator"

Scientific American Articles

1. The Silicon Micro Strip Detector, May 1995
2. The Search for Dark Matter, March 2003
3. The Large Hadron Collider, July 2000
4. Solving the Solar Neutrino Problem, April 2003
5. Detecting Massive Neutrinos, August 1999
6. Cosmic Antimatter, April 1998
7. Discovery of the Top Quark, September 1997
8. Cosmic Rays and the Energy Frontier, January 1997
9. Ripples in Space-time, April 2002
10. Gamma Ray Bursts, July 1997
11. Echoes from the Big Bang, October 2002
12. Low-Energy Ways to Observe High-Energy Phenomena, September 1994
13. A Little Big Bang, March 1999
14. The Asymmetry between Matter and Antimatter, October 1998
15. The Mysteries of Mass, July 2005

Books:

Understanding the Universe: From Quarks to the Cosmos, by Don Lincoln

http://rkb.home.cern.ch/rkb/titleD.html (Higher End)
There is a good chapter on accelerators.

The Cloud Chamber: In the Nobel Prize and in the Classroom

The cloud chamber is a device that allows one to see tracks left by electrically charged particles (ions) as they pass through suitably prepared air. The instrument has been important in the history of particle physics. At least four Noble prizes have been awarded for work based on use of cloud chambers in particle physics.

The 1927 Nobel Prize was split between C. T. R. Wilson for his invention of the Wilson cloud chamber and A. H. Compton for his discovery of the Compton Effect. The website http://nobelprize.org/physics/ (laureate/1927) is a good place to start an investigation of the cloud chamber. In particular, the selection of Wilson's Nobel Lecture entitled "On the Cloud Method of Making Visible Ions and the Track of Ionizing Particles" is quite good. This is a 264kb file in *.pdf format. (The overall format of the Nobel Prize website is a biography of the laureate, her or his Nobel Lecture and also the Banquet Speech.)

The 1936 Nobel Prize was split between Victor Hess, for his discovery of naturally occurring radiation called cosmic rays, and Carl Anderson, for his discovery of the positron, the anti-electron. Hess did not use the cloud chamber for his discovery, but in his lecture he does refer to the use to which cloud chambers were put to further study cosmic rays. Anderson used the cloud chamber to observe the positron in cosmic rays. Again, the information from the site, http://nobelprize.org/physics/ (laureates/1936), should be consulted.

P. M. S. Blackett was awarded the 1948 Physics Prize "for his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation." His Nobel lecture is entitled "Cloud Chamber Researches in Nuclear Physics and Cosmic Rays." Use http://nobelprize.org/physics/ (laureates/1948) for further information.

The cloud chamber was augmented and superseded by numerous particle-detecting devices. In particular, the bubble chamber has produced many compelling visual presentations of interesting collisions in the history of particle physics. But the cloud chamber was first by a long shot, and a version the cloud chamber can be purchased and used in the classroom!

The website, http://w4.lns.cornell.edu/~adf4/cloud.html, provides instructions on how to build a cloud chamber and has good advice on how to use and view the tracks in the chamber. This is a rather short document, but one with lots of practical advice. Sections include:
What you will need to build the chamber.
What you will need to run the chamber.
What you will see.
What else you could do.
Troubleshooting.
How does this work?

Cloud chambers suitable for classroom use may also be purchased. One source is Sargent-Welch. Their catalog item WL6892-A is called a Cloud Chamber Kit, listed for $61.35. A five-set kit is $293.00. Dry ice and alcohol must be purchased separately. The dry ice needed for this may be purchased at some ice cream shops. Alcohol from Walgreens, or whomever, has worked well for us. An alternate "radiation" source that many teachers have found to work well is the lantern material for a Coleman-type lantern.

The well-prepared teacher should set up several demonstration chambers, as all may not produce tracks. The teacher should also have a backup of pictures (Digital are cheap.) of tracks of chambers from a time when the chamber was working very well. A backup video of a well-functioning chamber is also a good item to have available for review purposes.

Another good source for information on cloud chambers is a sister QuarkNet site, http://www.physics.smu.edu/~olness/quarknet/info.html.

Websites Explored at the Columbia-Nevis QuarkNet Workshop October 16, 2004

http://ed.fnal.gov/samplers/hsphys/activities/top_quark_intro.html – The Top Quark Activity from Fermilab

http://quarknet.fnal.gov/ – QuarkNet Main Page

http://www.colorado.edu/physics/phet/ – PhET Physics Tutorials from University of Colorado

http://ParticleAdventure.org – The Particle Adventure

http://www.onscreen-sci.com/ – OnScreen Particle Physics

http://www.walter-fendt.de/ph11e/ – Physics Java Applets

http://www.physicsclassroom.com/ – The Physics Classroom

http://www-pnp.physics.ox.ac.uk/~atlas/webcam.shtml – ATLAS Webcam

http://quarknet.fnal.gov/cosmics/ – QuarkNet Online Cosmic Ray Detector

http://www2.slac.stanford.edu/vvc/cosmicrays/crslac.html – SLAC Online Cosmic Ray Detector

http://quarknet.fnal.gov/grid – QuarkNet Grid Website for Cosmic Ray Airshowers

Radioactivity Unit
Lesson Plans

Day 1:

1. Pass out The Half-Life of Donkey Kong Dice Lab.
2. Have students read lab and do prelab, including data tables.
3. Review definition of half-life and lab procedure.
4. Students perform lab in groups of 2-3.
5. Each group records their data on board.
6. Combine group data to get class totals.
7. Students complete graphs, analysis, and conclusion.

Homework:
Complete lab report.

Day 2:

1. Question of the Day: What is half-life?
   *Question of the Day is a short question at the beginning of the class posed to the students lasting 2-3 minutes. Students may use their notes; however, they may not talk to one another. It is useful while the teacher is taking attendance.
2. Discuss the results of the lab, including how to determine half-life from the graph of the class data.
3. Do some sample half-life problems on the board.
4. Students do Half-life Practice worksheet.

Homework:
Complete Half-life Practice worksheet and read pages 609-619 (Hewitt's *Conceptual Physics*).

Day 3:

1. Question of the Day: What is a Geiger counter?
2. Real Radioactive Measurements and The Half-life of Cesium-137 Lab
3. Data is collected as a class using a Geiger counter. Have students time and record data on the board.

Homework:
Complete the lab report and read pages 620-626 (Hewitt's *Conceptual Physics*).

Day 4:

1. Question of the Day: A half-life graph problem
2. PowerPoint presentation on radioactivity and lecture on:
   a. Types of radioactivity
   b. Isotope notation
   c. Nuclear reaction equations
3. As a class, do Practice Book page 143 (write out the nuclear reactions for each step) and page 144.

Homework:
Practice Book page 141 and read pages 629-642 (Hewitt's *Conceptual Physics*).

Day 5:

1. Question of the Day: What is the difference between fission and fusion?
2. Discuss fission and fusion.
3. As a class, do Practice Book page 145.
4. Review radioactivity.
5. As a class, do Review Questions and Think and Explain Questions on pages 626-628 (Hewitt's *Conceptual Physics*).

Homework:
Study for tomorrow's quiz.

Day 6:

Quiz

End of the Year – Particle Physics Unit

This seven-day unit (*with optional extra lab for day eight) is designed to introduce students to particle physics. Students will learn about today's Standard Model and how scientists investigate these particles through detectors. The material in this unit is designed for either a conceptual physics class with little math or a higher-level physics class. There are some activities that are appropriate for all students, but other activities have been written specifically for one class or the other. These specific activities are clearly labeled.

Day One – History of Electron

Pre-electron
Discuss the electron before 1885.
*Review Thompson's e/m experiment.

Homework:

- Advanced Physics: The Electron worksheet
- Conceptual Physics: The History of the Electron worksheet

Teacher Resources:

1. Notes on the Electron PowerPoint Presentation (Word file)
2. The Electron worksheet (Student copy and answers)
3. The History of the Electron worksheet (Student copy)
4. Electron PowerPoint presentation and a Word file containing notes about the presentation

Day Two – Standard Model Intro Activity

Today's activity will focus on introducing the Standard Model to the students. Instead of simply presenting the Standard Model, we have created activities for your class to learn about it through an investigation. We have two options for you. One focuses on classification and organization. This mixer gives details about particles, and students are to classify and organize the information into a suitable form. The second activity concentrates on how quarks combine. For this activity you may want to briefly introduce some aspects of the Standard Model (i.e., there are particles found in nature known as quarks, etc.).

OPTION #1
Standard Model Mixer - focus on organizing & classification

OPTION #2
The Quark Zoo – focus on how quarks combine

Homework:

Textbook reading or web article on the Standard Model

Teacher Resources:

1. Standard Model Mixer
2. The Quark Zoo
3. List of Web resources to find an appropriate article

Day Three – Standard Model

Present the Standard Model.
Students should work on worksheet that reviews today's work and finish for homework

Optional Homework/Extra Credit:

- Ask the students to find out *where* the Standard Model is NOT working.

Teacher's Resources:

1. Particle Zoo PowerPoint presentation
2. Standard Model worksheet (student copy and answers)

Day Four – Accelerators

Discuss types of accelerators and how they work.
Use the small demonstration of the "ruler" accelerometer.

Homework:

- Advanced Physics: Particle accelerator problems worksheet
- Conceptual Physics: Web article to read

Teacher's Resources:

1. Accelerator PowerPoint presentation
2. Instructions to make the "ruler" accelerometer…see the list of web resources to find articles and other info that show you how to make and use it.
3. Accelerometer worksheet

Day Five – Detectors

Watch the Anatomy of a Detector (6 min 30 sec).
Cloud Chamber – consider a demo for the class
Discuss current particle detectors.
Scintillators vs. Calorimeters
Discuss how they operate.
Discuss what they measure.
Discuss results detectors have given us.

Homework:

- Review the Conservation of Momentum worksheet.

Teacher's Resources:

1. Anatomy of a Detector (CDF detector overview): http://quarknet.fnal.gov/run2/boudreau.shtml
2. Conservation of Momentum worksheet
3. Results of web search about cloud chambers

Day Six – Review of Momentum Lab (OPTIONAL)

Teacher's Resources:

1. Conservation of Momentum Lab

Day Seven – Activity

Z Boson Mass Reconstruction

Homework:

- Study for test.

Teacher's Resources:

1. Z Boson Mass Reconstruction Activity

Day Eight – Test

Particle Physics Test

Teacher's Resources:

1. Particle Physics Test