OBJECTIVE: Develop tools to help us understand how the neutrino was hypothesized and discovered.

1. Scales
   - atom: 10^{-8} cm (Dalton 1808)
   - nucleus: 10^{-12} cm (Bohr 1913 proposed nuclear atom)
   - nuclear particles: 10^{-13}cm (1932 neutron, ? proton)
   - electron: (Thomson 1897)
   - quark: originally called aces (proposed in 1963 by Gell-Mann and Zweig)
2. Fundamental Forces
   - Gravity: Newton discovered gravity in the 1680's → Newton's Law of Gravity
     - works on infinite scales
     - strength: 10^{-39}
     - $F = \frac{GMm}{r^2}$
   - Electromagnetic:
     - works on infinite scales
     - strength: 10^{-2}
     - $F = \frac{kq_1 q_2}{r_{12}^2}$
     - repulsion between two protons is 10^{36} times that of gravity
   - Strong: This is the force that holds the nucleus together. It works against the electromagnetic force in cases where the nucleus is composed of more than one proton. Recall opposite charges attract, similar charges repel.
     - acts at approximately 10^{-13} cm
     - strength: 1
   - Weak: This is the force that is responsible for beta decay and all other neutrino interactions.
     - acts at distances less than 10^{15}
     - strength: 10^{-13}

   NOTE: STRENGTHS ARE ARBITRARY AND VARY SOMEWHAT ON DISTANCES.
3. Types of Energy
   - Kinetic Energy: "energy of motion"
     - $T = \frac{1}{2}mv^2$
   - Potential Energy: "stored energy"
     - $U = mgh$
     - gravitational potential energy: $U = -\frac{GMm}{r}$
   - Electrostatic Energy:
     - $dU = -q_0 E \cdot dl$ or $\Delta U = -q_0 E \Delta l$
   - Other Energies: thermal, chemical, ...etc.
   - Mass Energy: given to us by Einstein
     - $E = m_0 c^2$

- Example: Given the masses of the following particles, find their mass energy.

  electron: 9.109×10^{-31} kg
  proton: 1.672×10^{-27} kg
  neutron: 1.674×10^{-27} kg

  Start with Einstein's equation.

  $$E = m_0 c^2$$

  Plug in the numbers we know.

  $$E = (9.109 \times 10^{-31} kg) \times (3 \times 10^8 \tfrac{m}{s})^2$$
  $$E = 8.19 \times 10^{-14} J$$

  Now convert joules to eV. Recall $1eV = 1.602 \times 10^{-19} J$
  Thus,

  $$E = 511KeV$$

  We can also represent the mass of the particle in units $\frac{\mathcal{K}\rceil\mathcal{V}}{\rceil^2}$.

  $$E_{m_e} = 511KeV = mc^2$$
  $$m_e = 511\frac{KeV}{c^2}$$

  Sometimes physicists work in funny units where they set $c = 1$ to make things simpler. This is often the way particle physicists work. So then it looks as if mass and energy have the same units!

  $$m_e = 511KeV$$

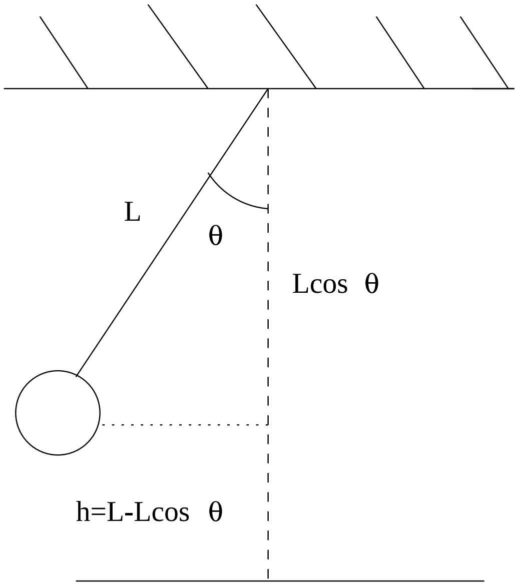
  I leave it as an exercise for the students to calculate the rest energy of the proton and neutron. They are

  $$E_{m_n} = 939.57MeV$$
  $$E_{m_p} = 938.27MeV$$

4. Conservation of Energy

   Recall the conservation of energy states that your initial energy must equal your final energy.

   - Simple Pendulum Example: What is the speed of the pendulum, length L, at the bottom of its swing. Assume the pendulum is initially pulled an angle θ away from center.



ANSWER: From the conservation of energy we know that:

$$E_i = E_f$$

$$mgh = \frac{1}{2}mv^2$$

where h is the height the pendulum is pulled.

$$h = L - L\cos\theta$$

Thus,

$$v = \sqrt{2gL(1-\cos\theta)}$$

where g is the gravitational constant.

5. Beta Decay: Why the neutrino exists and how it was discovered.

- Beta decay occurs in nuclei that have too many or too few neutrons for stability.
- Energy released during beta decay is given by the expression

$$\Delta E = MeE_{m_i} - E_{m_f}$$

- Let's try it for the neutron.

$$n \rightarrow p + e$$

recall the rest mass for the neutron, proton and electron.

$$n = 939.57MeV$$

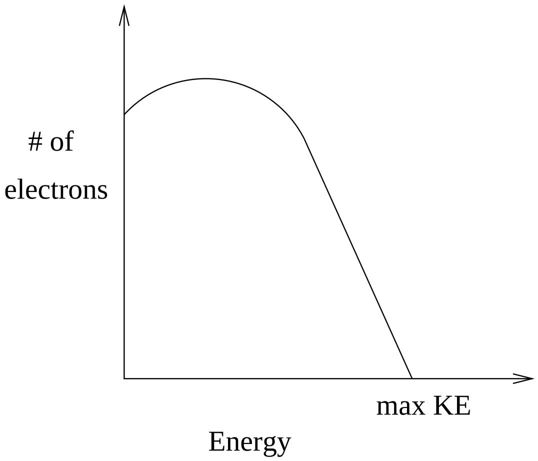
$$p = 938.27MeV$$

$$e = 0.51MeV$$

thus,

$$\Delta E = 0.79MeV$$

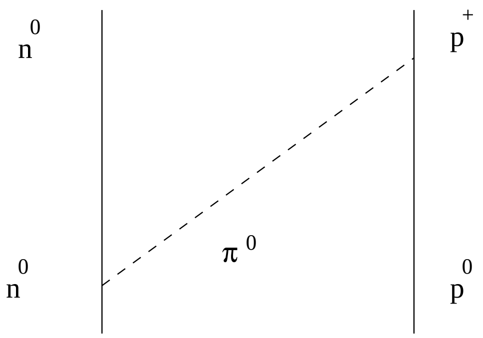
- However, it was experimentally shown that the kinetic energy of the electron varied from 0 to some maximum value! Was this a non-conservation of energy?



- In 1930 Pauli suggested a particle, now called the neutrino, to resolve the apparent non-conservation of energy.
- The neutrino was first observed experimentally in 1957 by Cowan and Reines. Today we know that there are 3 flavors of neutrinos, ν_e, ν_μ, ν_τ .

OBJECTIVE: To understand why cosmic rays are important to AMANDA. To learn the history and development of particle physics. To understand how we got to AMANDA.

1. Cosmic Rays
   - What are they and why are they important.
     - Cosmic ray are ionized nuclei that hit the earth's atmosphere at a rate of about 1000 per square meter per second. Their composition is 90% protons, 9%alpha particles and 1% heavier nuclei.
     - Neutrinos are produced in collisions of cosmic rays with material near a site of cosmic ray acceleration such as supernovas.
     - Cosmic rays provide background for our detector. (Muons are produced in collisions of "primary" and "secondary" cosmic rays such as protons and pions with other nuclei in the earths atmosphere.)
   - Brief History of Cosmic Rays: Mystery of the Discharging Leaves
     - Around 1900 it was discovered that electroscopes discharged even if kept in dark rooms away from known sources of radioactivity.
     - It was thought that this phenomenon was caused by naturally radioactive elements in the earth's crust.
     - The 1910 balloon flight of Austrian physicist Victor Hess showed that radioactivity increased with height. (Hess won the 1936 Nobel prize in physics for his discovery.)
     - This radiation was given the name "cosmic rays" by American physicist Robert Millikan who contributed greatly to its investigation.
   - Types of Early Detectors
     - Photographic Plates:
       - As fast charged particles pass through photographic emulsion they will produce tracks that show up after development.
       - Heavier particles left thicker lines. Lighter particles left thinner lines.
     - Cloud Chambers:
       - Invented in 1927 by C.T.R. Wilson.
       - As radioactive particles pass through the chamber they produced ions that serve as centers for vapor condensation (i.e. we see a line of fog as particles pass through the chamber).
     - Bubble Chamber:
       - Invented in 1952 by Glazer and Alvarez.
       - Similar in principle to cloud chamber.
       - A sudden reduction in the pressure of a liquid close to its boiling point produces "super-heating". This means that the boiling point drops as the pressure of the liquid decreases. Thus, the liquid is hotter than its boiling point. As particles travel through the chamber, bubbles of gas form around ions.
       - Glazer conceived of the idea when opening a bottle of beer and observing gas bubbles forming.
   - Particles, Particles and More Particles
     - In 1935, Yukawa proposed a particle that would be the carrier of the strong force. This particle eventually became known as the pion. It was thought to be the last particle to be discovered.



  - People began to look for the pion in cosmic rays.
  - Side Note: Proton collides with nuclei in the upper atmosphere and produce pions. Pions collide with atomic nuclei in the upper atmosphere and produce muons. These muons are background for the AMANDA detector.
  - In 1936, C.D. Anderson and S.H. Heddermeyer found a particle that behaved as Yukawa predicted. There was one exception. It did not show any desire to interact with nuclei. As it turns out Anderson discovered the muon!
  - In 1947, C.F. Powell finally discovered Yukawa's particle, the pion.
  - These events opened a Pandora's box that would leave physicists puzzled for nearly 2 decades.
  - As people continued to study cosmic rays they found more and more particles. Eventually, they decided they wanted to control the source of these rays. This started us down the road to modern accelerators.
  - The first accelerator was built in the early 30's, although it was not till the 40's that people really began to push the building of these machines.
  - As the years wore on, accelerators were built bigger and better to probe higher and higher energies.
  - Physicists kept finding more and more particles. By the 1960's it was a zoo. Some of the particles known at this time were:

pions $\pi^{\pm 0}$
kions $K^{\pm 0}$
etas η^0
proton $p^{\pm}$
neutron n
lambda Λ^0
sigma $\Sigma^{\pm 0}$
xi $\Xi^{\pm 0}$
omega Ω
electron $e^{\pm}$
muon μ
neutrinos ν_e, ν_μ

We'll come back to this later.

- Notice: there was more than one variety of neutrino known at that time. Their interactions take place via the weak force.

$$\nu_e + n \to p + e^-$$
$$\nu_\mu + n \to p + \mu^-$$

(Today we also know that a third variety, the tau neutrino, ν_τ, exits.)

- To further study these neutrino particles, we need to go to higher energy. For higher energy, we need bigger detectors. Bigger detectors cost more money.

SOLUTION: AMANDA/IceCube

EXAMPLE: To build a detector to investigate the energies AMANDA does would cost $10,000 per square foot. That would be $10 billion dollars for a kilometer detector. IceCube will only be about $200 million.

2. Standard Model

- From the Beginning: “Quarks”
  - Today we know of 6 kinds of quarks. They are named up, down, charm, strange, top and bottom or beauty. Also known as u, d, c, s, t, b. They are fundamental particles. This means we can not reduce them any further.
  - Examine the neutron and proton.
    - The neutron and proton are composed of up and down quarks. The up quark has a charge of $+\frac{2}{3}$ and the down has a charge of $-\frac{1}{3}$. Thus, to make a proton of charge $+1$ we use 2 up quarks and 1 down quark. Similarly to make a neutron of zero charge we use 1 up quark and 2 down quarks.

$$p \to uud$$

$$n \to udd$$

  - In the reaction where a neutrino interacts with a proton or neutron to give off a muon, the neutrino interacts not with the whole proton or neutron, but just one quark within these particles. This is done through the weak force.
- Categorizing Particles
  - To keep everything straight, physicists started to notice some particles had some things in common and lumped them together.
  - For AMANDA and IceCube the particles we deal with fit in two categories.
    Leptons: Not affected by the strong force. Interact via the weak force. This family contains: ν_e, ν_μ, ν_τ, e, μ, and τ.
    Baryons: Affected by the strong force. This family includes the proton and neutron.