Introduction to Cosmic Rays

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July 21, 2007

Introduction

Modern science often makes indirect measurements to determine the properties of things which are not directly observable through our human senses such as vision and touch. Cosmic rays are an example of a physical phenomenon which is not directly observable and the rays provide a tool for indirect exploration of even more phenomena which are beyond our senses. The Quarknet Muon Counter is provided to you so that you can experience for yourself how indirect measurements can lead to a description of aspects of nature which we cannot sense directly. At sea level most (about 95%) cosmic rays are muons, named after the Greek letter μ (pronounced mu), so we will start with a short history of the discovery of cosmic rays and then an introduction to the muon.

The Discovery of Cosmic Rays

The work which led to the discovery of cosmic radiation began about 1900 as an attempt to understand the electrical conductivity of gases. A gas of neutral atoms should not conduct electricity but, if a few atoms which are broken apart into an electron and a positive ion, these electrons and ions should conduct electricity. The radiation from radioactive substances was known to break up a few of the atoms of a gas and thus to increase the conductivity of a gas. It was first speculated that traces of radioactive substances in walls and floors were responsible for the conductivity when no known sources were present. Thus air at high altitudes or over lakes should conduct electricity less efficiently than inside a building. Measurements at the top of the Eiffel Tower (Wulf, a Jesuit priest in 1910), over the water, and at mountain altitudes showed reduced conductivity and thus that most, but not all, of the ionization was produced by such radioactivity. The "not all" was the stumbling block for this idea. If not from earth and rocks, where did the ionizing particles come from? If not from below then from above, but what is up there to produce it? The notion of extraterrestrial radiation was vigorously opposed by many physicists until data from balloon borne experiments in 1910 (Hess) and 1919 (Kolhörster, data up to 30,000 feet above sea-level) showed that the ionization first decreased as the instruments got away from the radioactive elements in the earth and then increased to much higher levels with increasing altitude. (The preceding is from pp. 1-3 of *Cosmic Rays*, L. Janossy, 1950, Oxford Clarendon Press, The International Series of Monographs on Physics. A briefer, more up-to-date discussion is in *American Scientist*, September 2000, article by Alex Dzerba, *et al.*, p 406.) The study of the cosmic radiation was pursued with new vigor in the period from 1940 to 1960, the period before particle accelerators had been developed, when these energetic particles from outer space were used to explore the newly discovered force which binds the neutrons and protons into nuclei.

The primary Cosmic Radiation is protons with a few percent of helium and heavier elements (and perhaps some neutrinos) with a spectrum of energies per particle up to at least 100 Joules: a single proton in the cosmic radiation can have an energy comparable to that of a very fast baseball moving at about 40 m/s. That energy expressed in the energy units convenient for this field is 10^{22} eV (electron Volts) or 10^{13} GeV (billion eV). Cosmic rays with such dramatically high energies are rare, about one per square mile in a century, but the flux is much higher at lower energies and protons from outer space with energies roughly a billion times lower, that is about 10 000 GeV, are enough more numerous to produce the effects which we observe with our small counters at the surface of the earth. While sources and detailed mechanisms for accelerating particles to these extreme energies are still not understood, it is becoming clear that pulsars, black holes, and rotating neutron stars are likely candidates. In fact the energy spectrum of primary cosmic rays is now one of the experimental tools for studying these objects. Unfortunately, the magnetic fields in outer space deflect the charged particles so their trajectories measured on Earth no longer point back to the source. Measurement of the uncharged (neutrino) component is only now becoming possible by experiments such as the AMANDA and ICE CUBE projects at the South Pole, and the hope is that measurements of the directions of very high energy neutrinos will help identify the sources of cosmic rays.

What happens when one of these high energy protons hits the top of the atmosphere? To explore this question we first need to be a little bit specific about first the atmosphere and then about how particles penetrate matter.

The density of air decreases with altitude and is about 1% as dense at 20 miles height as at sea level, so we will call that the top of the atmosphere. The weight of the air above a square centimeter is approximately a kilogram, or the same as 10 meters of water: we live at the bottom of an ocean of air which is equivalent to 10 meters (33 feet) of water. This ocean of air protects us from the much lower energy particles emitted by our sun, but will measure the effects of the much more penetrating cosmic rays.

The high energy protons in the cosmic radiation have the characteristic hadronic interaction mean free path (100 g/sq cm column density = 1 m of water) which is about a tenth of the atmosphere. That is, the typical high energy proton incident vertically at the top of the atmosphere (about 20 miles above sea level) penetrates about a tenth of the atmosphere and then collides with the nucleus of an air atom. Some of the energy is usually turned into matter in the collision and typically ten to fifty new particles are produced, each having some fraction of the original particle energy. Since we are interested in the big picture here, I will pick 20 as a typical number in this discussion and make the further simplification that the energy is divided equally among the particles. Most of the particles which are produced are pions. The charged pions interact with nuclei in the same way protons do, so each of the 20 produces 20 new particles after penetrating another tenth of the atmosphere. So after 2/10 of the atmosphere we have $20 \times 20 = 20^2$ particles, after 3/10, 20^3 particles, *etc.* An extremely crude picture of the fate of a high energy proton which hits the top of the atmosphere is that it generates a cascade of particles which increases in number and decreases in average energy per particle. The particles with energies below a few tens of GeV drop out of this model because they do not have enough energy to produce new particles and hence no longer participate in the cascade process. They lose energy only by atomic processes until they stop in a few meters of air or a few cm of solid or liquid material. The number of particles in the cascade increases exponentially with depth and the energy of the initial particle is distributed among the particles. When the average energy per particle is reduced to a few tens of GeV, the multiplication stops and the cascade ends within a few meters. In addition to the charged pions, neutral pions are also produced. The neutral pions have such a short lifetime that they usually decay into two gamma rays before they have time to interact, and the hadron cascade thus generates a number of electromagnetic cascades of photons and electron pairs which is similar in general structure to the charged particle cascade. Note that this crude model predicts that the number of steps, and thus the length, of a cascade is proportional to the logarithm of the incident energy. With our typical numbers, increasing the energy of the incident proton by a factor of 20 would increase the length of the shower by only another tenth of the atmosphere. The cosmic rays come from all directions and we have to figure the oblique path length for those which are not vertical. The overall result of this cascade process is that the background from cosmic rays reaches a maximum at an altitude of about 60,000 feet and only a few of the protons or pions reach sea level. Artist's renditions of what these cascades or showers might look like if we could see the paths of the particles are available on the web. The home page of the Quarknet project has a rendition which makes the point although the angles in cosmic ray cascades are much smaller so that the showers spread out much less than shown here:

http://www11.i2u2.org:8080/elab/cosmic/project.jsp

and the home page of the Pierre Auger Cosmic Ray Observatory

http://www.auger.org/

has a dramatic simulated shower picture with earth below and a galaxy in the sky. One of the collaborators in the Pierre Auger Cosmic Ray project has a more detailed view

http://www.physics.adelaide.edu.au/astrophysics/pierre/index.html

If most of the protons and pions don't make it down to where we live, what does? This problem is emphasized by the observation that the cosmic rays penetrate deep into the earth. Clearly the answer to this problem is a different kind of particle, one which does not make showers as protons and pions do. The pion itself supplies the answer. The charged pion has a half life time of 1.8×10^{-8} seconds and some small fraction of pions will decay before they have time to interact. One of the decay products, the muon, does not interact strongly as the pion and proton do, so it does not participate in the cascade process and simply looses energy by bumping into atomic electrons, a process analogous to friction rather than head on collisions. It is these muons which make up most (about 98%) of the charged flux at sea level.

The fact that the muon passes through a lot of air before it stops and subsequently decays is the original proof that the muon does not interact strongly - that it cannot be the "field particle" predicted by the early field theorists to explain the strong nuclear force. We now recognize it as the "electron" of the second generation in the standard model of the constituents of matter. It has a mass which is 106 MeV (roughly 210 times heavier than the electron) and decays into an electron and two neutrinos. The average of quality measurements of the lifetime is 2.19703 ± 0.00004 microseconds [Particle Data Group: Review of Particle Physics, *The European Physical Journal*, **15**, 2000]. [**Comment: I just saw a new paper with an improved measurement. I should quote it and**

note that these are averages lifetimes not half lives and half life is 0.69314718 x average lifetime.] The Quarknet counters are not well suited to measurement of the muon lifetime, but we encourage highly motivated students to work with us using a Vanderbilt Intermediate Lab Apparatus to measure the muon lifetime. You can put bricks between the counters of the Quarknet device to show that muons are not strongly absorbed by even several thicknesses of bricks.

At sea level, the muons have an angular distribution which is approximately proportional to the square of the cosine of the angle to the vertical. The energy spectrum is inversely proportional to the cube (2.7 power is somewhat more accurate) of the energy for energies above a few hundred MeV. (See the Cosmic Ray section in the PDG review, *loc. cit.*, pp 150-155, for more detail.) The energy loss of these muons is almost entirely to excitation and ionization of the material which the muon passes through and this is, analogous to friction) about 2 MeV per g/sq cm (column density) until the muon is within a few centimeters of the end of its range. Near the end, the rate of energy loss increases dramatically (as $1/\mathrm{v}^2$). Consequently a few muons stop in a slab of material but most simply pass through with only a very minor decrease in energy and higher energy muons continue to penetrate several kilometers into the earth.

The Muon – Its role in Modern Physics The discovery of the muon (μ) was the first real break in the "standard model" of the early 1900s which viewed electrons, protons and neutrons as the fundamental building blocks of matter. Today we have a more penetrating view of matter and our revised "standard model" goes a step further to also describe the quarks which are inside the protons and neutrons of the previous "standard model". The muon didn't fit into the previous electron, neutron, and proton picture and is now identified as the lepton or "electron" of the second quark generation of the revised standard model.

Even before the role of the muon in the new standard model was understood the muon was the principal actor in one of the most famous dramas of physics history, the verification of relativistic time dilation. First predicted by Einstein, time dilation is the prediction that a moving clock runs more slowly than one we keep with us. It is the basis of the twin paradox and is often invoked in science fiction to explain how space travelers can live long enough to travel the enormous distances between stars or even galaxies. Time dilation is very important for muons because they usually are going very fast and they decay. The half life of the muon is 1.5 microseconds (0.0000015 seconds). (If you could put a thousand muons in a box, there would be only 500 left in the box after 1.5 microseconds, 250 after 2x1.5 microseconds, 125 after 3x1.5 microseconds, *etc.*: the number would decrease by a factor of 2 every 1.5 microseconds.) The cosmic ray muons move with a speed very close to the speed of light (one of the measurements we can make) so we can calculate the time it takes a muon to descend from mountain elevation to a lower elevation. The original experiment was done [**Comment: reference 2 Rossi, Stearns papers here**] in Denver and nearby Mt. Evans. Denver is one mile above sea level and the top of Mt. Evans is almost three miles above sea level. The difference is 2 miles or about 10 000 feet and that is 10 microseconds at the speed of light. It takes 10/1.5 or about 7 muon lifetimes to go that two miles, so the flux of muons would have to be $2^7 = 128$ times greater at Mt.

Evans than in Denver if the moving clock of the muon ticked as rapidly as our clock. The measured flux difference is much smaller than a factor of 128, supporting the ideas about moving clocks.