18.4: Cosmic Rays and Accelerators

Early Cosmic Ray Results

Earlier we indicated that particles interacted with each other via the exchange of a virtual intermediary particle that interchanges energy, momentum, and other physical properties between the interacting particles. This idea originated with the Japanese physicist Hideki Yukawa in 1935 in an effort to understand the forces between nucleons. Yukawa hypothesized that the force that holds nucleons together is associated with the exchange of a boson, i. e., a particle with integer spin, with rest energy $mc^2 \approx 100$ MeV. The range of this force at low momentum transfers is $\mathrm{I} \approx \hbar/(\mathrm{mc}) \approx 2 \times 10^{-15}\ \mathrm{m}$, or comparable to the observed size of an atomic nucleus.

In 1947 two new particles were discovered in cosmic rays, the negatively charged muon with a rest energy of 106 MeV, and the pion, which comes in three varieties, the π^+, the π^-, and the π^0, which respectively have positive, negative, and zero charge. The rest energies of the π^+ and π^- are 140 MeV while that of the π^0 is 135 MeV. All of these particles are unstable in that they decay into other, more stable particles in a tiny fraction of a second. In particular, the negative pion decays into a muon and an antineutrino, while the neutral pion decays into two gamma rays, or high energy photons. The antineutrino that results from pion decay is actually distinct from the antineutrino emitted in nuclear beta decay; it is called the mu antineutrino since it is associated with the muon in the same way that the antineutrino in beta decay is associated with the electron. To further distinguish between the two, the latter is called the electron antineutrino. The muon itself decays into an electron, a mu neutrino, and an electron antineutrino.

The muon and its associated neutrino are rather peculiar. In all respects except mass, the muon appears to be identical to the electron. The physicist I. I. Rabi is reputed to have responded “Who ordered that?” upon learning of the properties of the muon. Furthermore, the electron neutrino only interacts with the electron and the muon neutrino only interacts with the muon. This is the first hint that elementary particles occur in families that appear to be replicated at higher energies.

Since the muon is a fermion with spin $1/2$, it can’t be Yukawa’s intermediary particle since all intermediary particles are bosons with integral spin. Furthermore, as with the electron, it is not subject to the nuclear force. The pions are more promising candidates for being intermediary particles of the nuclear force, since they are bosons with spin 0. However, as we shall see, the situation is more complex than Yukawa imagined, and the force between nucleons cannot be so simply treated. However, Yukawa’s idea of intermediary particle exchange lives on in today’s theories of sub-nuclear particles.

Particle Accelerators

Soon after the discovery of muons and pions in cosmic rays, a whole plethora of unstable particles was uncovered. Central to these discoveries was the particle accelerator. In these devices, charged particles, typically electrons or protons, are accelerated to high energy and then smashed into a target. Detectors of various sorts are used to examine the particles created by the collisions of the accelerated particles and the atomic nuclei with which they collide. Sometimes an elastic collision occurs, in which the accelerated particle simply “bounces off” of the target particle, transferring a good bit of its momentum to this sparticle. However, under many circumstances the collision results in the production of new particles that didn’t exist before the collision. This is referred to as an inelastic collision.

The simplest type of target is liquid hydrogen since the nucleus consists of a single proton. The orbital electrons of the target atoms are so light that they are generally just “brushed aside” without greatly affecting the trajectories of the accelerated particles. However, a variety of targets are used under different circumstances.

Size and Structure of the Nucleus

In the late 1950s and early 1960s Robert Hofstadter of Stanford University extended the Geiger-Marsden experiment to much shorter de Broglie wavelengths using high energy electrons from an accelerator, rather than alpha particles, as the probe. The type of results obtained by Hofstadter are shown in Figure $18.4.5$. After accounting for some effects having to do with the electron spin, these experiments should agree with the Rutherford formula if the nucleus is truly a point particle. This is shown by the solid line in Figure $18.4.5$. However, the actual results (dashed line) show probabilities that drop off more rapidly with increasing momentum transfer q than is predicted by the Rutherford model.

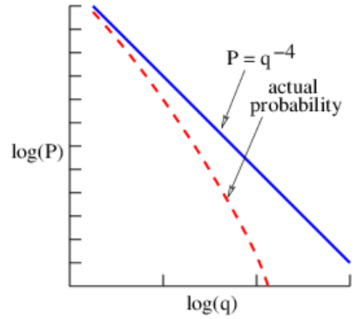

Figure 18.4.5:: Schematic illustration of Robert Hofstadter's results for scattering of electrons off of atomic nuclei. The solid line shows the relative probability (in log-log coordinates) of elastic scattering as a function of the momentum transfer by a point particle. The dashed curve illustrates the observed probability distribution.

These results are related to the fact that the nucleus is actually of finite size. The diffraction effects discussed in the section on the scattering of moonlight come into play here, in that little scattering takes place for scattering angles larger than roughly $\lambda/(2\,\mathrm{d})$, where λ is the de Broglie wavelength of the probing particle and d is the diameter of the target. For a small scattering angle (which we now call θ), it is clear from Figure 18.4.4 that

$$\theta \approx q/p \tag{18.4.1}$$

where p is the momentum of the incident electron and q is the momentum transfer. If q_{max} is the maximum momentum transfer for which there is significant scattering, then we can write

$$q_{\max}/p = \theta_{\max} \approx \lambda/d, \tag{18.4.2}$$

where the factor of 2 in the denominator on the right side has been dropped since this is an approximate analysis. However, since $\lambda = h/p$, we find that

$$q_{\max} \approx \frac{h}{d} \tag{18.4.3}$$

Thus, the momentum transfer for which the dashed line in Figure 18.4.5 becomes small compared to the solid line gives us an immediate estimate of the diameter of an atomic nucleus: $\mathrm{d} \approx \mathrm{h}/\mathrm{q}_{\max}$. The results obtained by Hofstadter show that nuclear diameters are typically a few times 10^{-15} m.

More than just size information can be extracted from this analysis. Hofstadter's experiments also led to a great deal of information about the internal structure of atomic nuclei.

Deep Inelastic Scattering of Electrons from Protons

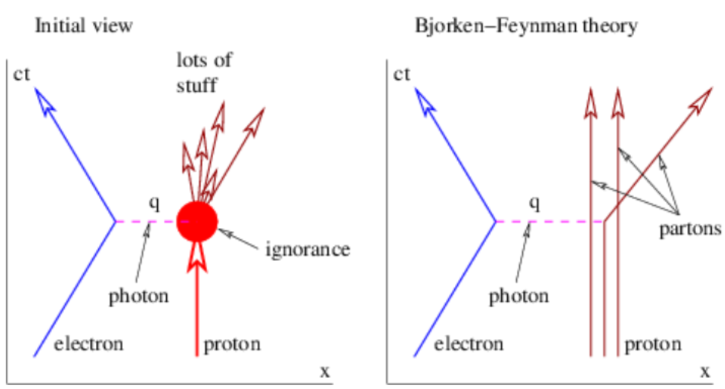

Figure 18.4.6:: Deep inelastic scattering of a high energy electron by a proton occurs when the momentum transfer q is large and many particles are produced. According to the Bjorken-Feynman theory of this process, the proton consists of a number of partons flying in "loose formation". A sufficiently energetic photon, i. e., with large momentum transfer q, kicks out just one of these partons, leaving the others undisturbed.

The construction of the Stanford Linear Accelerator Center (SLAC), which accelerates electrons up to 40 GeV, allowed experiments like Hofstadter's to be carried out at much higher energies. At these energies, many of the collisions between electrons and protons and neutrons are inelastic — generally a great mess of short-lived particles is spewed out, and are very difficult to interpret. However, the so-called deep inelastic collisions, where the electron scatters through a large angle and therefore transfers a large momentum, q, to the proton, yield very interesting results. In particular, these collisions occur essentially with a probability proportional to q^{-4} — just as in the Geiger-Marsden experiment!

The electron is a point particle as far as we know. However, previous experiments showed the proton to have a finite size, of order 10^{-15} m. Therefore, the scattering probability should drop off more rapidly with increasing momentum transfer q than with q^{-4}, as in the earlier Hofstadter experiments.

James Bjorken and Richard Feynman showed a way out of this dilemma. They proposed that the proton actually consists of a small number of point particles bound together by weakly attractive forces. A sufficiently energetic photon is able to knock a single one of these particles out of the proton, as illustrated in the right panel of Figure 18.4.6. This leads to a subsequent set of reactions that produce the profusion of particles seen in the left panel of this figure. Feynman called the particles that make up the proton partons. However, we now know that they are actually quarks, spin 1/2 particles with fractional electronic charge that are thought to be the fundamental building blocks of matter, and gluons, the massless spin 1 intermediary particles that carry the strong force.

Storage Rings and Colliders

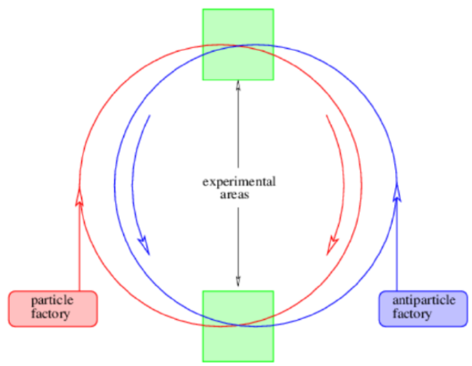

Figure 18.4.7:: Schematic model of a particle-antiparticle collider. The particles and antiparticles are injected into the storage rings shown and are made to go in a circle by magnetic fields. The beams cross at two points and equipment is set up around these points to observe the products of collisions.

An alternate way to create interesting collisions is to crash particles and antiparticles of the same energy into each other. This is done via a storage ring, as shown in Figure 18.4.7:. A set of magnets forces particles and antiparticles (which have opposite charges) to move in opposing circles within a high vacuum. The circles are slightly offset so that the beams cross at only two points. Collisions occur at these points and are observed by various types of experimental equipment.

An alternate type of collider has two storage rings that intersect at only one point. This type of system can be used to collide particles of the same type together, e. g., protons colliding with protons.

Proton-Antiproton Collisions

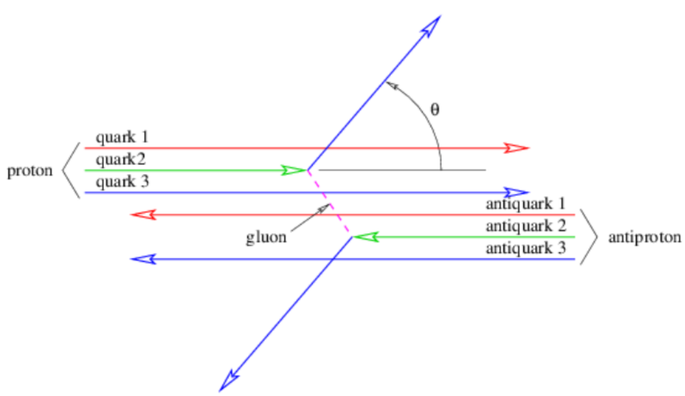

Figure 18.4.8:: Illustration of what happens in a high energy collision between a proton and an antiproton according to the Bjorken-Feynman parton model.

If collisions occur by the exchange of a single intermediary particle of zero mass between point particles, the q^{-4} dependence of the collision probability on momentum transfer will occur in proton-antiproton collisions as in the Geiger-Marsden experiment. However, if the colliding particles are not point particles, a form factor that decreases for increasing momentum transfer will occur as with the Hofstadter experiments.

When collisions between protons and antiprotons of a few hundred GeV are arranged, certain types of events called two-jet events are recorded. In these events, two jets, each containing many particles, are emitted in opposite directions at wide angles (i. e., with large momentum transfer) from the colliding beams. Furthermore, these jets show a probability distribution as a function of momentum transfer very close to q^{-4}. This indicates that the colliding particles are point-like, at least down to the minimum spatial resolutions available to today's accelerators.

According to the Bjorken-Feynman parton model of the proton, the collision between highly energetic protons and antiprotons should operate as shown in Figure 18.4.8. The actual collision is between individual partons. Figure 18.4.8 illustrates the collision between a quark in the proton and an antiquark in the antiproton. The result of this interaction is the scattering of these particles out of the incident particles, resulting ultimately in a two jet event as described above.

Electron-Positron Collisions

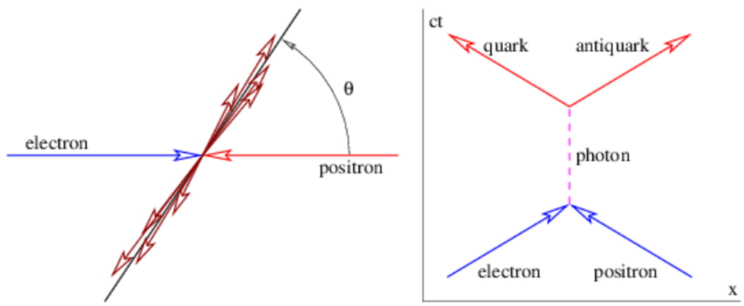

Figure 18.4.9:: Two-jet events resulting from the annihilation of high energy electrons and positrons. The virtual photon decays into a quark-antiquark pair that in turn generates the oppositely pointing jets of particles.

Two-jet events can also be created by the collision of high energy electrons and positrons. Figure 18.4.9 shows how this process is thought to work. The annihilation of the electron and positron results in a virtual photon, which in turn decays into a quark-antiquark pair. The quarks then produce the jets. These results suggest that quarks can indeed occur outside of protons, at least if they occur in quark-antiquark pairs.