2

The muon and the pion

The discoveries of the muon and charged pions in cosmic-ray experiments and the discovery of the neutral pion using accelerators, 1936–51

The detection of elementary particles is based on their interactions with matter. Swiftly moving charged particles produce ionization and it is this ionization that is the basis for most techniques of particle detection. During the 1930s cosmic rays were studied primarily with cloud chambers, in which droplets form along the trails of ions left by the cosmic rays. If the cloud chamber is in a region of magnetic field, the tracks show curvature. According to the Lorentz force law, the component of the momentum in the plane perpendicular to the magnetic field is given by $p(\mathrm{MeV}/c) = 0.300 \times 10^{-3}\, B(\mathrm{gauss}) r(\mathrm{cm})$, where r is the radius of curvature. By measuring the track of a particle in a cloud chamber it is possible to deduce the momentum of the particle.

The energy of a charged particle can be deduced by measuring the distance it travels before stopping in some medium. The charged particles other than electrons slow primarily because because they lose energy through the ionization of atoms in the medium. The range a particle of a given energy will have in a medium is a function of the mass density of the material and of the density of electrons.

The collisional energy loss per unit path length of a charged particle of velocity v depends essentially linearly on the density of electrons in the material, $\rho_e = \rho N_A Z/A$, where ρ is the mass density of the material, N_A is Avogadro's number, and Z and A represent the atomic number and mass of the material. The force between the incident particle of charge ze and each electron is proportional to $z\alpha$, where $\alpha \approx 1/137$ is the fine structure constant. The energy transferred to the electron in a collision is proportional to $(z\alpha)^2$. A good representation of the final result for the energy loss is

$$\frac{dE}{dx} = \frac{N_A Z}{A} \frac{4\pi z^2 \alpha^2 (\hbar c)^2}{m_e v^2} \left[\ln \frac{2 m_e v^2 \gamma^2}{I} - \frac{v^2}{c^2} \right]$$

where $x = \rho l$ measures the path length in g cm^{-2}. Here $\gamma^2 = (1 - v^2/c^2)^{-1}$ and $I \approx 16 Z^{0.9}$ eV is a measure of the ionization potential. A practical feeling for the result is obtained by using $N_A = 6.02 \times 10^{23}$ g^{-1} and $\hbar c = 197$ MeV fm $= 197$ MeV 10^{-13} cm to obtain the relation $4\pi N_A \alpha^2 \hbar^2 / m_e = 0.307$ MeV/(g/cm^2). The expression for dE/dx has a minimum when γ is about 3 or 4. Typical values of minimum ionization are 1 to 2 MeV/(g/cm^2).

Since the value of dE/dx depends on the velocity of the charged particle, it is possible to distinguish different particles with the same momentum but different masses by a careful measurement of dE/dx. In Figure 2.1 we show a contemporary application of this principle.

Energy loss by electrons is not dominated by the ionization process. In addition to losing energy by colliding with electrons in the material through which they pass, electrons lose energy by radiating photons whenever they are accelerated, a process called *bremsstrahlung* (braking radiation). Near the nuclei of heavy atoms there are intense electric fields. Electrons passing by nuclei undergo large accelerations. Although this in itself results in little energy loss directly (because the nuclei are heavy and recoil very little), the acceleration produces a good deal of bremsstrahlung and thus energy loss by the electrons. This mechanism is peculiar to electrons: Other incident charged particles do not lose much energy by bremsstrahlung because their greater mass reduces the acceleration they receive from the electric field around the nucleus. The modern theory of energy loss by electrons and positrons was developed by Bethe and Heitler in 1934.

The energy loss by an electron passing through a material is proportional to the density of nuclei, $\rho N_A/A$. The strength of the electrostatic force between the electron and a nucleus is proportional to $Z\alpha$ where Z is the atomic number of the material. The energy loss is proportional to $(Z\alpha)^2\alpha$, where the electromagnetic radiation by the electron accounts for the final factor of α. A good representation of the energy loss through bremsstrahlung is

$$\frac{dE}{dx} = \frac{N_A}{A} \frac{4Z(Z+1)\alpha^3(\hbar c)^2}{m_e^2 c^4} E \ln \frac{183}{Z^{1/3}} \equiv E/X_0$$

Of course this represents the energy loss, so the energy varies as $\exp(-x/X_0)$ where x is the path length (in g/cm^2) and X_0 is called the radiation length. A radiation length in lead is 6.37 g/cm^2 which, using the density of lead, is 0.56 cm. For iron the corresponding figures are 13.86 g/cm^2 and 1.76 cm.

If a photon produced by bremsstrahlung is sufficiently energetic, it may contribute to an electromagnetic shower. The photon can "convert", that is, turn into an electron-positron pair as discussed in the previous chapter. The newly created particles will themselves lose energy and create more photons, building up a shower. Eventually the energy of the photons created will be less than that necessary to create additional pairs and the shower will cease to grow. The positrons eventually slow down and annihilate with atomic electrons to produce photons. Thus all the energy in the initial electron is ultimately deposited in the material through ionization and excitation of atoms.

In 1937, Anderson, together with S. H. Neddermeyer, made energy loss measurements by placing a 1-cm platinum plate inside a cloud chamber. By measuring

Figure 2.1: Measurements of dE/dx (in keV/cm) for many particles produced in e^+e^- collisions at a center of mass energy of 29 GeV. Each dot represents a single particle. Bands are visible for several distinct particle types. The flat band consists of electrons. The vertical bands, from left to right, show muons, charged pions, charged kaons, and protons. There is also a faint band of deuterons. The curves show the predicted values of dE/dx. The data were obtained with the Time Projection Chamber (TPC) developed by D. Nygren and co-workers at the Lawrence Berkeley Laboratory. The ionization measurements are made in a mixture of argon and methane gases at 8.5 atmospheres pressure. The data were taken at the Stanford Linear Accelerator Center. [TPC/Two-Gamma Collaboration, *Phys. Rev. Lett.*, **61**, 1263, (1988)]

the curvature of the tracks on both sides of the plate, they were able to determine the loss in momentum. Since they observed particles in the 100–to–500 MeV/c momentum range, if the particles were electrons or positrons, they were highly relativistic and their energy was given simply by $E = pc$. According to the Bethe-Heitler theory, the particles should have lost in the plate an amount of energy proportional to their incident energy. Moreover, the particles with this energy should have been associated with an electromagnetic shower. What Neddermeyer and Anderson observed was quite different. The particles could be separated into two classes. The first class behaved just as the Bethe-Heitler theory predicted. The particles of the second class, however, lost nearly no energy in the platinum plate: They were "penetrating". Moreover, they were not associated with electromagnetic showers.

Since the Bethe-Heitler theory predicted large energy losses for electrons because they were light and could easily emit radiation, Neddermeyer and Anderson **(Ref. 2.1)** were led to consider the possibility that the component of cosmic rays that did not lose much energy consisted of particles heavier than the electron. On the other hand, the particles in question could not be protons because protons of the momentum observed would be rather slow and would ionize much more heavily in the cloud chamber than the observed particles, whose ionization was essentially the same as that of the electrons. Neddermeyer and Anderson gave as their explanation

> "there exist particles of unit charge with a mass larger than that of a normal free electron and much smaller than that of a proton .... [That they] occur with both positive and negative charges suggests that they might be created in pairs by photons."

While the penetrating component of cosmic rays had been observed by others before Neddermeyer and Anderson, the latter were able to exclude the possibility that this component was due to protons. Moreover, Neddermeyer and Anderson observed particles of energy low enough to make the application of the Bethe-Heitler theory convincing. At the time, many doubted that the infant theory of quantum electrodynamics, still plagued with perplexing infinities, could be trusted at very high energies. The penetrating component of cosmic rays could be ascribed to a failure of the Bethe-Heitler theory when the penetrating particles were extremely energetic. Neddermeyer and Anderson provided evidence for penetrating particles at energies for which the theory was believed to hold.

At nearly the same time, Street and Stevenson reported similar results and soon improved upon them **(Ref. 2.2)**. To determine the mass of the newly discovered particle, they sought to measure its momentum and ionization at the same time. Since the ionization is a function of the velocity, the two measurements would in principle suffice to determine the mass. However, the ionization is weakly dependent on the velocity except when the velocity is relatively low, that is, when the particle is near the end of its path and the ionization increases dramatically. To obtain a sample of interesting events, Street and Stevenson used counters in both coincidence and anticoincidence: The counters fired only if a charged particle passed through them and the apparatus was arranged so that the chamber was expanded to create supersaturation and a picture taken only if a particle entered the chamber (coincidence) but was not detected exiting (anticoincidence). This method of triggering the chamber was invented by Blackett and Occhialini. In addition, a block of lead was placed in front of the apparatus to screen out the showering particles. In late 1937, Street and Stevenson reported a track that ionized too much to be an electron with the measured momentum, but traveled too far to be a proton. They measured the mass crudely as 130 times the rest mass of the electron, an answer smaller by a factor 1.6 than later, improved results, but good enough to place it clearly between the electron and the proton.

In 1935, before the discovery of the penetrating particles, Hideki Yukawa predicted the existence of a particle of mass intermediate between the electron and the proton. This particle was to carry the nuclear force in the same way as the photon carries the electromagnetic force. In addition, it was to be responsible for beta decay. Since the range of nuclear forces is about 1 fm, the mass of the particle predicted by Yukawa was about $(\hbar/c)/10^{-13}\,\mathrm{cm} \approx 200\ \mathrm{MeV}/c^2$. When improved measurements were made, the mass of the new particle was determined to be about 100 MeV/c^2, close enough to the theoretical estimate to make natural the identification of the penetrating particle with the Yukawa particle.

How could this identification be confirmed? In 1940, Tomonaga and Araki showed that positive and negative Yukawa particles should produce very different effects when they came to rest in matter. The negative particles would be captured into atomic-like orbits, but with very small radii. As a result, they would overlap the nucleus substantially. Given that the Yukawa particle was designed to explain nuclear forces, it would certainly interact extremely rapidly with the nucleus, being absorbed long before it could decay directly. On the other hand, the positive Yukawa particles would come to rest between the atoms and would decay.

The lifetime of the penetrating particle was first measured by Franco Rassetti who found a value of about 1.5×10^{-6} s. Improved results, near 2.2×10^{-6} s were obtained by Rossi and Nereson, and by Chaminade, Freon, and Maze. Working under very difficult circumstances in Italy during World War II, Conversi, Pancini, and Piccioni **(Ref. 2.3)** investigated further the decays of positive and negative penetrating particles that came to rest in various materials. Using a magnetic-focusing arrangement that Rossi had developed, Conversi, Pancini, and Piccioni were able to select either positive or negative penetrating particles from the cosmic rays and then determine whether they decayed or not when stopped in matter. The positive particles did indeed decay, as predicted by Tomomaga and Araki. When the absorber was iron, the negative particles did not decay, but were absorbed by the nucleus, again in accordance with the theoretical prediction. However, when the absorber was carbon, the negative particles decayed. This meant that the Tomonaga-Araki prediction as applied to the penetrating particles was wrong by many orders of magnitude: These could not be the Yukawa particles.

Shortly thereafter, D. H. Perkins **(Ref. 2.4)** used photographic emulsions to record an event of precisely the type forecast by Tomonaga and Araki. Photographic emulsions provide a direct record of cosmic ray events with extremely fine resolution. Perkins was able to profit from advances in the technology of emulsion produced by Ilford Ltd. The event in question had a slow negative particle that came to rest in an atom, most likely a light atom like carbon, nitrogen, or oxygen. After the particle was absorbed by the nucleus, the nucleus was blasted apart and three fragments were observed in the emulsion. This single event apparently showed the behaviour predicted by Tomonaga and Araki, contrary to the results of the Italian group.

The connection between the results of Conversi, Pancini, Piccioni and the observation of Perkins was made by the Bristol group of Lattes, Occhialini, and Powell **(Ref. 2.5)** in one of several papers by the group, again using emulsions. Their work established that there were indeed two different particles, one of which decayed into the other. The observed decay product appeared to have fixed range in the emulsion. That is, it appeared always to be produced with the same energy. This indicated that the decay was into two bodies and not more. Because of inaccurate mass determinations, at first it was believed that the unseen particle in the decay could not be massless. Quickly, the picture was corrected and completed: The pion, π, decayed into a muon, μ (the names given by Lattes *et al.*), and a very light particle, presumably Pauli's neutrino. The π (which Perkins had likely seen) was much like Yukawa's particle except that it was not the origin of beta decay, since beta decays produce electrons rather than muons. The μ (which Anderson and Neddermeyer had found) was just like an electron, only heavier. The pion has two charge states, π^+ and π^- that are charge conjugates of each other and which yield μ^+ and μ^-, respectively, in their decays.

In modern parlance, bosons (particles with integral spin) like the pion that feel nuclear forces are called *mesons*. More generally, all particles that feel nuclear forces, including fermions like the proton and neutron are called *hadrons*. Fermions (particles with half-integral spin) like the muon and electron that are not affected by these strong forces are called *leptons*. While a negative pion would always be absorbed by a nucleus upon coming to rest, the absorption of the negative muon was much like the well-known radioactive phenomenon of K-capture in which an inner electron is captured by a nucleus while a proton is transformed into a neutron and a neutrino is emitted. In heavy atoms, the negative muon could be absorbed (because it largely overlapped with the nucleus) with small nuclear excitation and the emission of a neutrino, while in the light atoms it would usually decay, because there was insufficient overlap between the muon and the nucleus.

Cosmic rays were the primary source of high energy particles until a few years after World War II. Although proton accelerators had existed since the early 1930s, their low energies had restricted their applications to nuclear physics. The early machines included Robert J. Van de Graaff's electrostatic generators, developed at Princeton, the voltage multiplier proton accelerator built by J. D. Cockroft and E. T. S. Walton at the Cavendish Laboratory, and the cyclotron built by Ernest O. Lawrence and Stanley Livingston in Berkeley.

The cyclotron incorporated Lawrence's revolutionary idea, resonant acceleration of particles moving in a circular path, giving them additional energy on each circuit of the machine. The particles moved in a plane perpendicular to a uniform magnetic field. Cyclotrons typically contain two semi-circular "dees" and the particles are given a kick by an electric field each time they pass from one dee to the other, though the original cyclotron of Lawrence and Livingston contained just one dee. The frequency of the machine was determined by the Lorentz force law, $F = evB$, and the formula for the centripetal acceleration, $v^2/r = F/m = evB/m$ so that angular frequency is given by

$$\omega = \frac{eB}{m}$$

The cyclotron frequency is independent of the radius of the trajectory: As the energy of the particle increases, so does the radius in just such a way that the rotational frequency is constant. It was thus possible to produce a steady stream of high energy particles spiraling outward from a source at the center.

Cyclotrons of ever-increasing size were constructed by Lawrence and his team in an effort to achieve higher and higher energies. Ultimately the technique was limited by relativistic effects. The full equation for the frequency is actually

$$\omega = \frac{eB}{\gamma m}$$

where γ is the factor describing the relativistic mass increase, $\gamma = E/mc^2$. When protons were accelerated to relativistic velocities, the required frequency decreased.

The synchrocyclotron solved this problem by using bursts of particles, each of which was accelerated with an RF system whose frequency decreased in just the right way to compensate for the relativistic effect. The success of the synchrocyclotron was due to the development of the theory of "phase stability" developed by E. McMillan and independently by V. I. Veksler. In 1948, the 350-MeV, 184-inch proton synchrocyclotron at Berkeley became operational and soon thereafter Lattes and Gardner observed charged pions in photographic emulsions.

It was already known that cosmic-ray showers had a "soft" component, consisting primarily of electromagnetic radiation. Indeed, Lewis, Oppenheimer, and Wouthuysen had suggested that this component could be due to neutral mesons that decayed into pairs of photons. Such neutral mesons, partners of the charged pions, had been proposed by Nicholas Kemmer in 1938 in a seminal paper on isospin invariance, the symmetry relating the proton to the neutron.

Figure 2.2: Gamma-ray yields from proton–carbon collisions at 180 to 340 MeV proton kinetic energy. The marked increase with increasing proton energy is the result of passing the π^0 production threshold. The π^0 decays into two photons. (Ref. 2.6)

Strong circumstantial evidence for the existence of a neutral meson with a mass similar to that of the charged pion was obtained by Bjorklund, Crandall, Moyer, and York using the 184-inch synchrocyclotron (Ref. 2.6). See Figure 2.2. Bjorklund *et al.* used a pair spectrometer to measure the photons produced by the collisions of protons on targets of carbon and beryllium. The pair spectrometer consisted of a thin tantalum radiator in which photons produced electron–positron pairs whose momenta were measured in a magnetic field. When the incident proton beam had an energy less than 175 MeV, the observed yield of photons was consistent with the expectations from bremsstrahlung from the proton. However, when the incident energy was raised to 230 MeV, many more photons were observed and with an energy spectrum unlike that for bremsstrahlung. The most likely explanation of the data was the production of a neutral meson decaying into two photons.

Evidence for these photons was also obtained in a cosmic-ray experiment by Carlson, Hooper, and King working at Bristol (Ref. 2.7). The photons were observed by their conversions into e^+e^- pairs in photographic emulsion. See Figure 2.3. This experiment placed an upper limit on the lifetime of the neutral pion of 5×10^{-14} s. The technique used was a new one. The direction of the converted photon was projected back towards the primary vertex of the event. The impact parameter, the distance of closest approach of that line to the primary vertex, was measured. Because the neutral pion decayed into two photons, the direction of a single one, in principle, did not point exactly to the primary vertex. In fact, the lifetime could not be measured in this experiment since it turned out to be about 10^{-16}s, far less than the limit obtainable at the time.

Direct confirmation of the two-photon decay was provided by Steinberger, Panofsky, and Steller **(Ref. 2.8)** using the electron synchrotron at Berkeley. The synchrotron relied on the principle of phase stability underlying the synchrocyclotron, but differed in that the beam was confined to a small beam tube, rather than spiraling outward between the poles of large magnets. In the electron synchroton, the strength of the magnetic field varied as the particles were accelerated.

The electron beam was used to generate a beam of gamma rays with energies up to 330 MeV. Two photon detectors were placed near a beryllium target. Events were accepted only if photons were seen in both detectors. The rate for these coincidences was studied as a function of the angle between the photons and the angle between the plane of the final state photons and the incident beam direction. The data were consistent with the decay of a neutral meson into two photons with a production cross section for the neutral meson similar to that known for the charged mesons. The two-photon decay proved that the neutral meson could not have spin one since Yang's theorem forbids the decay of a spin-1 particle into two photons.

The proof of Yang's theorem follows from the fundamental principle of linear superposition in quantum mechanics, which requires that the transition amplitude, a scalar

Figure 2.3: An emulsion event showing an e^+e^- pair created by conversion of a photon from π^0 decay. The conversion occurs at the point marked P. (Ref. 2.7)

quantity, depend linearly on the spin orientation of each particle in the process. The decay amplitude for a spin-1 particle into two photons would have to be linear in the polarization vector of the initial particle and each of the two final-state photons. The polarization vector for a photon points in the direction of the electric field, which is perpendicular to the momentum. For a massive spin-1 state it is similar, except that it can point in any spatial direction, not just perpendicular to the direction of the momentum. In addition, the amplitude would have to be even under interchange of the two photons since they are identical bosons. Since real photons are transversely polarized, if the momentum and polarization vectors of a photon are $\mathbf{k}$ and $\boldsymbol{\epsilon}$, then $\mathbf{k} \cdot \boldsymbol{\epsilon} = 0$. Let the polarization vector of the initial particle in its rest frame be $\boldsymbol{\eta}$ and those of the photons be $\boldsymbol{\epsilon}_1$ and $\boldsymbol{\epsilon}_2$. Let the momentum of photon 1 be $\mathbf{k}$ so that of photon 2 is $-\mathbf{k}$. We must construct a scalar from these vectors.

If we begin with $\boldsymbol{\epsilon}_1 \cdot \boldsymbol{\epsilon}_2$ the only non-zero factor including $\boldsymbol{\eta}$ is $\boldsymbol{\eta} \cdot k$, but $\boldsymbol{\epsilon}_1 \cdot \boldsymbol{\epsilon}_2 \; \boldsymbol{\eta} \cdot \mathbf{k}$ is odd under the interchange of 1 and 2 since this takes $\mathbf{k}$ into $-\mathbf{k}$. If we start with $\boldsymbol{\epsilon}_1 \times \boldsymbol{\epsilon}_2$ we have as possible scalars $\boldsymbol{\epsilon}_1 \times \boldsymbol{\epsilon}_2 \cdot \boldsymbol{\eta}$, $(\boldsymbol{\epsilon}_1 \times \boldsymbol{\epsilon}_2) \cdot (\boldsymbol{\eta} \times \mathbf{k})$, and $\boldsymbol{\epsilon}_1 \times \boldsymbol{\epsilon}_2 \cdot \mathbf{k} \; \boldsymbol{\eta} \cdot \mathbf{k}$. The first and third are odd under the interchange of 1 and 2 and the second vanishes identically since $(\boldsymbol{\epsilon}_1 \times \boldsymbol{\epsilon}_2) \cdot (\boldsymbol{\eta} \times \mathbf{k}) = \boldsymbol{\epsilon}_1 \cdot \boldsymbol{\eta} \; \boldsymbol{\epsilon}_2 \cdot \mathbf{k} - \boldsymbol{\epsilon}_2 \cdot \boldsymbol{\eta} \; \boldsymbol{\epsilon}_1 \cdot \mathbf{k}$.

A year later, in 1951, Panofsky, Aamodt, and Hadley (Ref. 2.9) published a study of negative pions stopping in hydrogen and deuterium targets. Their results greatly expanded knowledge of the pions. The experiment employed a more sophisticated pair spectrometer, as shown in Figure 2.4. The reactions studied with the hydrogen target were

$$\pi^- p \to \pi^0 n$$

$$\pi^- p \to \gamma n$$

The latter process gave a monochromatic photon whose energy yielded $275.2 \pm 2.5 \; m_e$ as the mass of the π^-, an extremely good measurement. See Figure 2.5. The photons produced by the decay of the π^0 were Doppler-shifted by the motion of the decaying π^0. From the spread of the observed photon energies, it was possible to deduce the mass difference between the neutral and charged pion. Again, an excellent result, $m_{\pi^-} - m_{\pi^0} = 10.6 \pm 2.0 \; m_e$, was obtained. The capture of the π^- is assumed to occur from an s-wave state since the cross section for the lth partial waves is suppressed by k^l, where k is the momentum of the incident pion. Thus if the final π^0 is produced in the s-wave, then the parity of the neutral and charged pions must be the same. The momentum of the produced π^0, however, is not terribly small so this argument is not unassailable.

Parity is the name given to the reflection operation $\mathbf{r} \to -\mathbf{r}$. Its importance was first emphasized by Wigner in connection with Laporte's rule, which says that atomic states are divided into two classes and electric dipole transitions always take a state from one class into a state in the other. In the hydrogen atom, a state with orbital angular momentum l has the property

$$P\psi(\mathbf{r}) = \psi(-\mathbf{r}) = (-1)^l \psi(\mathbf{r})$$

Figure 2.4: The pair spectrometer used by Panofsky, Aamodt, and Hadley in the study of $\pi^- p$ and $\pi^- d$ reactions. A magnetic field of 14 kG perpendicular to the plane shown bent the positrons and electrons into the Geiger counters on opposite sides of the spectrometer. (Ref. 2.9)

The state is unchanged except for the multiplicative factor of modulus unity. We therefore say that the parity is $(-1)^l$. This result is not general. Consider a two-electron atom with electrons in states with angular momentum l and l'. The parity is $(-1)^{l+l'}$, but the total angular momentum, L, is constrained only by $|l - l'| \leq L \leq l + l'$. Thus, in general the parity need not be $(-1)^L$. Electric dipole transitions take an atom in a state of even parity ($P = +1$) to a state with odd parity ($P = -1$), and vice versa.

Elementary particles are said to have an “intrinsic” parity, $\eta = \pm 1$. The parity operation changes the wave function by a factor η, in addition to changes resulting from the explicit position dependence. By convention, the proton and neutron each have parity $+1$. Having established this convention, the parity of the pion becomes an experimental question. The deuteron is a state of total angular momentum one. The total angular momentum comes from the combined spin angular momentum, which takes the value 1, and the orbital angular momentum, which is mostly 0 (s-wave), but partly 2 (d-wave). The deuteron thus has parity $+1$. The standard notation gives the total angular momentum, J, and parity, P, in the form $J^P = 1^+$. The spin, orbital, and total angular momentum are displayed in spectroscopic notation as ${}^{2S+1}L_J$, that is ${}^3S_1$ and ${}^3D_1$ for the components of the deuteron.

Figure 2.5: The photon energy spectrum for $\pi^- p$ reactions at rest. The band near 70 MeV is due to photons from π^0 decay. The line near 130 MeV is due to $\pi^- p \rightarrow n\gamma$. (Ref. 2.9)

With the deuterium target, the reactions that could be observed in the same experiment were

$$\pi^- d \rightarrow nn$$

$$\pi^- d \rightarrow nn\gamma$$

$$\pi^- d \rightarrow nn\pi^0$$

In fact, the third was not seen, and the presence of the first had to be inferred by comparison to the data for $\pi^- p$. (See Figure 2.6). This inference was important because it established that the π^- could not be a scalar particle. If the π is a scalar and is absorbed from the s-wave orbital (as is reasonable to assume), the initial state also has $J^P = 1^+$. However, because of the exclusion principle, the only $J = 1$ state of two neutrons is $^3P_1$, which has odd parity. Thus if $\pi^- d \rightarrow nn$

Figure 2.6: The photon energy spectrum from $\pi^- d$ reactions at rest. The line near 130 MeV is due to $\pi^- d \to nn\gamma$. (Ref. 2.9)

occurs, the π^- cannot be a scalar. The absence of the third reaction was to be expected if the π^- and π^0 had the same parity. The two lowest nn states are ${}^1S$ and ${}^3P$. The former cannot be produced if the charged and neutral pions have the same parity. If the nn state is ${}^3P$, then parity conservation requires that the π^0 be in a p-wave. The presence of two p-waves in a process with such little phase space would greatly inhibit its production.

Subsequent experiments determined additional properties of the pions. The spin of the charged pion was obtained by comparing the reactions $pp \to \pi^+ d$ and $\pi^+ d \to pp$. The cross section for a scattering process with two final state particles is related to the Lorentz invariant matrix element, $\mathcal{M}$, by

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\frac{p'}{p}\,|\mathcal{M}|^2$$

In this relation s is the square of the total energy in the center of mass, p and p' are the center of mass momenta in the initial state and final states, and $d\Omega$ is the solid angle element in the center of mass. The matrix element squared is to be averaged over the spin configurations of the initial state and summed over those of the final state.

The reactions $pp \to \pi^+ d$ and $\pi^+ d \to pp$ have the same scattering matrix elements (provided time reversal invariance is assumed), so their rates (at the same center-of-mass energy) differ only by phase space factors (p/p') and by the statistical factors resulting from the spins:

$$\frac{d\sigma(\pi^+ d \to pp)/d\Omega}{d\sigma(pp \to \pi^+ d)/d\Omega} = \frac{(2s_p + 1)^2}{(2s_d + 1)(2s_\pi + 1)}\frac{p_{pp}^2}{p_{\pi d}^2}$$

where s_π is the spin of the π^+ and $p_{\pi d}$ and p_{pp} are the center-of-mass momenta for the πd and pp at the same center of mass energy. The proton and deuteron spins, s_p and s_d, were known. The pp reaction was measured by Cartwright, Richman, Whitehead, and Wilcox. The reverse reaction was measured independently by Clark, Roberts, and Wilson (Ref. 2.10) and then by Durbin, Loar, and Steinberger (**Ref. 2.11**).

The comparison showed the π^+ to have spin 0. Since the Panofsky, Aamodt, and Hadley paper had excluded $J^P = 0^+$ for the π^- and thus for its charge conjugate, the π^+ necessarily had $J^P = 0^-$. Since the π^0 decays into two photons it has integral spin and is thus a boson. Since it cannot have spin 1, it is reasonable to expect it has spin 0. Then, since its parity has been shown to be the same as that of the π^-, it follows that it, too, is 0^-. It is however, possible to measure the parity directly. A small fraction of the time, about 1/80, the neutral pion will decay into γe^+e^-, the latter two particles being called a Dalitz pair. About $(1/160)^2$ of the time it decays into two Dalitz pairs. By studying the correlations between the planes of the Dalitz pairs, it is possible to show directly that the π^0 has $J^P = 0^-$, as was demonstrated in 1959 by Plano, Prodell, Samios, Schwartz, and Steinberger (Ref. 2.12).

The π^0 completed the triplet of pions: π^-, π^0, π^+. The approximate equality of the charged and neutral pion masses was reminiscent of the near equality of the masses of the neutron and proton. Nuclear physicists had observed an approximate symmetry, isotopic spin or isospin. This symmetry explains the similarity between the spacing of the energy levels in ^{13}C $(6p, 7n)$ and ^{13}N $(6n, 7p)$. Just as the nucleons represent an isospin doublet, the pions represent an isospin triplet.

Isospin is so named because its mathematical description is entirely analogous to ordinary spin or angular momentum in quantum mechanics. The isospin generators satisfy

$$[I_x, I_y] = iI_z \qquad \text{etc.}$$

and states can be classified by $\mathbf{I}^2 = I(I+1)$ and I_z. Thus $I_z(p) = 1/2$, $I_z(n) = -1/2$, $I_z(\pi^+) = 1$, $I_z(\pi^0) = 0$, etc. The rules for addition of angular momentum apply, so a state of a pion ($I = 1$) and a nucleon ($I = 1/2$) can be either $I = 3/2$ or $I = 1/2$. The state π^+p has $I_z = 3/2$ and is thus purely $I = 3/2$, whereas π^+n has $I_z = 1/2$ and is partly $I = 1/2$ and partly $I = 3/2$.

The isospin and parity symmetries contrast in several respects. Parity is related to space-time, while isospin is not. For this reason, isospin is termed an "internal" symmetry. Parity is a discrete symmetry, while isospin is a continuous symmetry since it is possible to consider rotations in isospin space by any angle. Isospin is an approximate symmetry since, for example, the neutron and proton do not have exactly the same mass. Parity was believed, until 1956, to be an exact symmetry.

EXERCISES

2.1 Determine the expected slope of the line in Fig. 1 of Neddermeyer and Anderson, Ref. 2.1 assuming the particles are electrons and positrons.

2.2 Verify the estimate of the mass of the particle seen by Street and Stevenson, Ref. 2.2, using the measurement of $H\rho$ and the ionization.

2.3 Assume for simplicity that $dE/dx = (dE/dx)_{min}/\beta^2 \equiv C/\beta^2$. Prove that the range of a particle of initial energy $E_0 = m\gamma_0$ is $R = mc^2(\gamma_0 - 1)^2/(C\gamma_0)$. Find the range of a muon in iron ($C = 1.48$ MeV cm^2/g) for initial momentum between 0.1 GeV/c and 1 TeV/c. Do the same for a proton. Compare with the curves in the *Review of Particle Properties.*

2.4 What is the range in air of a typical α particle produced in the radioactive decay of a heavy element?

2.5 How is the mass of the π^- most accurately determined? The mass of the π^0? The *Review of Particle Properties* is an invaluable source of references for measurements of this sort.

2.6 How is the lifetime of the π^0 measured?

2.7 * Use dimensional arguments to estimate very crudely the rate for π^- absorption by a nucleus from a bound orbital. Assume any dimensionless coupling is of order 1.

2.8 * Use classical arguments to estimate the time required for a μ^- to fall from the radius of the lowest electron orbit to the lowest μ orbit in iron. Assume the power is radiated continuously in accordance with the results of classical electrodynamics.

2.9 * The π^0 decays at rest isotropically into two photons. Find the energy and angular distributions of the photons if the π^0 has a velocity β along the z axis.

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