# 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 $p(\mathrm{MeV}/c) = 0.300 \times 10^{-3}\, B(\mathrm{gauss}) r(\mathrm{cm})$ or $p(\mathrm{GeV}/c) = 0.300 \times B(\mathrm{T}) r(\mathrm{m})$, 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 they lose energy through the ionization of atoms in the medium, unless they collide with a nucleus. 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 $\rho$ 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

$$\frac{dE}{dx} = \frac{N_A Z}{A} \frac{4\pi z^2 \alpha^2 (\hbar c)^2}{m_e v^2} \left[ \ln \frac{2 m_e v^2 \gamma^2}{I} - \frac{v^2}{c^2} \right] \tag{2.1}$$

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 $\gamma$ is about 3 or 4. Typical values of minimum ionization are 1 to 2 MeV/(g cm$^{-2}$).



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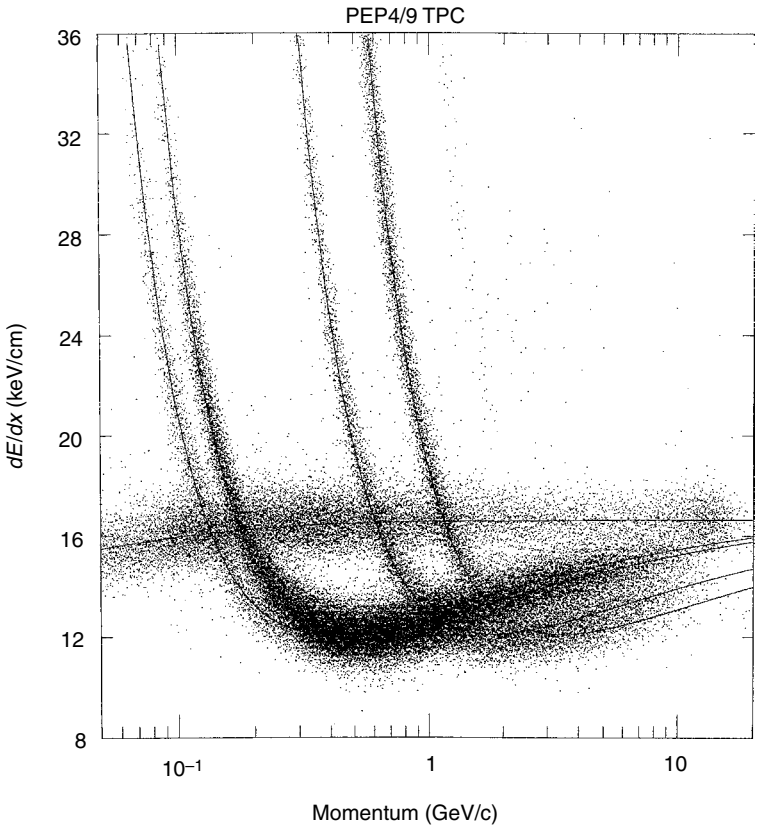



Figure 2.1. Measurements of $dE/dx$ (in keV cm$^{-1}$) for many particles produced in $e^+e^-$ collisions at a center of mass energy of 29 GeV. Each dot represents a single particle. Bands are visible for several distinct particle types. The flat band consists of electrons. The vertical bands, from left 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)]

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 an 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

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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 $\alpha$. A good representation of the energy loss through bremsstrahlung is

$$\frac{dE}{dx} = \frac{N_A}{A}\frac{4Z(Z+1)\alpha^3(\hbar c)^2}{m_e^2c^4}E\ln\frac{183}{Z^{1/3}} \equiv E/X_0. \tag{2.2}$$

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 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 100–500 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

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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 $(\hbar/c)/10^{-13}\,\text{cm} \approx 200\ \text{MeV}/c^2$. When improved measurements were made, the mass of the new particle was determined to be about $100\ \text{MeV}/c^2$, 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

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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 $1.5 \times 10^{-6}$ s. Improved results, near $2.2 \times 10^{-6}$ 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 Tomonaga 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 behavior 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, $\pi$, decayed into a muon, $\mu$ (the names given by Lattes *et al.*), and a very light particle, presumably Pauli's neutrino. The $\pi$ (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 $\mu$ (which Anderson and Neddermeyer had found) was just like an electron, only heavier. The pion has two charge states, $\pi^+$ and

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$\pi^-$ that are charge conjugates of each other and which yield $\mu^+$ and $\mu^-$, 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

$$\omega = \frac{eB}{m}. \tag{2.3}$$

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

$$\omega = \frac{eB}{\gamma m} \tag{2.4}$$

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

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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.

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 $5 \times 10^{-14}$ 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

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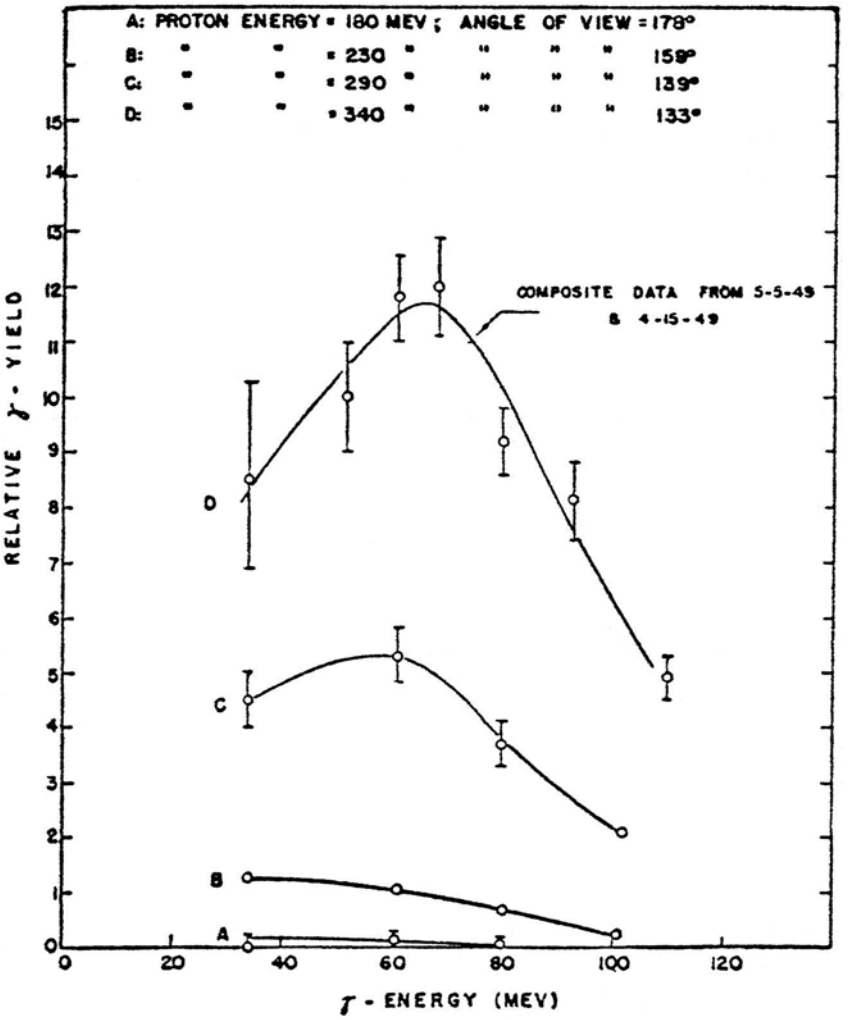



Figure 2.2. Gamma-ray yields from proton–carbon collisions at 180 to 340 MeV proton kinetic energy. The marked increase with increasing proton energy is the result of passing the $\pi^0$ production threshold. The $\pi^0$ decays into two photons. (Ref. 2.6)

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 quantity, depend linearly on the

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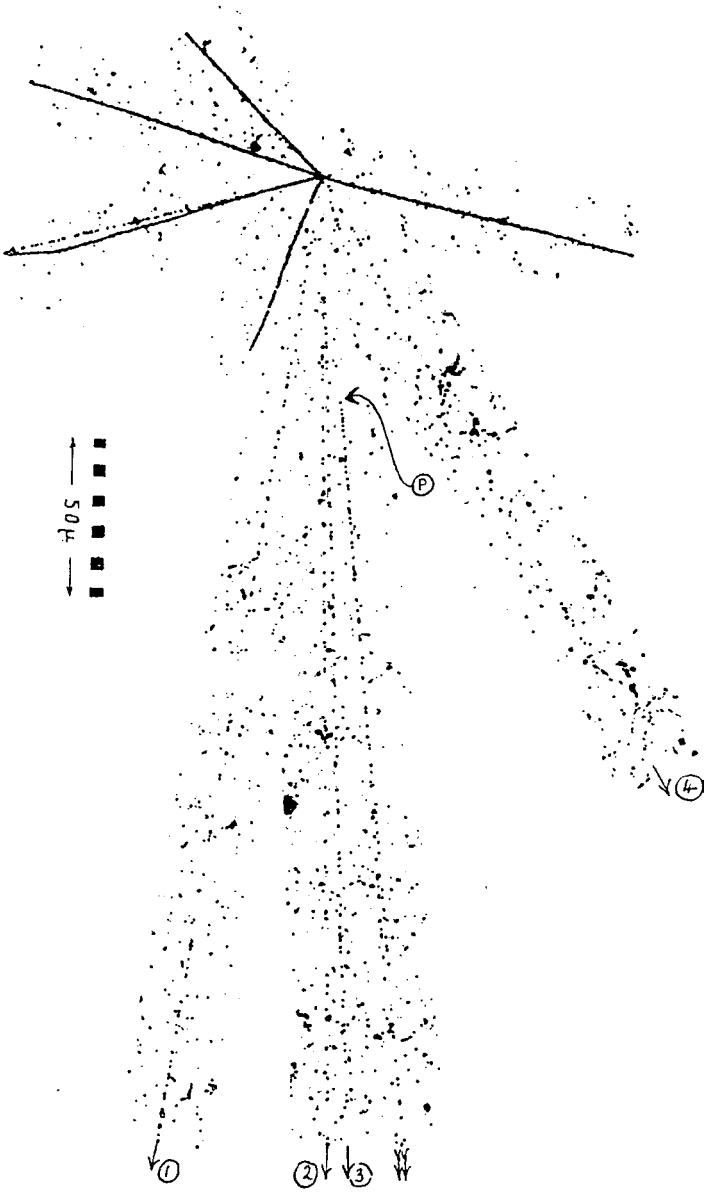



Figure 2.3. An emulsion event showing an $e^+e^-$ pair created by conversion of a photon from $\pi^0$ decay. The conversion occurs at the point marked $P$. (Ref. 2.7)

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,

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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 $\boldsymbol{\eta} \cdot \mathbf{k}$, 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 $\pi^-$, an extremely good measurement. See Figure 2.5. The photons produced by the decay of the $\pi^0$ were Doppler-shifted by the motion of the decaying $\pi^0$. 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 $\pi^-$ is assumed to occur from an s-wave state since the cross section for the $l$th partial waves is suppressed by $k^{2l}$, where $k$ is the momentum of the incident pion. If the final $\pi^0$ is produced in the s-wave, then the parity

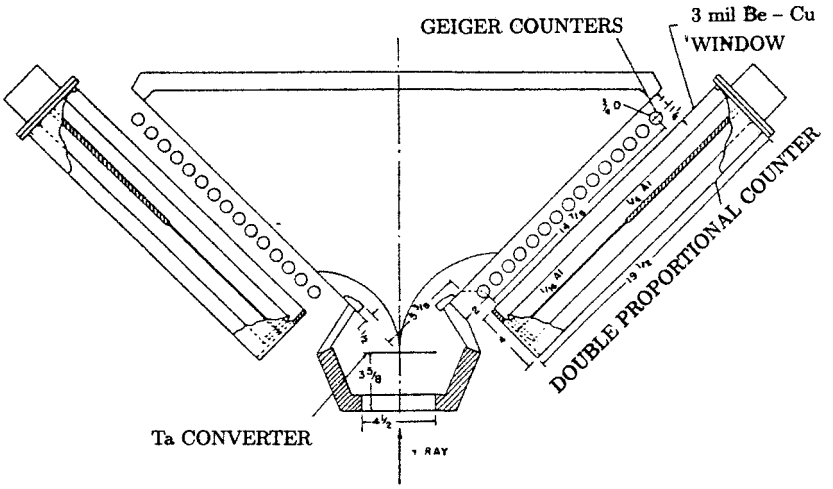



Figure 2.4. The pair spectrometer used by Panofsky, Aamodt, and Hadley in the study of $\pi^- p$ and $\pi^- d$ reactions. A magnetic field of 14 kG perpendicular to the plane shown bent the positrons and electrons into the Geiger counters on opposite sides of the spectrometer. (Ref. 2.9)

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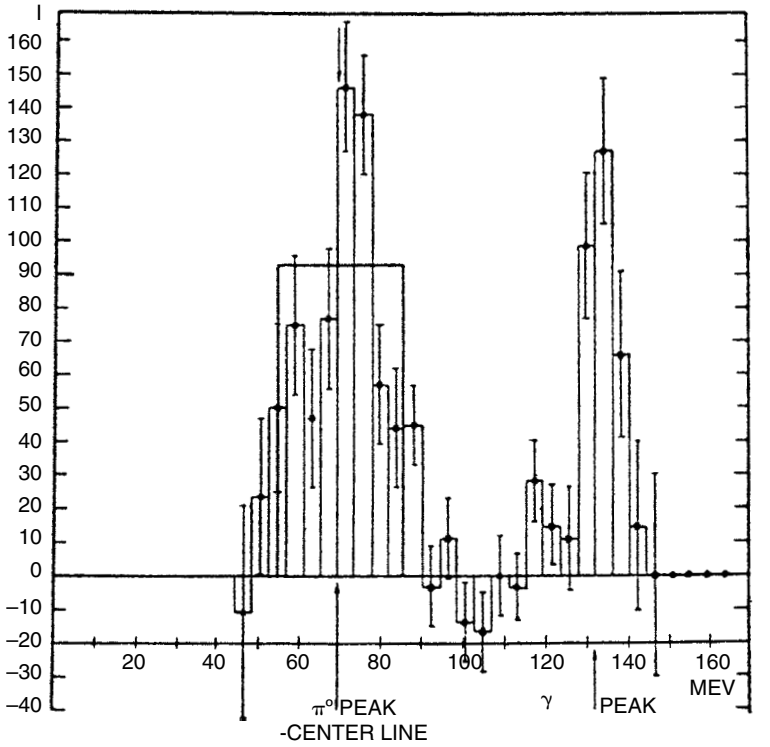



Figure 2.5. The photon energy spectrum for $\pi^- p$ reactions at rest. The band near 70 MeV is due to photons from $\pi^0$ decay. The line near 130 MeV is due to $\pi^- p \to n\gamma$. (Ref. 2.9)

of the neutral and charged pions must be the same. The momentum of the produced $\pi^0$, 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

$$P\psi(\mathbf{r}) = \psi(-\mathbf{r}) = (-1)^l \psi(\mathbf{r}). \tag{2.5}$$

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 $\eta$, 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,

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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.

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

$$\pi^- d \to nn$$
$$\pi^- d \to nn\gamma$$
$$\pi^- d \to nn\pi^0$$

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 $\pi^-$ could not be a scalar particle. If the $\pi$ 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 $\pi^- d \to nn$ occurs, the $\pi^-$ cannot be a scalar. The absence of the third reaction was to be expected if the $\pi^-$ and $\pi^0$ 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 $\pi^0$ 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

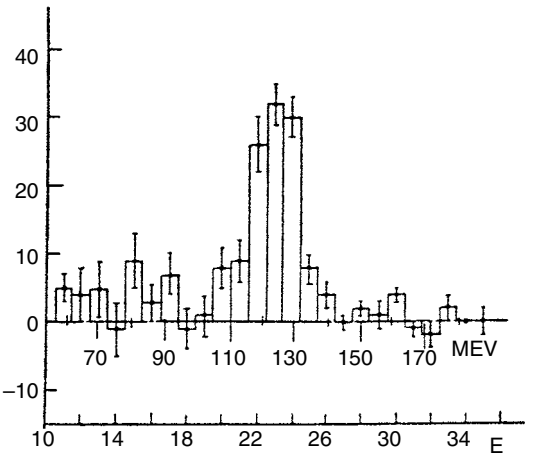



Figure 2.6. The photon energy spectrum from $\pi^- d$ reactions at rest. The line near 130 MeV is due to $\pi^- d \to nn\gamma$. (Ref. 2.9)

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cross section for a scattering process with two final state particles is related to the Lorentz invariant matrix element, $\mathcal{M}$, by

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\frac{p'}{p}|\mathcal{M}|^2 . \tag{2.6}$$

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 $pp \rightarrow \pi^+ d$ and $\pi^+ d \rightarrow pp$ 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:

$$\frac{d\sigma(\pi^+ d \rightarrow pp)/d\Omega}{d\sigma(pp \rightarrow \pi^+ d)/d\Omega} = \frac{(2s_p+1)^2}{(2s_d+1)(2s_\pi+1)}\frac{p_{pp}^2}{p_{\pi d}^2} \tag{2.7}$$

where $s_\pi$ is the spin of the $\pi^+$ and $p_{\pi d}$ and $p_{pp}$ are the center-of-mass momenta for the $\pi d$ 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 $\pi^+$ to have spin 0. Since the Panofsky, Aamodt, and Hadley paper had excluded $J^P = 0^+$ for the $\pi^-$ and thus for its charge conjugate, the $\pi^+$ necessarily had $J^P = 0^-$. Since the $\pi^0$ 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 $\pi^-$, 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 $\gamma e^+ e^-$, 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 $\pi^0$ has $J^P = 0^-$, as was demonstrated in 1959 by Plano, Prodell, Samios, Schwartz, and Steinberger (Ref. 2.12).

The $\pi^0$ completed the triplet of pions: $\pi^-$, $\pi^0$, $\pi^+$. 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

$$[I_x, I_y] = iI_z \qquad \text{etc.} \tag{2.8}$$

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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 $\pi^+ p$ has $I_z = 3/2$ and is thus purely $I = 3/2$, whereas $\pi^+ n$ 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$^{-1}$) 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 Physics*.

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

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

2.6 How is the lifetime of the $\pi^0$ measured?

2.7 * Use dimensional arguments to estimate very crudely the rate for $\pi^-$ 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 $\mu^-$ to fall from the radius of the lowest electron orbit to the lowest $\mu$ orbit in iron. Assume the power is radiated continuously in accordance with the results of classical electrodynamics.

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

## Further Reading

For the early history of particle physics, especially cosmic-ray work, see *Colloque international sur l'histoire de la physique des particules*, *Journal de Physique* **48**, supplement au no. 12. Dec. 1982. Les Editions de Physique, Paris 1982 (in English).

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Reminiscences of early work on the muon and the pion are contained in many of the articles in *The Birth of Particle Physics*, edited by L. M. Brown and L. Hoddeson, Cambridge University Press, Cambridge, 1983. See especially the article by S. Hayakawa for information on the independent developments in Japan that paralleled those discussed in this chapter.

For a flavor of particle physics around 1950 and for the opportunity to learn physics from one of the great masters, see *Nuclear Physics*, from a course taught by Enrico Fermi, notes taken by J. Orear, A. H. Rosenfeld, and R. A. Schluter, University of Chicago Press, Chicago, 1949.

For fundamentals of the interaction of elementary particles with matter and an early perspective on experimental particle physics, see *High Energy Particles*, by Bruno Rossi, Prentice-Hall, New York, 1952.

For a complete classical treatment of the interaction of charged particles with matter, see *Classical Electrodynamics*, Third Edition, by J. D. Jackson, Wiley, New York, 1999.

For information on particle masses, quantum numbers, and so on, and concise treatments of the behavior of high energy particles in matter, see *Review of Particle Physics*, written by the Particle Data Group and published biennially. A shortened version, the *Particle Properties Data Booklet*, is available for free by writing to the Particle Data Group, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA or to CERN Scientific Information Service, CH-1211, Geneva 23, Switzerland.

For the development of accelerators, see M. Stanley Livingston *Particle Accelerators: A Brief History*, Harvard University Press, Cambridge, Mass., 1969. Fundamental papers are reprinted in *The Development of High Energy Accelerators*, Classics of Science, v. III, edited by M. S. Livingston, Dover, 1966.

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2.7 A. G. Carlson, J. E. Hooper, and D. T. King, "Nuclear Transmutations Produced by Cosmic-Ray Particles of Great Energy – Part V. The Neutral Meson." *Phil. Mag.*, **41**, 701 (1950).


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**2.9** W. K. H. Panofsky, R. L. Aamodt, and J. Hadley, "The Gamma-Ray Spectrum Resulting from Capture of Negative $\pi$-Mesons in Hydrogen and Deuterium." *Phys. Rev.*, **81**, 565 (1951).
2.10 D. L. Clark, A. Roberts, and R. Wilson, "Cross section for the reaction $\pi^+ d \rightarrow pp$ and the spin of the $\pi^+$ meson." *Phys. Rev.*, **83**, 649 (1951).
**2.11** R. Durbin, H. Loar, and J. Steinberger, "The Spin of the Pion via the Reaction $\pi^+ + d \overset{\leftarrow}{\rightarrow} p + p$." *Phys. Rev.*, **83**, 646 (1951).
2.12 R. Plano *et al.*, "Parity of the Neutral Pion." *Phys. Rev. Lett.*, **3**, 525 (1959).

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MAY 15, 1937 PHYSICAL REVIEW VOLUME 51

# Note on the Nature of Cosmic-Ray Particles

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(Received March 30, 1937)

MEASUREMENTS[1] of the energy loss of particles occurring in the cosmic-ray showers have shown that this loss is proportional to the incident energy and within the range of the measurements, up to about 400 Mev, is in approximate agreement with values calculated theoretically for electrons by Bethe and Heitler. These measurements were taken using a thin plate of lead (0.35 cm), and the observed individual losses were found to vary from an amount below experimental detection up to the whole initial energy of the particle, with a mean fractional loss of about 0.5. If these measurements are correct it is evident that in a much thicker layer of heavy material multiple losses should become much more important, and the probability of observing a particle loss less than a large fraction of its initial energy should be very small. For the purpose of testing this inference and also for checking our previous measurements[2] which had shown the presence of some particles less massive than protons but more penetrating than electrons obeying the Bethe-Heitler theory, we have taken about 6000 counter-tripped photographs with a 1 cm plate of platinum placed across the center of the cloud chamber. This plate is equivalent in electron thickness to 1.96 cm of lead, and to 1.86 cm of lead for a $Z^2$ absorption. The results of 55 measurements on particles in the range below 500 Mev are given in Fig. 1, and in Fig. 2 the distribution of particles is shown as a function of the fraction of energy lost. The shaded part of the diagram represents particles which either enter the chamber accompanied by other particles or else themselves produce showers in the bar of platinum. It is clear that the particles separate themselves into two rather well-defined groups, the one consisting largely of shower particles and exhibiting a high absorbability, the other consisting of particles entering singly which in general lose a relatively small fraction of their initial energy, although there are four cases in which the loss is more than 60 percent. A considerable part of the spread on the negative abscissa can be accounted for by errors; it seems likely, however, that the case plotted at the extreme left represents a particle moving upward. Particles of both signs are distributed over the whole diagram, and moreover, the initial energies of the particles of each group are distributed over the whole measured range.

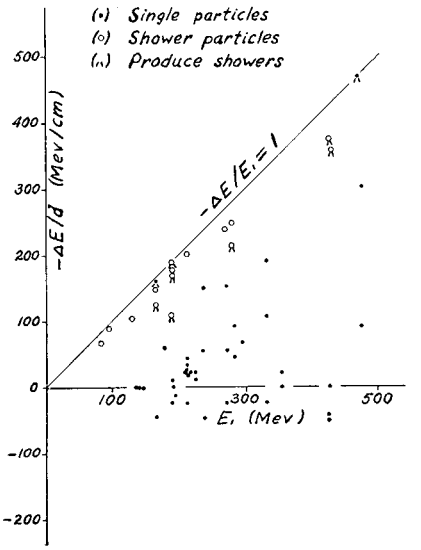



FIG. 1. Energy loss in 1 cm of platinum.

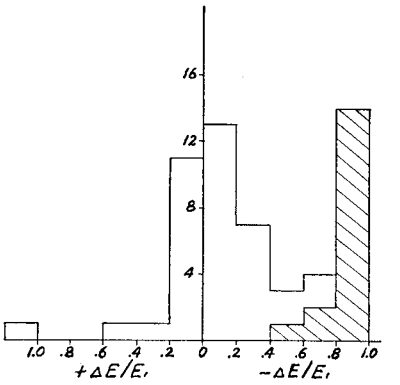



FIG. 2. Distribution of fractional losses in 1 cm of platinum.

[1] Anderson and Neddermeyer, Phys. Rev. **50**, 263 (1936).
[2] Anderson and Neddermeyer, Report of London Conference, Vol. 1 (1934), p. 179.



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The chief source of error in these experiments lies not in the curvature measurements themselves, but in the track distortions produced by irregular motions of the gas in the chamber. The distortions are much larger when a thick plate is inside the chamber than when it is left unobstructed. These distortions are not sufficient to alter essentially the distribution of observed losses for the nonpenetrating group, but they could have a very serious effect in the part of the distribution representing small losses. This is especially true inasmuch as this group represents a small percentage of the total number of tracks, selected solely on the basis that they should exhibit a measurable curvature and at the same time be free from obvious distortion. The problem of measuring small energy losses is then evidently an extremely difficult one compared to that of measuring energy distributions in an unobstructed chamber. While it is possible in many cases to distinguish a distortion as such when a magnetic field is present, it is necessary to obtain independent criteria as to the reliability of the measurements; it is not a satisfactory procedure to try to do this simply by measuring curvatures of tracks taken with no field and comparing the curvature distribution thus found with the one obtained when the field is present. Observations made with no magnetic field indicate that serious distortions occur on about 5 percent of the photographs, and show that they are by no means a uniform function of the orientation and position of the track in the chamber. It is therefore not possible to correct for distortion in individual cases. When large distortions do occur, however, they are likely to obey one or both of the following correlations: (*a*) a curvature concave upward when the track makes a considerable angle with the vertical; (*b*) a curvature concave toward the center of the chamber. The observed percentages of measured single tracks obeying the correlations

TABLE I. *Correlations between track curvatures and positions and orientations of tracks.*

| Designation (See text) | Percentage correlation | | |
|---|---|---|---|
| | Observed | Expected | Observed (excluding apparent gains) |
| (*a*) | 52 | 50 | 55 |
| (*b*) | 67 | 50 | 55 |
| (*a*) and (*b*) | 33 | 25 | 27 |
| neither | 15 | 25 | 18 |

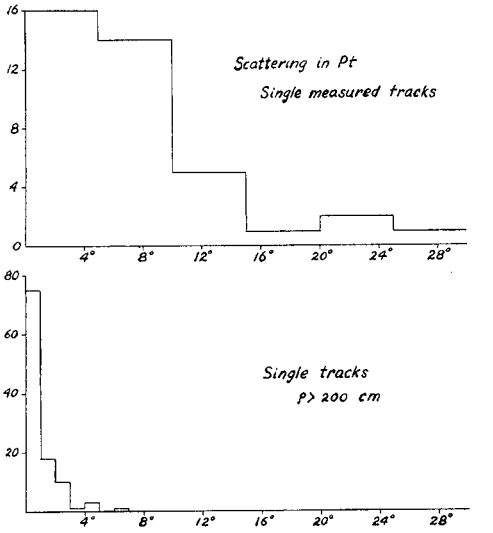



FIG. 3. Scattering distributions in 1 cm of platinum.

(*a*) and (*b*) are compared in Table I with the percentages expected if the observed curvatures have no relation to the positions and orientations of the tracks. If the 11 cases of apparent gains in energy are left out of consideration the observed percentages are brought somewhat closer to the expected values as shown in the last column.

A second independent check on the validity of the measurements can be obtained by measuring the scattering of the particles which show apparent curvatures, and comparing this with the scattering exhibited by those single tracks whose curvatures are just outside the range of measurability. In Fig. 3 are shown the distributions of scattering angles (the angles projected on the plane of the chamber) for the measured single tracks and for single tracks with a radius of curvature, $\rho \gtrsim 200$ cm (475 Mev). As it is scarcely conceivable that distortions could influence the scattering measurements by as much as 5°, these distributions constitute strong independent evidence that the measured tracks actually lie in the energy range indicated by the curvature determinations.

It has been known for a long time that there exist particles of both penetrating and nonpenetrating types. Crussard and Leprince-Ringuet[3] have recently made measurements of

[3] Crussard and Leprince-Ringuet, C. R. **204**, 240 (1937).

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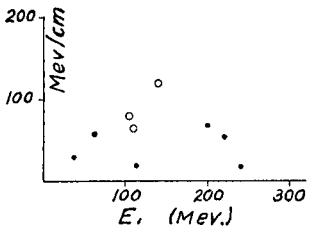



FIG. 4. Early measurements of energy loss in 0.7–1.5 cm of Pb. Dots indicate single particles; circles, shower particles.

energy loss in a range mainly above that covered in our experiments. They have concluded from their data that either the absorption law changes with energy or else that there is a difference in character among the particles. This same conclusion has already been twice stated by the writers.[4, 5] The present data appear to constitute the first experimental evidence for the existence of particles of both penetrating and nonpenetrating character in the energy range extending below 500 Mev. Moreover, the penetrating particles in this range do not ionize perceptibly more than the nonpenetrating ones, and cannot therefore be assumed to be of protonic mass. The lowest $H\rho$ among the penetrating group is $4.5\times10^5$ gauss cm. A proton of this curvature would ionize at least 25 times as strongly as a fast electron. It is interesting that our early measurements[2] of the energy loss in thicknesses of lead from 0.7 to 1.5 cm show a similar tendency to separate into two groups. They are reproduced in Fig. 4. If reinterpreted in the light of our present data they provide no evidence against high absorbability for electrons.

The nonpenetrating particles are readily interpreted as free positive and negative electrons. Interpretations of the penetrating ones encounter very great difficulties, but at present appear to be limited to the following hypotheses: (*a*) that an electron (+ or −) can possess some property other than its charge and mass which is capable of accounting for the absence of numerous large radiative losses in a heavy element; or (*b*) that there exist particles of unit charge, but with a mass (which may not have a unique value) larger than that of a normal free electron[6] and much smaller than that of a proton; this assumption would also account for the absence of numerous large radiative losses, as well as for the observed ionization. Inasmuch as charge and mass are the only parameters which characterize the electron in the quantum theory, assumption (*b*) seems to be the better working hypothesis. If the penetrating particles are to be distinguished from free electrons by a greater mass, and since no evidence for their existence in ordinary matter obtains, it seems likely that there must exist some very effective process for removing them.

The experimental fact that penetrating particles occur both with positive and negative charges suggests that they might be created in pairs by photons, and that they might be represented as higher mass states of ordinary electrons.

Independent evidence indicating the existence of particles of a new type has already been found, based on range, curvature and ionization relations; for example, Figs. 12 and 13 of our previous publication.[1] In particular the strongly ionizing particle of Fig. 13 cannot readily be explained except in terms of a particle of $e/m$ greater than that of a proton. The large value of $e/m$ apparently is not due to an $e$ greater than the electronic charge since above the plate the particle ionizes imperceptibly differently from a fast electron, whereas below the plate its ionization definitely exceeds that of an electron of the same curvature in the magnetic field; the effects, however, are understandable on the assumption that the particle's mass is greater than that of a free electron. We should like to suggest, merely as a possibility, that the strongly ionizing particles of the type of Fig. 13, although they occur predominantly with positive charge, may be related with the penetrating group above.

We wish to express our gratitude to Professor Millikan for his helpful discussions and encouragement. These experiments have been made possible by the Baker Company, who very generously loaned us the bar of platinum; and by funds supplied by the Carnegie Institution of Washington.

*Note added in proof:* Excellent experimental evidence showing the existence of particles less massive than protons, but more penetrating than electrons obeying the Bethe-Heitler theory has just been reported by Street and Stevenson, Abstract no. 40, Meeting of American Physical Society, Apr. 29, 1937.

[4] Reference 2, p. 182.
[5] Reference 1, p. 268.
[6] The energies referred to throughout are, of course, calculated on the assumption of electronic mass. For a mass $m\lesssim50m_e$ the actual energy is very roughly $E=E_{el}-mc^2$ in the range of curvature here considered.

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NOVEMBER 1, 1937 PHYSICAL REVIEW VOLUME 52

# LETTERS TO THE EDITOR

*Prompt publication of brief reports of important discoveries in physics may be secured by addressing them to this department. Closing dates for this department are, for the first issue of the month, the eighteenth of the preceding month, for the second issue, the third of the month. Because of the late closing dates for the section no proof can be shown to authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents.*

**Communications should not in general exceed 600 words in length.**

## New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron

Anderson and Neddermeyer[1] have shown that, for energies up to 300 and 400 Mev, the cosmic-ray shower particles have energy losses in lead plates corresponding to those predicted by theory for electrons. Recent studies of range[2] and energy loss[3] indicate that the singly occurring cosmic-ray corpuscles, even in the energy range below 400 Mev, are more penetrating than shower particles of corresponding magnetic deflection. Thus the natural assumptions have been expressed: the shower particles are electrons, the theory describing their energy losses is satisfactory, and the singly occurring particles are not electrons. The experiments cited above have shown from consideration of the specific ionization that the penetrating rays are not protons. The suggestion has been made that they are particles of electronic charge, and of mass intermediate between those of the proton and electron. If this is true, it should be possible to distinguish clearly such a particle from an electron or proton by observing its track density and magnetic deflection near the end of its range, although it is to be expected that the fraction of the total range in which the distinction can be made is very small. To examine this possibility experimentally we have used the arrangement of apparatus of Fig. 1. The three-counter telescope consisting of tubes 1, 2, and 3 and a lead filter $L$ for removing shower particles, selects penetrating rays directed toward the cloud chamber $C$ which is in a magnetic field of 3500 gauss. The type of track desired is one sc near the end of its range as it enters the chamber that there is no chance of emergence below. In order to reduce the number of photographs of high energy particles, the tube group 4 was used as a cut-off counter with a circuit so arranged that the chamber would be set off only in those cases when a coincident discharge of counters 1, 2, and 3 was unaccompanied by a discharge of 4. The tripping of the cloud chamber valve was delayed about one sec. to facilitate determination of the drop count along a track. Because of geometrical imperfections of the arrangement and of counter inefficiency the cut-off circuit prevented

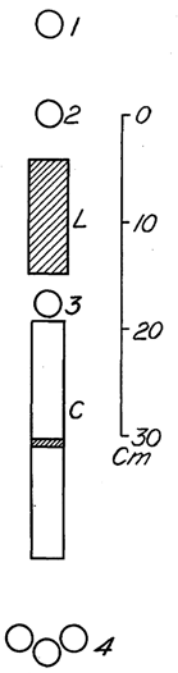



FIG. 1. Geometrical arrangement of apparatus.

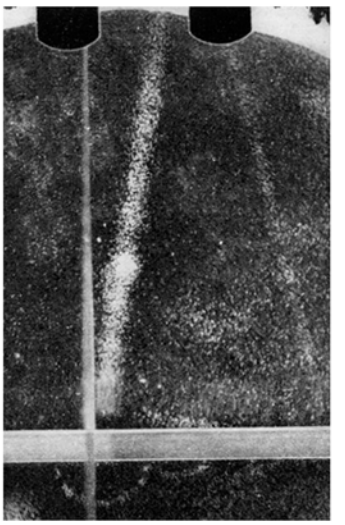


FIG. 2. Track $A$.



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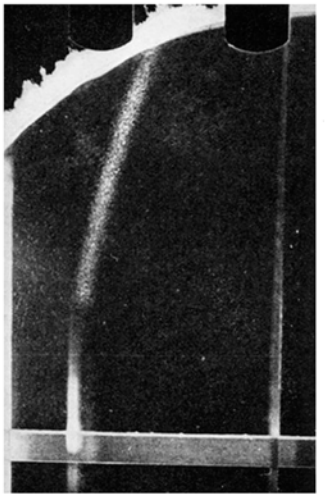


FIG. 3. Track $B$.

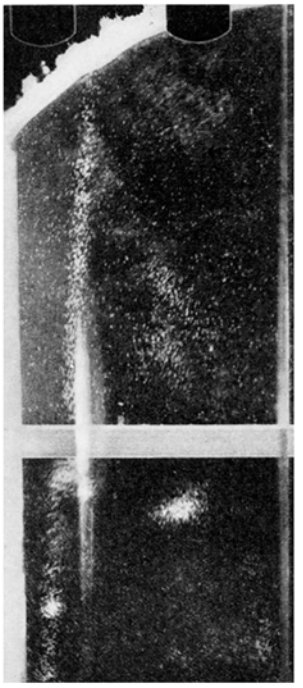


FIG. 4. Photograph of the track of a penetrating particle of high energy for comparison with $A$ and $B$.

expansion for only ¾ of the discharges of the telescope. At the present time 1000 photos have been taken (equivalent to 4000 if the cut-off counter had not been used). Two tracks of interest, in that they have ionization densities definitely greater than usual, have been obtained: one $A$ (see Fig. 2) is believed due to a proton and the other $B$ (see Fig. 3) to a particle of mass approximately 130 times the rest mass of an electron. Track $A$ which terminated in the lead strip at the center of the chamber exhibited an ionization density 2.4 times as great as the usual thin tracks and an $H\rho$ value approximately $2\times10^6$ gauss cm in a direction to indicate a positive particle. Track $B$ which passed out of the lighted region above the lead plate had an ionization density about six times as great as normal thin tracks (the ion density was too great to permit an accurate ion count) and an $H\rho$ value of $9.6\times10^4$ gauss cm. If it is assumed, as seems reasonable, that the particle entered from above, the sign is negative. If it is taken that the ionization density varies inversely as the velocity squared, the rest mass of the particle in question is found to be approximately 130 times the rest mass of the electron. Because of uncertainty in the ion count this determination has a probable error of some 25 percent. In any case it does not seem possible to explain this track as due to a proton traveling up, for the observed $H\rho$ value would indicate a proton of $4.4\times10^5$ electron volts energy and therefore with a range of approximately one cm in the chamber. The track is clearly visible for 7 cm in the chamber.

The only possible objection to the conclusions reached above is that the bending of track $A$ is largely due to distortion, but this is very unlikely, for the deflection is quite uniform and has a maximum value greater than ten times any distortions usually encountered in the thin tracks of high energy particles.

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E. C. STEVENSON

Research Laboratory of Physics,
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Cambridge, Massachusetts,
October 6, 1937.

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PHYSICAL REVIEW VOLUME 71, NUMBER 3 FEBRUARY 1, 1947

# Letters to the Editor

*PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is, for the issue of the 1st of the month, the 8th of the preceding month and for the issue of the 15th, the 23rd of the preceding month. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.*

## On the Disintegration of Negative Mesons

M. CONVERSI, E. PANCINI, AND O. PICCIONI*
*Centro di Fisica Nucleare del C. N. R. Istituto di Fisica dell'Università di Roma, Italia*

December 21, 1946

IN a previous Letter to the Editor,[1] we gave a first account of an investigation of the difference in behavior between positive and negative mesons stopped in dense materials. Tomonaga and Araki[2] showed that, becuase of the Coulomb field of the nucleus, the capture probability for negative mesons at rest would be much greater than their decay probability, while for positive mesons the opposite should be the case. If this is true, then practically all the decay processes which one observes should be owing to positive mesons.

Several workers[3] have measured the ratio $\eta$ between the number of the disintegration electrons and the number of mesons stopped in dense materials. Using aluminum, brass, and iron, these workers found values of $\eta$ close to 0.5 which, if one assumes that the primary radiation consists of approximately equal numbers of positive and negative mesons, support the above theoretical prediction. Auger, Maze, and Chaminade,[4] on the contrary, found $\eta$ to be close to 1.0, using aluminum as absorber.

Last year we succeeded in obtaining evidence of different behavior of positive and negative mesons stopped in 3 cm of iron as an absorber by using magnetized iron plates to concentrate mesons of the same sign while keeping away mesons of the opposite sign (at least for mesons of such energy that would be stopped in 3 cm of iron). We obtained results in agreement with the prediction of Tomonaga and Araki. After some improvements intended to increase the counting rate and improve our discrimination against the "mesons of the opposite sign," we continued the measurements using, successively, iron and carbon as absorbers. The recording equipment was one which two of us had previously used in a measurement of the meson's mean life.[5] It gave threefold (III) and fourfold (IV) delayed coincidences. The difference (III)−(IV) (after applying a slight correction for the lack of efficiency of the fourfold coincidences) was owing to mesons stopped in the absorber and ejecting a disintegration electron which produced a delayed coincidence. The minimum detected delay was about 1 $\mu$sec. and the maximum about 4.5 $\mu$sec. Our calculations of the focusing properties of the magnetized plates (20 cm high; $\beta = 15{,}000$ gauss) and including roughly the effects of scattering, showed that we should expect almost complete cut-off for the "mesons of the opposite sign." This is confirmed by our results, since otherwise it would be very hard to explain the almost complete dependence on the sign of the meson observed in the case of iron.

TABLE I. Results of measurements on $\beta$-decay rates for positive and negative mesons.

| Sign | Absorber | III | IV | Hours | $M$/100 hours |
|---|---|---|---|---|---|
| (a) + | 5 cm Fe | 213 | 106 | 155.00′ | 67±6.5 |
| (b) − | 5 cm Fe | 172 | 158 | 206.00′ | 3 |
| (c) − | none | 71 | 69 | 107.45′ | −1 |
| (d) + | 4 cm C | 170 | 101 | 179.20′ | 36±4.5 |
| (e) − | 4 cm C+5 cm Fe | 218 | 146 | 243.00′ | 27±3.5 |
| (f) − | 6.2 cm Fe | 128 | 120 | 240.00′ | 0 |

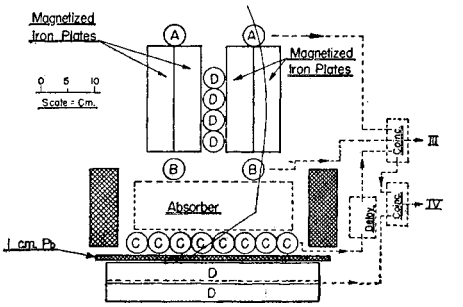



FIG. 1. Disposition of counters, absorber, and magnetized iron plates. All counters "D" are connected in parallel.

The results of our last measurements with two different absorbers are given in Table I. In this table "Sign" refers to the sign of the meson concentrated by the magnetic field. $M = (\mathrm{III}) - (\mathrm{IV}) - P(\mathrm{IV})$, the number of decay electrons, is corrected for the lack of efficiency ($p$) in our fourfold coincidences ($\sim 0.046$).

The value $M-$ (5 cm Fe) is but slightly greater than the correction for the lack of efficiency in our counting, so that we can say that perhaps no negative mesons and, at most, only a few ($\sim 5$) percent undergo $\beta$-decay with the accepted half-life.

The results with carbon as absorber turn out to be quite inconsistent with Tomonaga and Araki's prediction. We used cylindrical graphite rods having a mean effective thickness of 4 cm because we were unable to procure a graphite plate. In addition, when concentrating negative mesons, we placed above the graphite a 5-cm thick plate of iron to guard against the scattering of very low energy mesons which might destroy the concentrating effect of our magnets. We alternated the following three measurements:

A. Negative mesons with 4 cm C and 5 cm Fe,
B. Negative mesons with 6.2 cm Fe (6.2 cm Fe is approximately equivalent to 4 cm C+5 cm Fe as far as energy loss is concerned.
C. Positive mesons with 4 cm C.



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The comparison between A and B gave the difference in behavior between Fe and C, once we had established the fact that practically no disintegration electrons came from negative mesons in the 5-cm iron plate. The comparison between A and C gives the difference in behavior between negative and positive mesons in carbon. This must be considered as a qualitative comparison because of the slightly different action of the magnetic field in concentrating mesons of different ranges (4 cm C+5 cm Fe in one case and 4 cm of C in the other). We could not, of course, add 5 cm of Fe for the positive mesons too, since positive mesons do decay in Fe.

The great yield of negative decay electrons from carbon shows a marked difference between it and iron as absorbers. Tomonaga and Araki's calculation also give for carbon a much higher ratio of capture to decay probability for negative mesons, so we are forced to doubt their estimation. It is possible that a suitable dependence of the capture cross section, $\sigma_c$, on the nuclear charge, $Z$, might explain these results; however, if the ratio of the capture to decay probability also depends on the density as Tomonaga and Araki pointed out, then it would require a very irregular dependence on $Z$ to also explain the cloud-chamber pictures of some authors[6] showing negative mesons stopped in the chamber without any decay electrons coming out.

Concerning the difference between $M_+$ and $M_-$ in carbon, we should like to point out that it is not necessary to assume that $\sigma_c$ for carbon has an appreciable value for negative mesons. A positive excess, $(H_+-H_-)/(H_++H_-)$ of 20 percent in the hard component, as it seems to be[7] is sufficient to explain our results since this gives $H_+/H_-=1.5$ which is greater than $M_+/M_-$ for carbon. Impurities in the graphite could also explain some preference for $M_+$, with a suitable dependence of $\sigma_c$ on $Z$.

Further experiments on this subject are now in progress, in an attempt to calculate the capture cross section, and to know how it depends on $Z$.

* Now Visiting Research Associate at Massachusetts Institute of Technology, Cambridge, Massachusetts.

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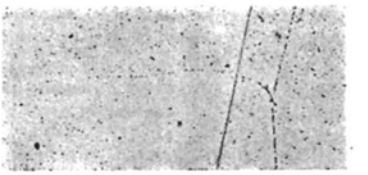


Fig. 1 *a*. PHOTOMICROGRAPH OF CENTRE OF STAR, SHOWING TRACK OF MESON PRODUCING DISINTEGRATION. (LEITZ 2 MM. OIL-IMMERSION OBJECTIVE. × 500)

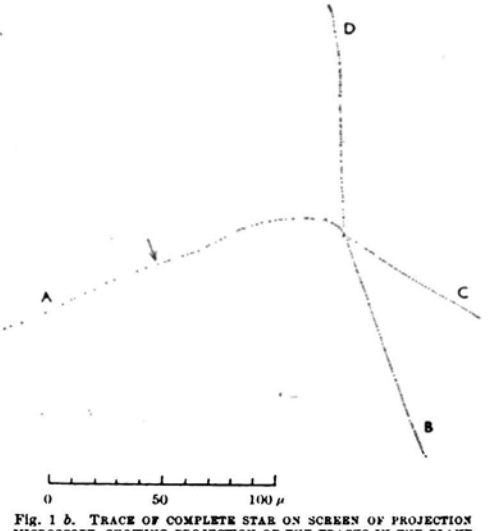



Fig. 1 *b*. TRACE OF COMPLETE STAR ON SCREEN OF PROJECTION MICROSCOPE, SHOWING PROJECTION OF THE TRACKS IN THE PLANE OF THE EMULSION. TRACK *A* CANNOT BE TRACED WITH CERTAINTY BEYOND THE ARROW

## Nuclear Disintegration by Meson Capture

RECENTLY, multiple nuclear disintegration 'stars', produced by cosmic radiation, have been investigated by the photographic emulsion technique. Plates coated with 50 μ Ilford B.1 emulsions[1] were exposed in aircraft for several hours at 30,000 ft. One of these disintegrations was of particular interest, for whereas all stars previously observed had been initiated by radiation not producing ionizing tracks in the emulsion, the one in question appears to be due to nuclear capture of a charged particle, presumably a slow meson.

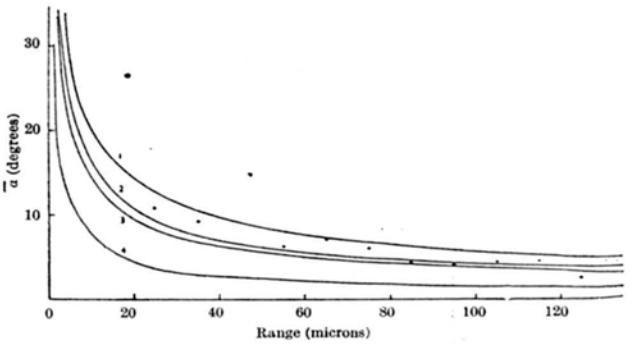
The star consists of four tracks *A*, *B*, *C* and *D* (Fig. 1). *A*, *B* and *D* lie almost in the plane of the emulsion, whereas *C* dips steeply (at about 40°) and ends in the glass. *D* is due to a proton of energy 3·7 MeV., and *C* also corresponds to a proton, of more than 3 MeV., and most likely about 5 MeV. Track *B* was most probably produced by a triton of 5·6 MeV. A short track, about 1 μ long, between *A* and *B* is apparently due to the residual recoil nucleus.

Track *A* appears to enter the emulsion surface about 150 μ from the star centre. On account of the relatively large distances between consecutive grains at this range, the track cannot be distinguished at all easily against the spontaneous background of grains, and only the last 100 μ of track (below arrow) can be traced with certainty. Assuming it to be singly charged, the mass of the particle producing track *A* has been roughly evaluated by the following methods.

(1) Both ionization and scattering increase towards the origin of the star, hence the particle was definitely travelling *towards* the disintegration point.

An electron is discounted because the observed ionization is far too high (an electron track of this range would, in fact, not be detected at all), and the scattering too small. On the other hand, a proton is discounted since the observed scattering is too great (Fig. 2). We must, therefore, conclude that the particle had a mass intermediate between that of electron and proton

The grain density along track *A* does, in fact, agree well with that to be expected of a meson of the observed range of about one tenth of the proton mass. The range-energy curve for mesons in the emulsion has been obtained from that for protons (kindly lent by Dr. C. F. Powell), using the ratio of the masses of the two particles.




Curve 1 : $M = 100\ m_e$ ; curve 2 : $M = 200\ m_e$ ; curve 3 : $M = 300\ m_e$ ; curve 4 : $M = 1{,}800\ m_e$

Fig. 2. MULTIPLE SCATTERING OF MESONS AND PROTON IN THE EMULSION. $\bar{\alpha}$ DENOTES THE MEAN ANGLE OF SCATTERING FOR A 10 μ LAYER OF THE EMULSION. CURVES CALCULATED FOR PARTICLES OF MASS 100 $m_e$, 200 $m_e$, 300 $m_e$ AND 1,800 $m_e$ (PROTON). $m_e$ BEING THE ELECTRON MASS. EXPERIMENTAL POINTS, FROM MEASUREMENTS ON TRACK *A*, INDICATED BY DOTS

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(2) The elastic scattering of mesons and protons can be calculated from the known emulsion constitution, using Williams's formula[2] for the mean square angle of multiple scattering, and is shown plotted against range in Fig. 2. Bearing in mind the fact that the single scattering will introduce large fluctuations, the experimental points appear to be consistent with a meson mass between 100 $m_e$ and 300 $m_e$, $m_e$ being the electron mass. Only the horizontal projection of the scattering along the track can actually be measured; on the average, multiplying this by a factor $\sqrt{2}$ will give the true value. The scattering of fast electrons cannot be found from any simple formula, but it is certainly much greater than the observed values.

(3) A value of the meson mass can also be arrived at from the energy required in the nuclear disintegration. In this process, the emitted particles must have sufficient energy to surmount the potential barrier, so that the disintegrating nucleus in this case cannot be that of silver or bromine, and must, therefore, be either carbon, oxygen or nitrogen (in the gelatin).

An approximate calculation of the momentum of the recoil nucleus indicates that at least one neutron must be postulated to conserve momentum; the kinetic energy of this neutron must be around 4 MeV. If we assume that a negative meson is captured by a nucleus nearly at the end of its range and is annihilated, so that the rest energy of the meson becomes nuclear excitation energy, we could have disintegration schemes such as

$$Y^- + O_8^{16} \rightarrow N_7^{16*} \rightarrow H_1^3 + 2H_1^1 + n_0^1 + Be_4^{10*} \quad (\text{or } 2n_0^1 + Be_4^8)$$

$$Y^- + N_7^{14} \rightarrow C_6^{14*} \rightarrow H_1^3 + 2H_1^1 + n_0^1 + Li_3^{6*}$$

$$Y^- + C_6^{12} \rightarrow B_5^{12*} \rightarrow H_1^3 + 2H_1^1 + n_0^1 + He_2^{6*}$$

As the recoil nucleus would be expected to have a fairly high excitation energy (5–10 MeV.) above the ground-state, it must be relatively stable against further disintegration into charged particles. With this limitation, there are still a large number of possible reactions (considering all isotopes of carbon, oxygen and nitrogen), but it appears that in general the mass excess of the recoil nucleus $\sim$ 15 MeV., whereas that of the initial one $\sim$ 5 MeV. or less. The negative $Q$ value of the reaction, allowing for excitation energy, is then found to be $\sim$ 60 MeV., and the total kinetic energy of the ejected particles $\sim$ 20 MeV. The total excitation energy of the original nucleus would then be $\sim$ 80 MeV., probably with an error of $\pm$ 20 MeV. (to allow for the various numbers of neutrons emitted, etc.).

On the above hypothesis, the meson should, therefore, have a rest energy of 60–100 MeV., that is, a mass of between 120 $m_e$ and 200 $m_e$.

Near the end of the meson track, a small number of grains are observed slightly off the main track. If these are due to fast secondary electrons, their ranges appear to be considerably greater than would be expected from the energy of the primary.

I am indebted to the A.O.C., Royal Air Force, Benson, Oxon., for kindly exposing the plates.

D. H. Perkins
Imperial College of Science and Technology,
London, S.W.7.
Jan. 8.

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# OBSERVATIONS ON THE TRACKS OF SLOW MESONS IN PHOTOGRAPHIC EMULSIONS*

By C. M. G. LATTES, Dr. G. P. S. OCCHIALINI and Dr. C. F. POWELL

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*INTRODUCTION.* In recent experiments, it has been shown that charged mesons, brought to rest in photographic emulsions, sometimes lead to the production of secondary mesons. We have now extended these observations by examining plates exposed in the Bolivian Andes at a height of 5,500 m., and have found, in all, forty examples of the process leading to the production of secondary mesons. In eleven of these, the secondary particle is brought to rest in the emulsion so that its range can be determined. In Part 1 of this article, the measurements made on these tracks are described, and it is shown that they provide evidence for the existence of mesons of different mass. In Part 2, we present further evidence on the production of mesons, which allows us to show that many of the observed mesons are locally generated in the 'explosive' disintegration of nuclei, and to discuss the relationship of the different types of mesons observed in photographic plates to the penetrating component of the cosmic radiation investigated in experiments with Wilson chambers and counters.

## Part I. Existence of Mesons of Different Mass

As in the previous communications[1], we refer to any particle with a mass intermediate between that of a proton and an electron as a meson. It may be emphasized that, in using this term, we do not imply that the corresponding particle necessarily has a strong interaction with nucleons, or that it is closely associated with the forces responsible for the cohesion of nuclei.

We have now observed a total of 644 meson tracks which end in the emulsion of our plates. 451 of these were found, in plates of various types, exposed at an altitude of 2,800 m. at the Observatory of the Pic du Midi, in the Pyrenees; and 193 in similar plates exposed at 5,500 m. at Chacaltaya in the Bolivian Andes. The 451 tracks in the plates exposed at an altitude of 2,800 m. were observed in the examination of 5 c.c. emulsion. This corresponds to the arrival of about 1·5 mesons per c.c. per day, a figure which represents a lower limit, for the tracks of some mesons may be lost through fading, and through failure to observe tracks of very short range. The true number will thus be somewhat higher. In any event, the value is of the same order of magnitude as that we should expect to observe in delayed coincidence experiments at a height of 2,800 m., basing our estimates on the observations obtained in similar experiments at sea-level, and making reasonable assumptions about the increase in the number of slow mesons with altitude. It is therefore certain that the mesons we observe are a common constituent of the cosmic radiation.

Photomicrographs of two of the new examples of secondary mesons, Nos. III and IV, are shown in Figs. 1 and 2. Table 1 gives details of the characteristics of all events of this type observed up to the time of writing, in which the secondary particle comes to the end of its range in the emulsion.

TABLE 1

| Event No. | Range in emulsion in microns of Primary meson | Secondary meson |
|---|---|---|
| I | 133 | 613 |
| II | 84 | 565 |
| III | 1040 | 621 |
| IV | 133 | 591 |
| V | 117 | 638 |
| VI | 49 | 595 |
| VII | 460 | 616 |
| VIII | 900 | 610 |
| IX | 239 | 666 |
| X | 256 | 637 |
| XI | 81 | 590 |

Mean range $614 \pm 8\,\mu$. Straggling coefficient $\sqrt{\Sigma\Delta_i^2/n} = 4{\cdot}3$ per cent, where $\Delta_i = R_i - \bar{R}$, $R_i$ being the range of a secondary meson, and $\bar{R}$ the mean value for $n$ particles of this type.

* This article contains a summary of the main features of a number of lectures given, one at Manchester on June 18 and four at the Conference on Cosmic Rays and Nuclear Physics, organised by Prof. W. Heitler, at the Dublin Institute of Advanced Studies, July 5–12. A complete account of the observations, and of the conclusions which follow from them, will be published elsewhere.

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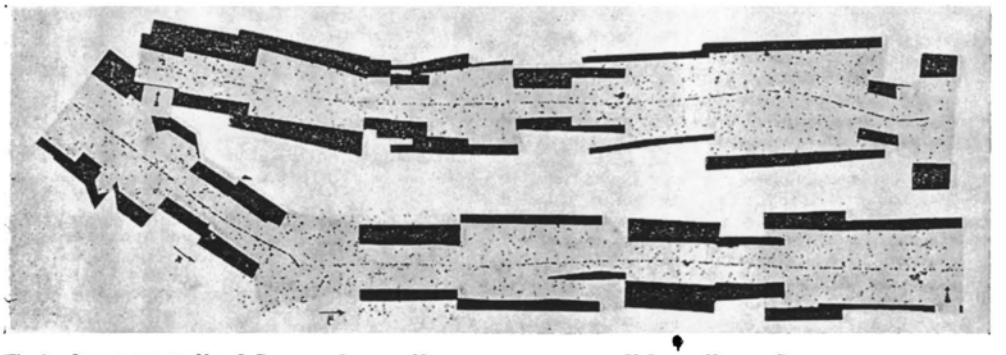


Fig. 1. Observation by Mrs. I. Powell. Cooke × 95 achromatic objective; *C2* Ilford Nuclear Research emulsion loaded with boron. The track of the $\mu$-meson is given in two parts, the point of junction being indicated by *a* and an arrow

meson, produced in a process of the type which we observe, will remain within the emulsion, of thickness 50 $\mu$, for a distance greater than 500 $\mu$. If we assume, as a first approximation, that the trajectories are rectilinear, we obtain a value for the probability of 1 in 20. The marked Coulomb scattering of mesons in the Nuclear Research emulsions will, in fact, increase the probability of 'escape'. The six events which we observe in plates exposed at 2,800 m., in which the secondary particle remains in the emulsion for a distance greater than 500 $\mu$, therefore correspond to the occurrence in the emulsion of 120 $\pm$ 50 events of this particular type. Our observations, therefore, prove that the production of a secondary meson is a common mode of decay of a considerable fraction of those mesons which come to the end of their range in the emulsion.

Second, there is remarkable consistency between the values of the range of the secondary mesons, the variation among the individual values being similar to that to be expected from 'straggling', if the particles are always ejected with the same velocity. We can therefore conclude that the secondary mesons are all of the same mass and that they are emitted with constant kinetic energy.

If mesons of lower range are sometimes emitted in an alternative type of process, they must occur much less frequently than those which we have observed; for the geometrical conditions, and the greater average grain-density in the tracks, would provide much more favourable conditions for their detection. In fact, we have found no such mesons of shorter range. We cannot, however, be certain that mesons of greater range are not sometimes produced. Both the lower ionization in the beginning of the trajectory, and the even more unfavourable conditions of detection associated with the greater lengths of the tracks, would make such a group, or groups, difficult to observe. Because of the large fraction of the mesons which, as we have seen, can be attributed to the observed process, it is reasonable to assume that alternative modes of decay, if they exist, are much less frequent than that which we have observed. There is, therefore, good evidence for the production of a single homogeneous group of secondary mesons, constant in mass and kinetic energy. This strongly suggests a fundamental process, and not one involving an interaction of a primary meson with a particular type of nucleus in the emulsion. It is convenient to refer to this process

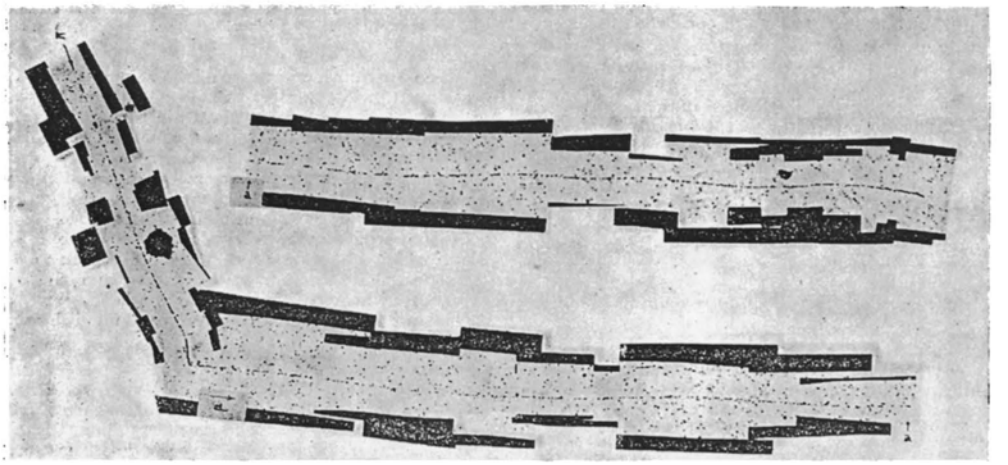


Fig. 2. Cooke × 95 achromatic objective. *C2* Ilford Nuclear Research emulsion loaded with boron

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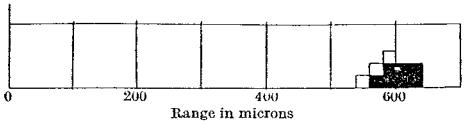



Fig. 3. DISTRIBUTION IN RANGE OF TEN SECONDARY MESONS. THOSE MARKED ■ STOP IN THE EMULSION; THE THREE MARKED □ LEAVE THE EMULSION WHEN NEAR THE END OF THEIR RANGE. MEAN RANGE OF SECONDARY MESONS, 606 MICRONS. THE RESULTS FOR EVENTS NOS. VIII TO XI ARE NOT INCLUDED IN THE FIGURE

in what follows as the $\mu$-decay. We represent the primary mesons by the symbol $\pi$, and the secondary by $\mu$. Up to the present, we have no evidence from which to deduce the sign of the electric charge of these particles. In every case in which they have been observed to come to the end of their range in the emulsion, the particles appear to stop without entering nuclei to produce disintegrations with the emission of heavy particles.

Knowing the range-energy relation for protons in the emulsion, the energy of ejection of the secondary mesons can be deduced from their observed range, if a value of the mass of the particles is assumed. The values thus calculated for various masses are shown in Table 2.

TABLE 2

| Mass in $m_e$ | 100 | 150 | 200 | 250 | 300 |
|---|---|---|---|---|---|
| Energy in MeV. | 3·0 | 3·6 | 4·1 | 4·5 | 4·85 |

No established range-energy relation is available for protons of energies above 13 MeV., and it has therefore been necessary to rely on an extrapolation of the relation established for low energies. We estimate that the energies given in Table 2 are correct to within 10 per cent.

## Evidence of a Difference in Mass of $\pi$- and $\mu$-Mesons

It has been pointed out[1] that it is difficult to account for the $\mu$-decay in terms of an interaction of the primary meson with the nucleus of an atom in the emulsion leading to the production of an energetic meson of the same mass as the first. It was therefore suggested that the observations indicate the existence of mesons of different mass. Since the argument in support of this view relied entirely on the principle of the conservation of energy, a search was made for processes which were capable of yielding the necessary release of energy, irrespective of their plausibility on other grounds. Dr. F. C. Frank has re-examined such possibilities in much more detail, and his conclusions are given in an article to follow. His analysis shows that it is very difficult to account for our observations, either in terms of a nuclear disintegration, or of a 'building-up' process in which, through an assumed combination of a negative meson with a hydrogen nucleus, protons are enabled to enter stable nuclei of the light elements with the release of binding energy. We have now found it possible to reinforce this general argument for the existence of mesons of different mass with evidence based on grain-counts.

We have emphasized repeatedly[1] that it is necessary to observe great caution in drawing conclusions about the mass of particles from grain-counts. The main source of error in such determinations arises from the fugitive nature of the latent image produced in the silver halide granules by the passage of fast particles. In the case of the $\mu$-decay process, however, an important simplification occurs. It is reasonable to assume that the two meson tracks are formed in quick succession, and are subject to the same degree of fading. Secondly, the complete double track in such an event is contained in a very small volume of the emulsion, and the processing conditions are therefore identical for both tracks, apart from the variation of the degree of development with depth. These features ensure that we are provided with very favourable conditions in which to determine the ratio of the masses of the $\pi$- and $\mu$-mesons, in some of these events.

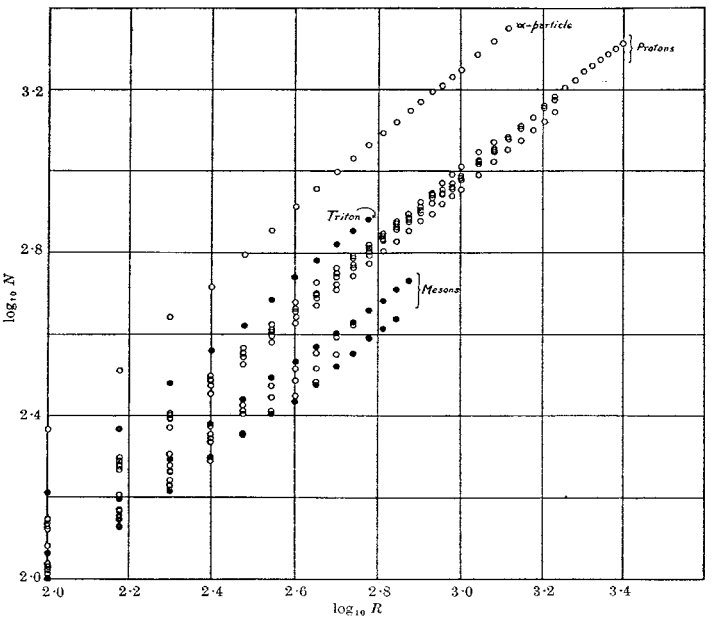



Fig. 4. $N$ IS TOTAL NUMBER OF GRAINS IN TRACK OF RESIDUAL RANGE $R$ (SCALE-DIVISIONS). 1 SCALE-DIVISION = 0·85 MICRONS

In determining the grain density in a track, we count the number of individual grains in successive intervals of length 50 $\mu$ along the trajectory, the observation being made with optical equipment giving large magnification (× 2,000), and the highest available resolving power. Typical results for protons and mesons are shown in Fig. 4. These results were obtained from observations on the tracks in a single plate, and it will be seen that there is satisfactory resolution between the curves for particles of different types. The 'spread' in the results for

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different particles of the same type can be attributed to the different degrees of fading associated with the different times of passage of the particles through the emulsion during an exposure of six weeks.

Applying these methods to the examples of the μ-decay process, in which the secondary mesons come to the end of their range in the emulsion, it is found that in every case the line representing the observations on the primary meson lies above that for the secondary particle. We can therefore conclude that there is a significant difference in the grain-density in the tracks of the primary and secondary mesons, and therefore a difference in the mass of the particles. This conclusion depends, of course, on the assumption that the π- and μ-particles carry equal charges. The grain-density at the ends of the tracks, of particles of both types, are consistent with the view that the charges are of magnitude $|e|$.

A more precise comparison of the masses of the π- and μ-mesons can only be made in those cases in which the length of the track of the primary meson in the emulsion is of the order of 600 μ. The probability of such a favourable event is rather small, and the only examples we have hitherto observed are those listed as Nos. III and VIII in Table 1. A mosaic of micrographs of a part only of the first of these events is reproduced in Fig. 1, for the length of the track of the μ-meson in the emulsion exceeds 1,000 μ. The logarithms of the numbers of grains in the tracks of the primary and secondary mesons in this event are plotted against the logarithm of the residual range in Fig. 5. By comparing the residual ranges at which the grain-densities in the two tracks have the same value, we can deduce the ratio of the masses. We thus obtain the result $m_\pi/m_\mu = 2{\cdot}0$. Similar measurements on event No. VIII give the value 1·8. In considering the significance which can be attached to this result, it must be noticed that in addition to the standard deviations in the number of grains counted, there are other possible sources of error. Difficulties arise, for example, from the fact that the emulsions do not consist of a completely uniform distribution of silver halide grains. 'Islands' exist, in which the concentration of grains is significantly higher, or significantly lower, than the average values, the variations being much greater than those associated with random fluctuations. The measurements on the other examples of μ-decay are much less reliable on account of the restricted range of the π-mesons in the emulsion; but they give results lower than the above values. We think it unlikely, however, that the true ratio is as low as 1·5.

The above result has an important bearing on the interpretation of the μ-decay process. Let us assume that it corresponds to the spontaneous decay of the heavier π-meson, in which the momentum of the μ-meson is equal and opposite to that of an emitted photon. For any assumed value of the mass of the μ-meson, we can calculate the energy of ejection of the particle from its observed range, and thus determine its momentum. The momentum, and hence the energy of the emitted photon, is thus defined; the mass of the π-meson follows from the relation

$$c^2 m_\pi = c^2 m_\mu + E_\mu + h\nu.$$

It can thus be shown that the ratio $m_\pi/m_\mu$ is less than 1·45 for any assumed value of $m_\mu$ in the range from 100 to 300 $m_e$, $m_e$ being the mass of the electron (see Table 3). A similar result is obtained if it is assumed that a particle of low mass, such as an electron or a neutrino, is ejected in the opposite direction to the μ-meson.

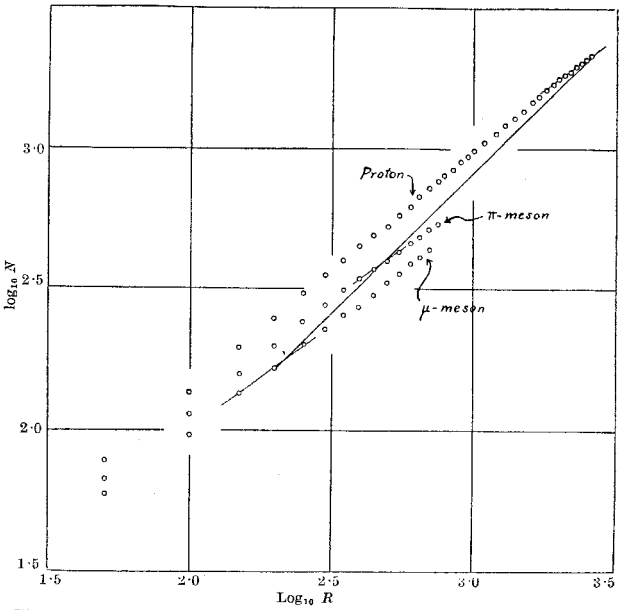



Fig. 5. $N$ IS TOTAL NUMBER OF GRAINS IN TRACK OF RESIDUAL RANGE $R$ (SCALE-DIVISIONS). 1 SCALE-DIVISION = 0·85 MICRONS
THE 45°-LINE CUTS THE CURVES OF THE MESONS AND PROTON IN THE REGION OF THE SAME GRAIN DENSITY

TABLE 3

| Assumed mass $m_\mu$ | $E$ (MeV.) | $h\nu$ (MeV.) | $m_\pi$ | $m_\pi/m_\mu \pm 3$ per cent |
|---|---|---|---|---|
| 100 $m$ | 3·0 | 17 | 140 $m_e$ | 1·40 |
| 150 | 3·6 | 23 | 203 | 1·35 |
| 200 | 4·1 | 29 | 264 | 1·32 |
| 250 | 4·5 | 34 | 325 | 1·30 |
| 300 | 4·85 | 39 | 387 | 1·29 |

On the other hand, if it is assumed that the momentum balance in the μ-decay is obtained by the emission of a neutral particle of mass equal to the μ-meson mass, the calculated ratio is about 2·1 : 1.

Our preliminary measurements appear to indicate, therefore, that the emission of the secondary meson cannot be regarded as due to a spontaneous decay of the primary particle, in which the momentum balance is provided by a photon, or by a particle of small rest-mass. On the other hand, the results are consistent with the view that a neutral particle of approximately the same rest-mass as the μ-meson is emitted. A final conclusion may become possible when further examples of the μ-decay, giving favourable conditions for grain-counts, have been discovered.

[1] *Nature*, **159**, 93, 186, 694 (1947).

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PHYSICAL REVIEW VOLUME 78, NUMBER 6 JUNE 15, 1950

# Evidence for the Production of Neutral Mesons by Photons*

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(Received April 28, 1950)

In the bombardment of nuclei by 330-Mev x-rays, multiple gamma-rays are emitted. From their angular correlation it is deduced that they are emitted in pairs in the disintegration of neutral particles moving with relativistic velocities and therefore of intermediate mass. The neutral mesons are produced with cross sections similar to those for the charged mesons and with an angular distribution peaked more in the forward direction. The production cross section in hydrogen and the production cross section per nucleon in C and Be are comparable.

## I. INTRODUCTION

NEUTRAL mesons which are coupled strongly to nuclei must be expected to be unstable against decay into two or more gamma-rays. The modes of decay, and expected lifetimes, have been discussed extensively.[1] These gamma-rays are then supposed to be responsible for the soft showers which often accompany energetic cosmic-ray nuclear events.[2] The evidence in favor of the existence of the neutral meson has recently been greatly strengthened by the discovery at Berkeley[3] of gamma-rays which behave in all ways as if they were due to the disintegration of a neutral meson. They are produced by proton bombardment of various nuclei and have a production cross section which depends on proton energy much like that of charged mesons. Their energy is approximately 70 Mev on the average, half that of the charged $\pi$-meson, and the energy spread is in agreement with the Doppler shift due to the velocity of the parent mesons. The lifetime of the mesons is less than $10^{-13}$ sec., which is in agreement with the theoretical expectations.

The evidence is therefore already much in favor of the existence of a gamma-unstable neutral meson. However, until now, coincidences between the two gamma-rays have never been observed. We report here the detection of such coincidences, produced by the bombardment of various nuclei in the x-ray beam of the Berkeley synchrotron. This must be regarded as strong additional evidence supporting the existence of the neutral meson.

## II. EXPERIMENTAL ARRANGEMENT

The apparatus is sketched in Fig. 1. The synchrotron x-ray beam of 330-Mev maximum energy is collimated in two successive collimators. The second collimator serves only to intercept some of the electrons produced at the edge of the first collimator. The beam then strikes a target, which, for most of the experiment, is a cylinder of beryllium, $1\frac{1}{2}$ inches long and 2 inches in diameter. The particles produced in the target are detected in two telescopes, each consisting of three scintillation counters. A converter, usually $\frac{1}{4}$ inch of lead, is inserted between the two crystals nearest the target in each telescope. An event is recorded if simultaneous (resolving time $10^{-7}$ sec.) pulses are recorded in the outer four crystals, but none in the two near the target. That is, we require that there be two particles, one in each telescope, neutral at first which are converted into charged particles by the lead, and which penetrate one crystal and enter the next. With a beam intensity of about $10^{11}$ Mev/min. the counting rate for such coincidences at favorable orientations of the telescopes is about 10 counts/min.

## III. NATURE OF THE COINCIDENCES

Let us first describe the experiments which identify the particles as gamma-rays, indicate their energy and show that their origin is the nuclear rather than the Coulomb field. In Table I we list the relative detection

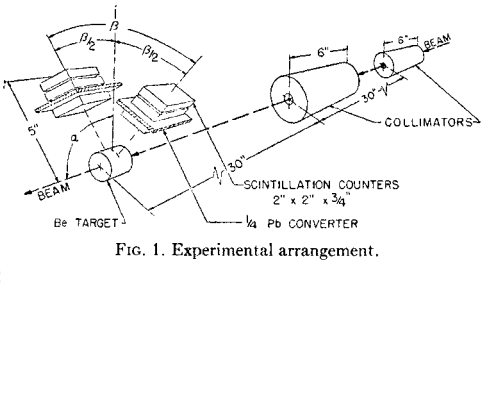



FIG. 1. Experimental arrangement.

* This work was performed under the auspices of the AEC.

[1] Y. Tanikawa, Proc. Phys. Math. Soc. Japan **24**, 610 (1940). R. J. Finkelstein, Phys. Rev. **72**, 414 (1947). H. Fukuda and Y. Miamoto, Prog. Theor. Phys. **4**, 347 (1949). Ozaki, Oneda, and Sasaki, Prog. Theor. Phys. **4**, 524 (1949). J. Steinberger, Phys. Rev. **76**, 1180 (1949). C. N. Yang, Phys. Rev. **77**, 243 (1950).

[2] The implications of the gamma-decay of neutral mesons for the soft component in the cosmic radiation were pointed out by J. R. Oppenheimer (Phys. Rev. **71**, 462 (T) (1947). It was assumed that in high energy nuclear events neutral mesons are emitted with multiplicities similar to those for charged mesons. The neutral mesons decay into photons and account for the early development of extensive showers, as well as the large total amount of soft radiation. These bursts of soft radiation accompanying energetic nuclear events were then actually observed in the cloud chamber by W. Fretter, Phys. Rev. **73**, 41 (1948), **76**, 511 (1949); C. Y. Chao, Phys. Rev. **75**, 581 (1949); Gregory, Rossi, and Tinlot, Phys. Rev. **77**, 299 (1949); and J. Green, Thesis, University of California, 1950. They were found in photographic plates by Kaplan, Peters, and Bradt, Phys. Rev. **76**, 1735 (1949). Both the cloud-chamber pictures and the photographic star show that the showers begin with gamma-rays rather than electrons.

[3] Bjorklund, Crandall, Moyer, and York, Phys. Rev. **77**, 213 (1950).



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efficiency for various converter materials and thicknesses. Without converters the counting rate is almost zero, then increases as the converter thickness in each arm is increased to $\frac{1}{4}$ inch of lead, and only slightly from $\frac{1}{4}$ inch to $\frac{1}{2}$ inch. This is as expected from shower theory for about 100-Mev photons. Copper of $\frac{1}{4}$ inch thickness has approximately the same conversion efficiency as has $\frac{1}{16}$ inch of lead, again in agreement with shower theory, since the number of shower units is the same for these thicknesses.

The coincidences are attenuated by a factor of four when $\frac{1}{4}$ inch of lead is inserted between the target and the anticoincidence crystals. This again is as expected for photons. Furthermore, it can be seen from Table I that both telescopes require converters, so that both particles must be photons.

To measure the energy of the conversion electrons, aluminum absorbers were inserted between the last two crystals of one of the telescopes. Unfortunately, at these energies the radiation losses are important, and therefore the straggling large. We have plotted in Fig. 2 the coincidence counting rate as a function of the average energy required to traverse the telescope. Because the photons originate in moving mesons, the average gamma-ray energy is expected to be approximately 100 Mev, and the average electron energy 50 Mev, quite in agreement with the observed attenuation.

The nuclear origin of the photons is demonstrated by the fact that the cross section for these coincidences is only six times as big for a lead nucleus as for beryllium, which is less than the ratio of the nuclear areas. On the other hand, ordinary shower cross sections increase by a factor of 400.

Finally, we have looked for coincidences with the beam energy reduced to about 175 Mev with angles $\alpha$ and $\beta$ of the telescope both 90°. The cross section per $Q$ (the number $Q$ for a bremsstrahlung beam is equal to the total energy divided by the maximum energy of the spectrum) is at least 50 times smaller here than at 330 Mev. This steep excitation function is also observed for charged meson production.

We believe, therefore, that it is demonstrated that the observed coincidences are caused by gamma-rays of about 100-Mev average energy, of non-Coulombic origin, and with a threshold similar to that for charged mesons.

## IV. ANGULAR CORRELATION AND DISTRIBUTION OF THE GAMMA-RAYS

To study further the properties of these coincidences, we have measured their rate as a function of the angle, $\alpha$, between the beam direction and the plane of the telescopes and of the correlation angle $\beta$ (see Fig. 1). Consider first the variation with $\beta$ at a fixed $\alpha$, say 90°. 180° coincidences are rare. The counting rate increases with decreasing $\beta$ to a maximum at 90°, and then drops sharply. This behavior must actually be expected of gamma-rays which are the decay products of neutral

TABLE I. Relative detection efficiency as a function of absorber material and thickness.

| Converter in telescope 1 | Converter in telescope 2 | Relative counting rate $\alpha=\beta=90°$ |
|---|---|---|
| none | none | 0.01±0.005 |
| $\frac{1}{32}$-in. Pb | $\frac{1}{32}$-in. Pb | 0.17±0.013 |
| $\frac{1}{16}$-in. Pb | $\frac{1}{16}$-in. Pb | 0.3 ±0.02 |
| $\frac{1}{8}$-in. Pb | $\frac{1}{8}$-in. Pb | 0.67±0.08 |
| $\frac{1}{4}$-in. Pb | $\frac{1}{4}$-in. Pb | 1.00±0.06 |
| $\frac{1}{4}$-in. Cu | $\frac{1}{4}$-in. Cu | 0.39±0.03 |
| none | $\frac{1}{4}$-in. Pb | 0.15±0.05 |
| $\frac{1}{16}$-in. Pb | $\frac{1}{4}$-in. Pb | 0.62±0.07 |
| $\frac{1}{2}$-in. Pb | $\frac{1}{4}$-in. Pb | 1.07±0.1 |
| $\frac{1}{4}$-in. Pb | $\frac{1}{4}$-in. Pb | 0.28±0.05 |

$\frac{1}{4}$-in. Pb absorbers placed in front of both telescopes.

mesons, because of the motion of the decaying mesons. A meson at rest decaying into two gamma-rays, emits them in opposite direction. But when this is seen from a system in which the meson has a total energy $E$, then the included angle $\beta$ varies between $\pi$ and $2\sin^{-1}(1/E)$ with a probability which favors the small angles tremendously. The median angle is $2\sin^{-1}[2/(3E^2+1)^{\frac{1}{2}}]$. $E$ is the total meson energy in units of its rest energy.

For 70-Mev mesons the minimum angle of $\beta$ is 84° and the median angle 92°. Since the distribution is so heavily peaked, not much error is introduced if one assumes, as is done in the following, that to an angle $\beta$ corresponds a unique energy, that of the median angle. Therefore a measurement of the distribution in $\beta$ is a measure of the distribution in energy of the neutral mesons, although the angular resolution of our telescopes is insufficient to give more than a glimpse of the energy distribution. We have included in Fig. 3 curves in which the observed[4] energy distributions of the $\pi^+$-meson made by the same x-rays on hydrogen are transformed into distributions in $\beta$ and arbitrarily normalized. All corrections due to scattering and angular resolution are omitted. The general shape of the curves is certainly well reproduced by the experiment. It is

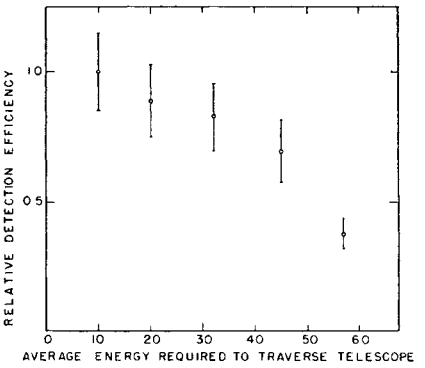



FIG. 2. Absorption of conversion electrons in aluminum. The energy includes the average radiation loss.

[4] Bishop, Cook, and Steinberger (to be published).

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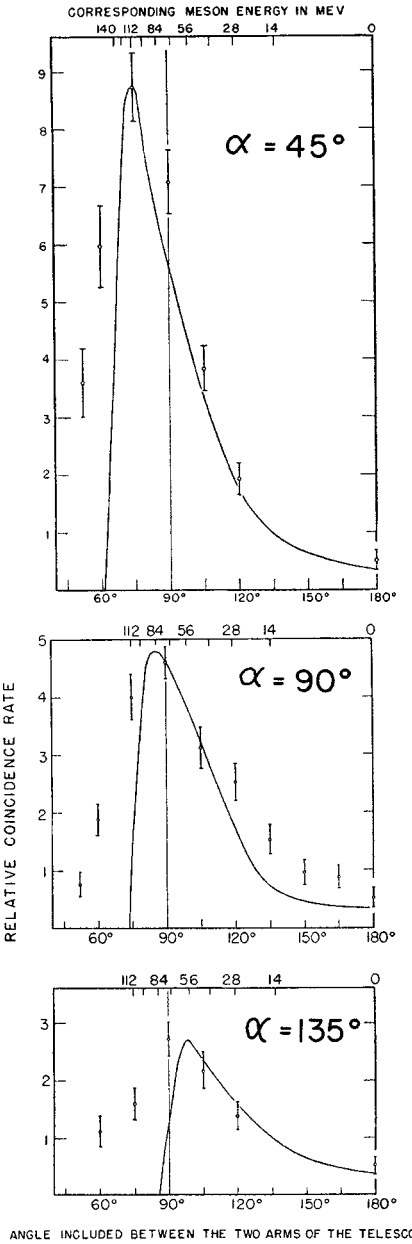



FIG. 3. Variation of coincidence rate with the included angle $\beta$ between the two arms of the telescope. The curves are those expected on the assumption that the gamma-rays are the decay products of a neutral meson, emitted with the same energy distribution as are $\pi^+$-mesons from hydrogen. The curves are arbitrarily normalized for each angle $\alpha$.

therefore clear that if the gamma-rays are the decay product of intermediate particles, these particles must move with velocities of the order of $v/c \simeq 0.8$. Excited nucleons of this velocity cannot be produced by x-rays of 330 Mev; the particles must therefore have an intermediate mass. Furthermore, it is possible to see that the decay must be into only 2 photons, since the expected angular distributions for a decay into more than two photons would not show a valley for small angles $\beta$.

The distribution in the angle $\alpha$ of the beam with the plane of the telescope shown in Fig. 4, is interesting chiefly because of the difference between this distribution and the angular distribution of $\pi^+$-photo-mesons[5] from either carbon or hydrogen targets. This is not particularly surprising, since various theories also give quite different results for charged and neutral mesons.

## V. HYDROGEN CROSS SECTION AND TOTAL CROSS SECTION

At one setting of the telescopic angles, $\alpha = \beta = 90°$, we have compared the cross sections of hydrogen and carbon. This was done by comparing the count from a polyethylene ($CH_2$) block and a perforated carbon block of the same size and carbon content as the $CH_2$. The result is: $\sigma H_{\pi^0}/\sigma C_{\pi^0} = 0.12 \pm 0.03$. This again differs from the results for positive mesons, where $\sigma H_{\pi^+}/\sigma C_{\pi^+} \simeq 0.55$. The difference is probably in part caused by the fact that both neutrons and protons can contribute to neutral meson production, but only protons to $\pi^+$-production. In part, it may also be possible to ascribe this to the same phenomenon which, according to Chew,[6] is responsible for the large hydrogen-carbon ratio for the positive mesons. In the case of $\pi^+$-production, the reaction is inhibited by the fact that, when the proton is changed into a neutron, there is an oversupply of neutrons in the immediate neighborhood and the number of states available to it is small because of the Pauli principle. This is not significant in the neutral case because the nucleon's charge does not change.

The curves in Fig. 3 can be integrated to yield a total cross section for beryllium. $\sigma_{Be} = 7.5 \times 10^{-28}$ cm$^2$ per $Q$, while for carbon and hydrogen, assuming the same angular distribution, $\sigma_C = 10 \times 10^{-28}$ and $\sigma_H = 1.3 \times 10^{-28}$ cm$^2$ per $Q$. The absolute x-ray intensity is known[7] to about 10 percent, but the efficiency of the detecting system only to within a factor of two, so that there is a corresponding error in the above cross sections. The hydrogen cross section is approximately the same as that for $\pi^+$-production;[5] those for carbon and beryllium are somewhat higher.[8]

One might assume that the charge of the meson would play an important role in the production of mesons in the electromagnetic field of the photon. This

[5] J. Steinberger and A. S. Bishop, Phys. Rev. **78**, 493 (1950).
[6] G. Chew (private communication).
[7] Blocker, Kenney, and Panofsky (to be published).
[8] McMillan, Peterson, and White, Science **110**, 579 (1949).

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is contradicted by the observed angular distribution of $\pi^+$-mesons produced by photons in $H_2$. The angular distribution indicates that the principal process responsible for charged meson production is the interaction of the photon with the spin of the nucleon. If the neutral meson has the same transformation properties as the charged, it then appears plausible that the production cross sections in hydrogen should be comparable, as seems to be the case. However, actual calculations on the basis of pseudoscalar theory, both in the classical and in the perturbation theory approximation, which give a reasonable angular distribution for the $\pi^+$-production, give smaller values for neutral meson production. Whether or not this is a new difficulty in a theory which already has several, is not clear. From a less restricted point of view it is not a surprising result.

## VI. SUMMARY

In the bombardment of various nuclei by 330-Mev x-rays, photons with the following properties are emitted:

(1) At least two are emitted in coincidence.
(2) They each have an average energy of about 100 Mev.
(3) The $Z$ dependence of the production indicates that they have their origin in a nuclear interaction, and not in the Coulomb field.
(4) The threshold for their production is at least 150 Mev.
(5) The angular correlation of the photons shows that they are emitted in pairs as the only decay products of particles moving with velocities of the order of $v/c=0.8$, and therefore of intermediate mass.
(6) The total cross section for production from hydrogen is about the same as that for production of $\pi^+$-mesons; other light nuclei cross sections are somewhat higher than those for the positive mesons.

It is clear from these properties that the gamma-rays are the decay products of neutral mesons. Since spin $\frac{1}{2}$, and spin 1 mesons are forbidden to decay into two photons,[1] the spin must be zero, excluding the possibility of very high intrinsic angular momenta. It seems reasonable, and it is in good agreement with all observations, to assume that both charged and neutral mesons are of the same type. It then follows from the angular distribution of the x-ray produced $\pi^+$-mesons, and the high cross sections for making neutral mesons by x-rays, that the $\pi$-meson is a pseudoscalar. This remark applies, of course, only to the character of the meson, and not to any particular field theory for the interaction of mesons with nucleons.

All phases of this experiment have been discussed with Professor Edwin McMillan and his advice has been of great help. The bombardments were carried out by the synchrotron crew under the direction of W. Gibbons.

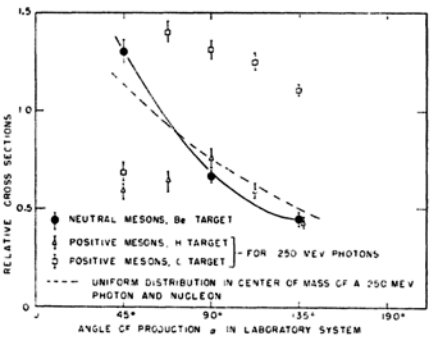



FIG. 4. Variation with the angle $\alpha$ between the plane of the telescope and the beam. Each point represents an integral over the angle $\beta$.

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PHYSICAL REVIEW VOLUME 83, NUMBER 3 AUGUST 1, 1951

# The Spin of the Pion via the Reaction $\pi^+ + d \rightleftharpoons p + p$

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(Received June 21, 1951)

It is possible to determine the spin of the pion by comparing the forward and backward rates of the reaction $\pi^+ + d \rightleftharpoons p + p$. The backward rate has been measured in Berkeley. We have measured the forward rate. Comparison of the two results shows the spin to be zero. In the light of other recent experimental results the meson is then pseudoscalar.

DURING the past few years there has accumulated an increasing amount of evidence that the pion is pseudoscalar. This consists chiefly of the following:

(a) The pion has integral spin. This follows from star formation in the capture of $\pi^-$ mesons in photographic emulsions, as well as from angular momentum conservation in such reactions as $p+p \rightarrow \pi^+ + d$; $p + h\nu \rightarrow \pi^+ + n$.

(b) The neutral pion does not have spin one, since it decays into two $\gamma$-rays and such a transition is forbidden for systems with angular momentum $\hbar$.[1]

(c) Because of their similar masses and their similar nuclear production cross sections, as well as from the evidence on charge independence of nuclear forces, it is likely that neutral and charged mesons have the same transformation properties, so that charged pions also cannot have spin one.

(d) The pion is not scalar. This follows from the experiment on the capture of stopped negative pions in deuterium,[2] as well as the results on the production of pions, both charged and uncharged, by $\gamma$-rays.[3] Both experiments give best theoretical agreement in the pseudoscalar meson theory. It has therefore appeared quite probable that the pion is pseudoscalar; but the evidence, especially against a spin of two or greater, is poor.

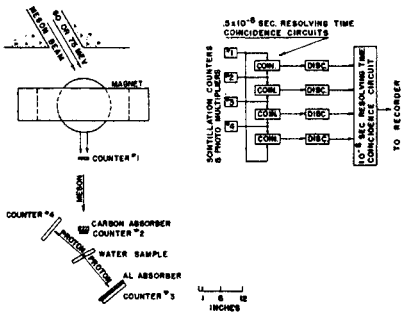



FIG. 1. Arrangement of the beam collimation, water sample, and detectors. Block diagram of circuits.

It has been pointed out by Cheston and Marshak[4] that the reaction $\pi^+ + d \rightleftharpoons p + p$ lends itself to a determination of the spin of the pion. The forward and backward reactions are related by a detailed balancing argument, if one assumes initially unpolarized particles, so that

$$\frac{d\sigma(\rightarrow)}{d\Omega} \Big/ \frac{d\sigma(\leftarrow)}{d\Omega} = \frac{4}{3} \frac{p^2}{q^2(2s+1)},$$

where $s$ is the spin of the meson, and $p$, $q$, are the momenta of the proton and meson in the center-of-mass system. The cross sections, of course, are also in the center-of-mass system. The argument is rigorous, independent of meson theory, and in this rests its chief contribution. The reaction $p+p \rightarrow \pi^+ + d$ has been measured by Cartwright, Richman, Whitehead, and Wilcox[5] for 340-Mev protons, corresponding to a meson energy of 21 Mev in the center-of-mass system. We present here results on the inverse reaction.

The experimental arrangement is shown in Fig. 1. The Nevis cyclotron delivers a beam of approximately 20 positive mesons per square centimeter per second outside the concrete shielding. These are produced when the 380-Mev protons strike an internal Be target. The mesons are magnetically analyzed in the fringing field of the cyclotron, and by a small magnet outside the shielding. The energy resolution is $\pm 4$ Mev at 75 Mev and the composition of the beam is 90 percent $\pi^+$, and 10 percent $\mu^+$ mesons.[6] The beam is defined by the

* This research has been supported by a joint program of the ONR and AEC.

[1] Steinberger, Panofsky, and Steller, Phys. Rev. **78**, 802 (1950); C. N. Yang, Phys. Rev. **77**, 242 (1950).

[2] Panofsky, Aamodt, and Hadley, Phys. Rev. **82**, 97 (1951); Brueckner, Serber, and Watson, Phys. Rev. **81**, 575 (1951).

[3] Bishop, Steinberger, and Cook, Phys. Rev. **80**, 291 (1950).

[4] R. E. Marshak, Phys. Rev. **82**, 313 (1951); W. B. Cheston, to be published.

[5] Cartwright, Richman, Whitehead, and Wilcox, Phys. Rev. **81**, 652 (1951); V. Peterson, Phys. Rev. **79**, 407 (1950); C. Richman and M. H. Whitehead, to be published. We are most indebted to Professors Richman and Wilcox, Mr. Cartwright, and Miss Whitehead for the privilege of quoting as yet unpublished results, and in particular, the fine meson spectrum shown in Fig. 5.

[6] The beam is analyzed in the following way: Heavy particles and electrons are detected in a measurement of the velocity distribution of the beam particles by means of a time of flight measurement. The mesons have velocities $\sim 0.7c$, the electrons which penetrate the counters have the velocity of light, and heavy particles have smaller velocities. The $\mu$-mesons are measured at the end of their range by means of the delayed coincidences of their electron decay product. This is only possible in the $\pi^-$ beam, since $\pi^+$ mesons at the end of their range are not captured but produce $\mu^+$ mesons and interfere. We have assumed that, since the $\mu$-mesons in the beam are the result of the decay in flight of the $\pi$-meson and since $\pi^-$ and $\pi^+$ mesons have at least approximately the same lifetime [Lederman, Booth, Byfield, and Kessler,



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crystal scintillation counters 1 and 2, and the energy reduced in the carbon absorber. The liquid scintillation counters 3 and 4 are set with respect to the water sample so that protons emitted 180° apart in the center-of-mass system of the meson and deuteron will be detected.[7] The water sample is 2.5 g/cm² thick. The aluminum absorber in front of counter No. 3 is thin enough to transmit the protons emitted in the meson absorption under study, but stops scattered protons or deuterons. The difference in counting rate using heavy water and light water targets is entirely due to the reaction $\pi^+ + d \rightarrow p + p$. It is in principle quite easy to check that this is so. In actuality, the counting rate is small and only a limited number of checks have been made, to wit: (1) Plateau. In the beginning of each experiment the counters are placed so that the meson beam penetrates all four, and the voltages (amplification) of the phototubes adjusted so that mesons are detected with full efficiency. But the proton pulses in counters 3 and 4 should be larger by a factor two or three than the

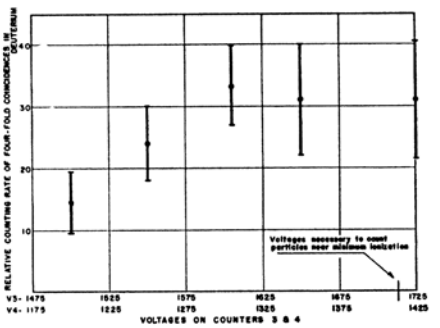



FIG. 2. Counting rate of fourfold events after subtraction, as a function of phototube voltage (amplification) in the proton detection counters 3 and 4.

meson pulses. Figure 2 shows that the pulses responsible for the subtracted fourfold coincidences are large. The $D_2O - H_2O$ difference is counted with full efficiency at voltages 100 volts (i.e., a factor of two in gain) below those necessary to count mesons. (2) When counters 3 and 4 were moved out of line to angles improper for the detection of protons with 180° c.m. angular correlation, no events were observed within statistical accuracy.

Figure 3 shows the energy dependence of the reaction at 45° in the c.m. system. It is sufficiently flat that errors due to energy spread of the meson beam and finite target thickness are small.

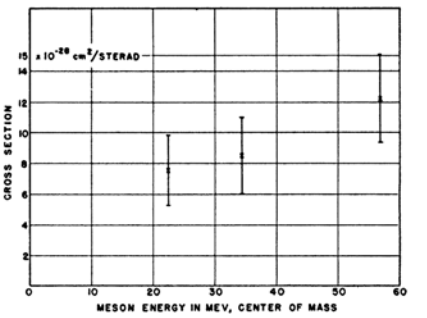



FIG. 3. Differential cross section for the emission of a proton at 45° (and one at 135°) to the meson beam in the c.m. system.

The results on the differential cross section at three angles are shown in Fig. 4. They are the combined results of three determinations, under conditions which varied somewhat. For instance, counters No. 3 and No. 4 were sometimes 4½ in. and at other times 8 in. in diameter. The average meson energy in the target for the three runs was 28 Mev. The data are corrected for the geometrical efficiency of the detecting system which varied from 0.48 to 0.84, for the beam composition (90 percent $\pi^+$, 10 percent $\mu^+$), for the nuclear absorption of the mesons and the protons in the target (7 percent), and for an inefficiency of 8 percent in the circuits due to blocking.

The cross sections expected under the assumption of spins zero and one, on the basis of the results of Cartwright, Richman, Whitehead, and Wilcox, and of Peterson[5] are also shown. The Berkeley group has measured the energy distribution of mesons produced in the bombardment of hydrogen by 340 Mev protons.

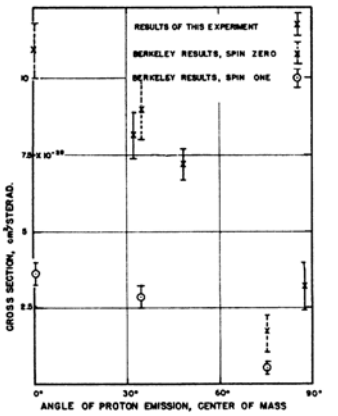



FIG. 4. Differential cross section of the reaction $\pi^+ + d \rightleftharpoons p + p$ at three angles of emission of the proton in the c.m. system. The average meson energy is 28 Mev in the c.m. system. The dotted points show the cross sections expected for spin one and spin zero pions on the basis of the Berkeley results (see reference 5).

Phys. Rev. 83, 686 (1951)], the $\mu$-contamination is independent of charge.

[7] The center-of-mass transformation is small, approximately 0.05$c$. The correlation angles in the laboratory system do not differ from 180° by more than 15°. Angular distribution measurements are easier in this reaction than in the inverse, where the large center-of-mass transformation results in a large variation of experimental conditions with angle.

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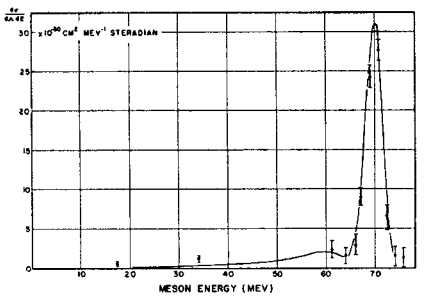



FIG. 5. The spectrum of mesons produced in the collision of 340 Mev protons in the forward direction. This experiment has been performed by Cartwright, Richman, Whitehead, and Wilcox (see reference 5).

(See Fig. 5.) This spectrum consists of a continuum due to the reaction $p+p\rightarrow\pi^{+}+n+p$, and a sharp peak at an energy which exceeds the theoretical limit of the continuum and is due to the reaction $p+p\rightarrow\pi^{+}+d$.[8] The cross section is obtained by integrating the energy spectrum under the peak.

Comparison of the two results shows that the $\pi^{+}$ meson spin is zero, quite outside the possible limits of error in the two experiments. Combining this result with those of Panofsky[2] and those on the photomeson production,[3] the meson is very likely pseudoscalar.

It is necessary to point out that the same ratio of cross sections could be obtained also for non-zero spin mesons provided that pions were completely polarized both in the $p+$Be and $p+p$ meson production reactions. Such polarization is theoretically possible, but only in the longitudinal mode, that is, in the mode with zero component of angular momentum along the propagation axis. This seems a rather remote possibility.

A similar experiment has been performed by D. L. Clark, A. Roberts, and R. Wilson, who have reached the same conclusions. We are indebted to them for a pre-publication copy of their results.

The experiment is being continued. The reaction is interesting also in other connections. As Bethe[9] has pointed out, the angular distribution is quite perplexing. Furthermore, the energy dependence will shed some light on the momentum dependence of the meson nucleon interaction. We are therefore in the process of measuring the angular distribution at several energies.

We wish to acknowledge our indebtedness to the engineering staff of the Nevis Cyclotron Laboratory, especially Mr. Harrison Edwards and Mr. Julius Spiro.

[8] The actual production of deuterons in coincidence with mesons has been observed by Crawford, Crowe, and Stevenson, Phys. Rev. **82**, 97 (1951).

[9] H. A. Bethe, letter to R. E. Marshak with copies to C. Richman and J. Steinberger. We wish to express our thanks to Professor Bethe for this communication.

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