3

Strangeness

The discoveries of the strange particles, 1943–1959.

The elucidation of the $\pi \rightarrow \mu\nu$ decay sequence left particle physics in a relatively simple state. Yukawa's particle had been found and the only unanticipated particle was the muon, of which I. I. Rabi is said to have remarked "Who ordered that?" The question remains unanswered. The cosmic-ray experiments of the next few years quickly and thoroughly destroyed the simplicity that had previously prevailed. The proliferation of new particles, many with several patterns of decay, produced great confusion. The primary source of confusion was whether each new decay mode represented a new particle or was simply an alternative decay for a previously observed particle. Continued experimentation with improved accuracy and statistics eventually resolved these ambiguities, but basic uncertainties remained. What was the nature of these particles? How were they related to the more familiar particles? The examination of these questions led to the development of the concepts of associated production, strangeness, and ultimately, parity violation and $SU(3)$.

Remarkably, another meson seems to have been discovered before the pion. Working in the French Alps in 1943, Leprince-Ringuet and L'héritier took 10,000 triggered pictures in a 75 cm x 15 cm x 10 cm cloud chamber placed inside a magnetic field of 2500 gauss **(Ref. 3.1)**. This permitted careful measurements of the momenta of the charged tracks. One of the pictures showed an incident positive particle of about 500 MeV/c momentum produce a secondary of about 1 MeV/c. By assuming the incident particle had scattered elastically on an electron and using the measured angles, Leprince-Ringuet and L'héritier determined the mass of the incident particle to be 990 $m_e \pm 12\%$ (506 ± 61 MeV), astonishingly close to the mass of the K^+. It was impossible that this could have been a π (whose mass was known shortly after the French result was finally published in 1946). Hans Bethe showed that the data were consistent with the incident particle being a proton only if extreme errors were assigned to the measurements.

Cosmic-ray research just after World War II centered in a few laboratories, including Bristol, whose group was led by Powell; Manchester, led by Blackett; Ecole Polytechnique headed by Leprince-Ringuet; Caltech, headed by Anderson; and Berkeley, led by Brode and Fretter. In 1947, the year of the $\pi \rightarrow \mu\nu$ paper of Lattes, Occhialini, and Powell, G. D. Rochester and C. C. Butler published two cloud chamber pictures showing forked

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Table 3.1. *Comparison of old and current nomenclature for selected decays.*

Old	Current	
τ	$K^+ \to \pi^+\pi^+\pi^-$	$(K_{\pi 3})$
V_1^0	$\Lambda^0 \to p\pi^-$	
$V_2^0(\theta^0)$	$K_S^0 \to \pi^+\pi^-$	
κ	$K^+ \to \mu^+\nu_\mu$	$(K_{\mu 2})$
	$K^+ \to \mu^+\pi^0\nu_\mu$	$(K_{\mu 3})$
$\chi(\theta^+)$	$K^+ \to \pi^+\pi^0$	$(K_{\pi 2})$
V^+, Λ^+	$\Sigma^+ \to p\pi^0, n\pi^+$	

tracks **(Ref. 3.2)**. One proved to be the decay of a neutral particle into two charged particles and the other, the decay of a charged particle into another charged particle and at least one neutral. Whereas the event of Leprince-Ringuet and L'héritier may have established the existence of a particle with mass between the pion and the proton, the discovery of Rochester and Butler was much more revealing. It showed there were unstable particles decaying into other particles, perhaps pions. These unstable particles could be either charged or neutral, and had lifetimes on the scale of 10^{-9} to 10^{-10} s.

Surprisingly, the discovery of Rochester and Butler was not confirmed for over two years. Before that occurred, the Bristol group, using emulsions of increased sensitivity, observed the decay of a charged particle into three charged particles (**Ref. 3.3**). This particular decay came to be known as the tau meson. A guide to some of the old notation for the unstable particle decays is given in Table 3.1.

Confirmation of the events of Rochester and Butler was produced by the group at Caltech, which included C. D. Anderson, R. B. Leighton, and E. W. Cowan. Both neutral- and charged-particle decays were observed in their cloud chamber exposures, but no accurate estimate of the masses of the decaying particles was possible. A year later, in 1951, the Manchester group published results they obtained by taking their cloud chamber to the Pic-du-Midi in the Pyrenees. Studying the neutral decays, they were able to infer the existence of two distinct neutral particles, V_1^0 and V_2^0.

The progress on the charged-particle decays was slower. There was confirmation of the tau meson decay. In addition, O'Ceallaigh, working at Bristol, produced emulsion evidence for the decay of a charged particle into a μ^+ and one or more neutrals, the κ decay (Ref. 3.4). In one exposure, the μ^+ was convincingly identified through its decay into e^+. (See Figure 3.1).

While the tau meson mass had been measured quite well, the mass of the V_2^0 or θ^0 was not determined until the work of R. W. Thompson and co-workers at Indiana University (**Ref. 3.5**). They were able to establish a Q value for the decay of 214 MeV, in good agreement with the present value ($M_K - 2M_\pi = 219$ MeV). This indicated that the tau and

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Figure 3.1. A κ (K) meson stops at P, decaying into a muon and neutrals. The muon decays at Q to an electron and neutrals. The muon track is shown in two long sections. Note the lighter ionization produced by the electron, contrasted with the heavy ionization produced by the muon near the end of its range. The mass of the κ was measured by scattering and grain density to be 562 ± 70 MeV (Ref. 3.4).

theta mesons had just about the same mass and set the stage for the famous puzzle about the parities of these particles.

The year 1953 marked a turning point in the investigation of the new V-particles. The great achievements of cosmic-ray physics in exploring the new particles was summarized

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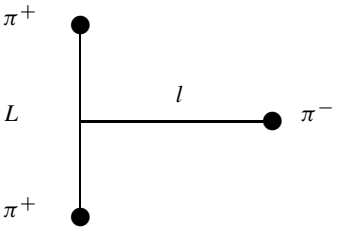


Figure 3.2. Diagram for the angular momentum in τ^+ meson decay. The $\pi^+\pi^+$ angular momentum, L, must be even. The orbital angular momentum, l, of the π^- must be added to L to obtain the total angular momentum (that is, the spin) of the tau.

in a meeting at Bagnères-de-Bigorre in France. The V_1^0 was well established, as was the tau. There were indications of both positive and negative hyperons (particles heavier than a proton). The negative hyperon was observed in a cascade that produced a neutral hyperon that itself decayed (Refs. 3.6, 3.7) There was a κ, which decayed into a muon plus neutrals, and a χ, which decayed into a charged pion plus neutrals. The $\theta \rightarrow \pi^+\pi^-$ was established, too.

At the Bagnères Conference, Richard Dalitz presented his analysis of the tau that was designed to determine its spin and parity through its decay into three pions. Some immediate observations about the spin and parity of the tau are possible. If there is no orbital angular momentum in the decay, the spin is zero and the parity is $(-1)^3$ because the parity of each pion is -1, and thus $J^P = 0^-$. The system of $\pi^+\pi^+$ can have only even angular momentum because of Bose statistics. Dalitz indicated this angular momentum by L and the orbital angular momentum of the system consisting of the π^- and the $(\pi^+\pi^+)$ by l. See Figure 3.2. Then the total angular momentum, J, was the vector sum of L and l. If $L = 0$, then $J = l$, and $P = (-1)^{J+1}$. For $L = 2$, other combinations were possible. Dalitz noted that since the sum of the pion energies was a constant, $E_1 + E_2 + E_3 = Q$, each event could be specified by two energies and indicated on a two-dimensional plot. (Here we are using kinetic energies, that is relativistic energies less rest masses.) If E_1 corresponds to the more energetic π^+ and E_2 to the less energetic π^+, all the points fall on one half of the plot. See Figure 3.3. If the decay involves no angular momentum and there are no effects from interactions between the produced pions, the points will be evenly distributed on the plot. Deviations from such a distribution give indications of the spin and parity. For example, as $E_3 \rightarrow 0$, the π^- is at rest and thus has no angular momentum. Thus $l = 0$, $J = L$ and $P = (-1)^{J+1}$. Hence if the tau is *not* in the sequence $0^-, 2^-, 4^-, \ldots$ there should be a depletion of events near $E_3 = 0$. As data accumulated in 1953 and 1954, it became apparent that there was no such depletion and thus it was established that τ^+ had J^P in the series $0^-, 2^-, \ldots$

The decay distribution for a two-body decay is given by Fermi's Golden Rule (which is actually due to Dirac) in relativistic form:

$$d\Gamma = \frac{1}{32\pi^2}|\mathcal{M}|^2 \frac{p_{cm} d\Omega}{M^2}. \tag{3.1}$$

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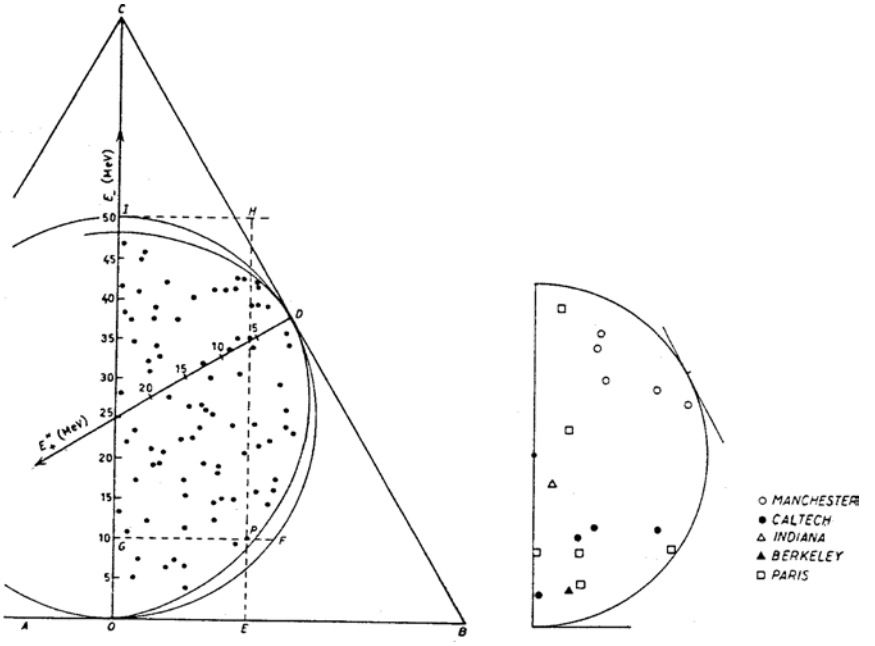


Figure 3.3. Dalitz plots showing worldwide compilations of tau meson decays ($\tau^+ \to \pi^+\pi^+\pi^-$) as reported by E. Amaldi at the Pisa Conference in June 1955 [*Nuovo Cimento Sup.* IV, 206 (1956)]. On the left, data taken in emulsions. On the right, data from cloud chambers. There is no noticeable depletion of events near $E_3 = 0$, *i.e.* near the bottom center of the plot. Parity conservation would thus require the tau to have $J^P = 0^-, 2^-$.

Here $d\Gamma$ is the decay rate, p_{cm} is the center-of-mass momentum of either final state particle, M is the mass of the decaying particle and $d\Omega$ is the solid angle element into which one final state particle passes. $\mathcal{M}$ is the Lorentz-invariant amplitude for the process. The amplitude $\mathcal{M}$ will involve the momenta of the various particles and factors to represent the spins of the particles.

For three-body decays there are more final state variables. If the particles are spinless or if polarization is ignored, however, there are only two variables necessary to specify the final state. They may be chosen to be the energies of the final state particles. The Golden Rule then takes the form

$$d\Gamma = \frac{1}{64\pi^3 M}|\mathcal{M}|^2 dE_1 dE_2. \tag{3.2}$$

Thus if $\mathcal{M}$ is constant, $d\Gamma \sim dE_1 dE_2$ and the events fall evenly on the Dalitz plot.

By examining the Dalitz plot, inferences can be drawn about spin and parity. Consider the $\tau \to 3\pi$. If the tau is spinless and the values of L and l are zero, $\mathcal{M}$ should be nearly constant. (Actually, it need not be absolutely constant. It may still depend on the Lorentz-invariant products of the momenta in the problem.) Suppose, on the contrary, tau has spin 1. Then it will be represented by a polarization vector, ϵ. The amplitude must be linear in ϵ. If we treat the pions as nonrelativistic, it suffices to consider just three-momenta rather than four-momenta. The amplitude, in order to be rotationally invariant, must be the dot product of ϵ with a vector made from the various pion momenta. In addition, because of Bose statistics, the amplitude must be invariant under interchange of the two

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π^+'s, particles 1 and 2. Two examples are

$$\epsilon \cdot \mathbf{p}_3$$
$$\epsilon \cdot (\mathbf{p}_1 - \mathbf{p}_2) \times \mathbf{p}_3 \; (\mathbf{p}_1 - \mathbf{p}_2) \cdot \mathbf{p}_3$$

Both represent spin-1 decays. The parity of the decaying object, assuming parity is conserved in the decay, is determined by examining the behavior of the quantity dotted into ϵ. In the first case, the single momentum contributes (-1) to the parity since the momenta are reversed by the operation. In addition, the intrinsic parities of the three pions contribute $(-1)^3$. Altogether, the parity is even, so the state is $J^P = 1^+$. In the second instance, there are four factors of momentum and the parity is finally odd. In both cases, the amplitude vanishes as p_3 goes to zero in accordance with the earlier argument.

Dalitz's analysis led ultimately to the τ–θ puzzle: were the θ^+ (which decayed into $\pi^+\pi^0$) and τ^+, whose masses and lifetimes were known to be similar, the same particle? Of course this would require them to have the same spin and parity. But the parity of the $\theta^+ \rightarrow \pi^+\pi^0$ was necessarily $(-1)^J$ if its spin was J. These values were incompatible with the results for the tau showing that it had J^P in the sequence $0^-, 2^-, \ldots$. How this contradiction was resolved will be seen in Chapter 6.

Cosmic-ray studies had found evidence for hyperons besides the $\Lambda = V_1^0$. Positive particles of a similar mass were observed and initially termed V_1^+ or Λ^+. Evidence for this particle, now called the Σ^+, was observed by Bonetti *et al.* (Ref. 3.8) in photographic emulsion, and by York *et al.* (Ref. 3.9) in a cloud chamber. See Figure 3.4. Furthermore, a hyperfragment, which is a Λ or Σ^+ bound in a nucleus, was observed by Danysz and Pniewski in photographic emulsion (Ref. 3.10). See Figure 3.5. Working at Caltech, E. W. Cowan confirmed the existence of a negative hyperon (now called the Ξ^-) that itself decayed into $\Lambda^0\pi^-$ (Ref. 3.11).

By the end of the year 1953, the Cosmotron at Brookhaven National Laboratory was providing pion beams that quickly confirmed the cosmic-ray results and extended them. The existence of the V_1^+ (Σ^+) was verified and the V_1^- (Σ^-) was discovered. An especially important result was the observation of four events in which a pair of unstable particles was observed (**Ref. 3.12**). Such events were expected on the basis of theories that Abraham Pais and Murray Gell-Mann developed to explain a fundamental problem posed by the unstable particles. These unstable particles were clearly produced with a large cross section, some percent of the cross section for producing ordinary particles, pions and nucleons. The puzzle was this: The new particles were produced in strong interactions and decayed into strongly interacting particles, but if the decays involved strong interactions, the particle lifetimes should have been ten orders of magnitude less than those observed.

The first step in the resolution was made by Pais, who suggested that the new particles could only be made in pairs. One could assign a multiplicative quantum number, a sort of parity, to each particle, with the pion and nucleon carrying a value +1 and the new particles, K, Λ, etc. carrying -1. The product of these numbers was required to be the same in the initial and final state. Thus $\pi^- p \rightarrow K^0\Lambda$ would be allowed, but $\pi^- p \rightarrow K^0 n$ would be forbidden. The Cosmotron result on the production of pairs of unstable particles was

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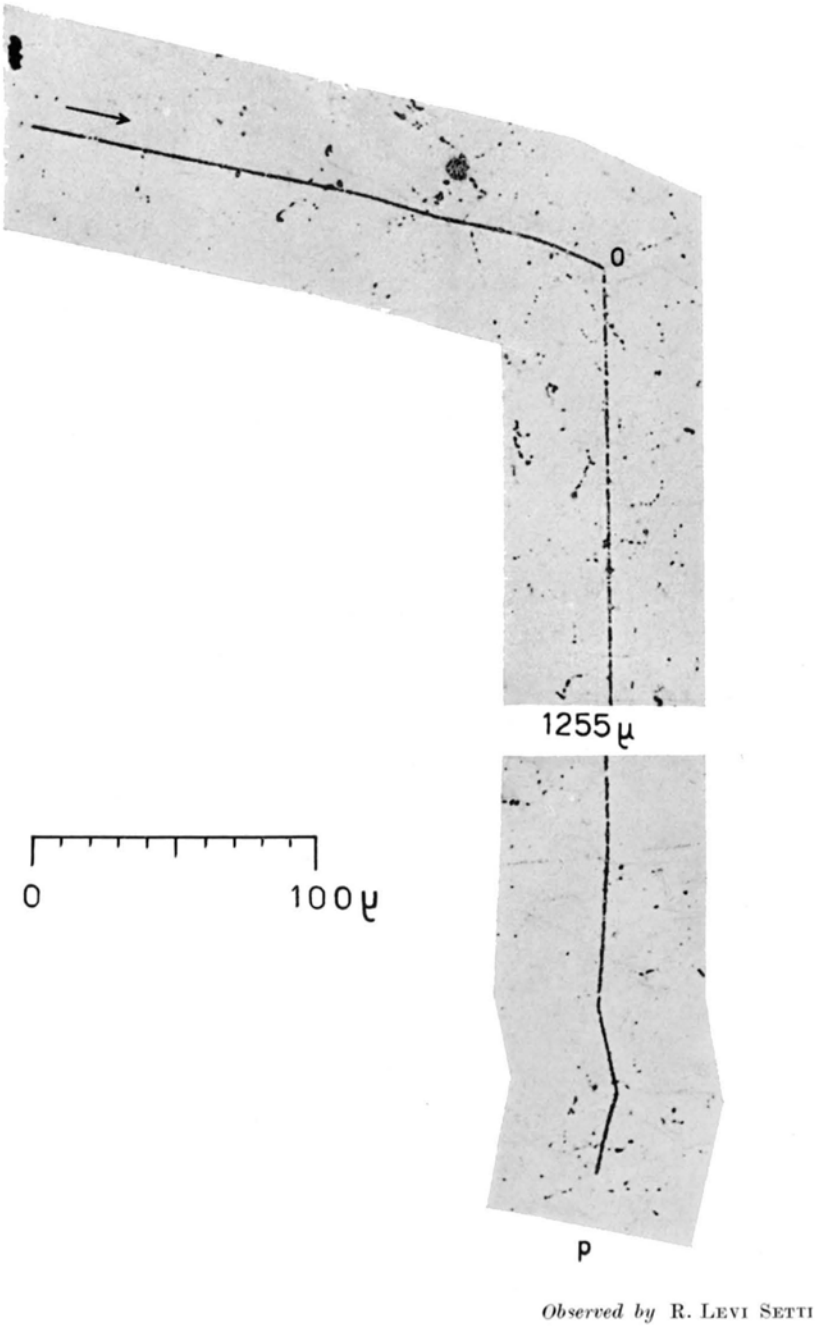


Figure 3.4. An emulsion event with a Σ^+ entering from the left. The decay is $\Sigma^+ \rightarrow p\pi^0$. The p is observed to stop after 1255 μm. (Ref. 3.8)

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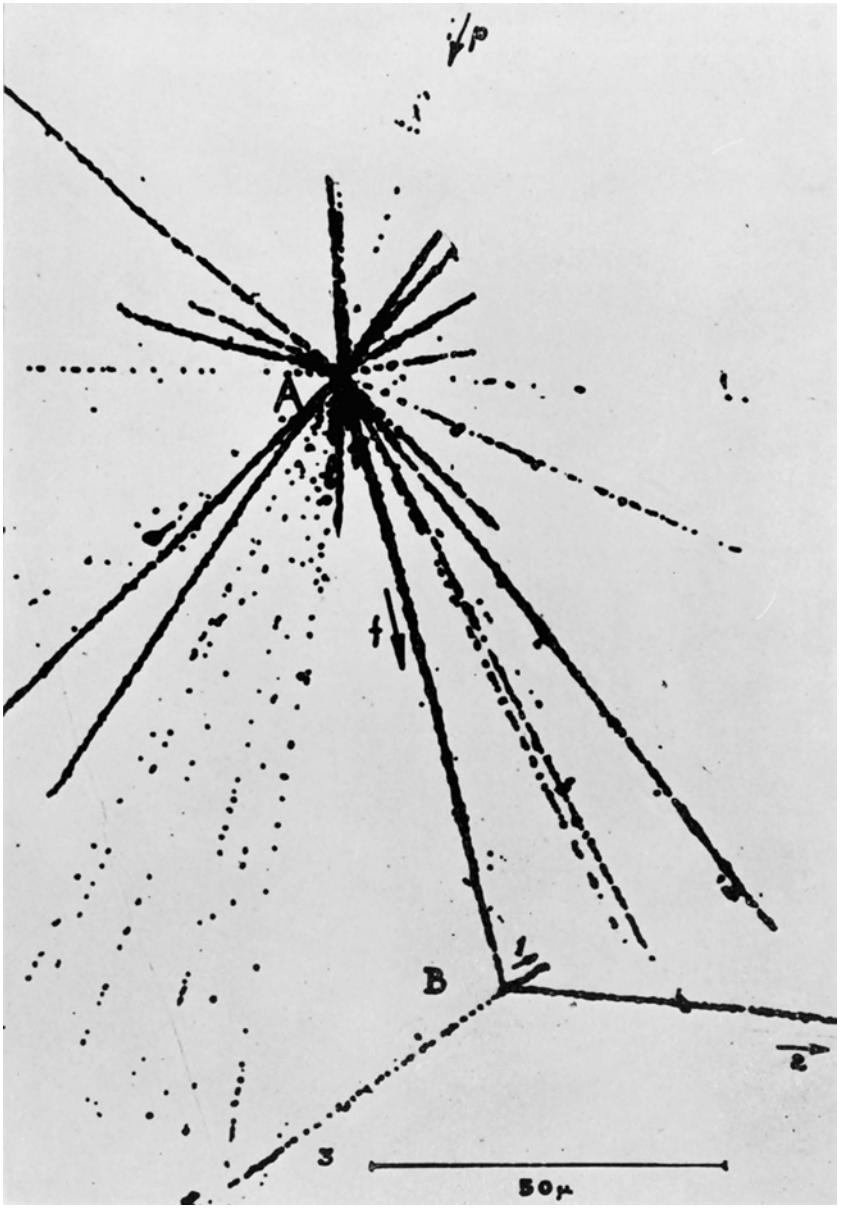


Figure 3.5. The star at A is caused by a cosmic-ray (marked p) incident from above colliding with a silver or bromine atom in the emulsion. The track f is due to a nuclear fragment with charge about 5. Its decay at point B shows that it contained a hyperon. The scale at the bottom indicates 50 μm. (Ref. 3.10)

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consistent with Pais's explanation. Pais's parity was to be conserved only in the strong (nuclear) interactions. The weak interactions were not to obey this rule, so weak decays like $\Lambda \rightarrow \pi^- p$ were allowed. However, because the weak interactions are quite feeble, the lifetimes of the unstable particles could be much longer than would have been the case if the decays went through the strong interaction.

The associated-production proposal of Pais was only a partial explanation. The full solution was given by Gell-Mann. In Gell-Mann's proposal, the new quantum number that was introduced was not multiplicative, but additive. Each strongly interacting particle has an additive quantum number called *strangeness*. For the old particles (pion and nucleon) the strangeness, S, is 0. For the K^+ the strangeness is +1, while for the Λ and Σ's it is -1. Pairs of mesons with identical masses but opposite electric charges are antiparticles of each other, just as the positron is the antiparticle of the electron. Each antiparticle is assigned the opposite strangeness from the particle. Thus the K^- has strangeness -1. While Gell-Mann's proposal allowed $\pi^- p \rightarrow K^+ \Sigma^-$ but not $\pi^- p \rightarrow K^0 n$, just as the scheme of Pais, some of its predictions were different. For example, Gell-Mann's rules forbid $nn \rightarrow \Lambda\Lambda$ while Pais's allow it. An especially important distinction was $\pi^- p \rightarrow K^- \Sigma^+$. This is forbidden by Gell-Mann's proposal (the final state has strangeness -2) but allowed by that of Pais. Gell-Mann proposed that the strong interactions conserved isospin and strangeness, and that electromagnetism conserved strangeness, but allowed a unit change of isospin. The weak interactions violated isospin and allowed a unit change of strangeness.

The proposal of Gell-Mann initially met severe opposition. His classification of the particles placed the K meson into two isospin doublets: (K^+, K^0) and $(\overline{K}^0, K^-)$. Two objections were raised: First he was requiring that a neutral meson not be its own antiparticle. Though Kemmer had shown years before that there was nothing wrong with this, it still seemed odd. Moreover, many thought it was impossible to have isodoublet bosons (the K's) and isovector fermions (the Σ's), rather than the better known isodoublet fermions (nucleons) and isovector bosons (the pions). The objections, of course, eventually gave way, as did the resistance to the name strangeness.

The proposal of Gell-Mann was arrived at independently by Nakano and Nishijima. The strangeness S, baryon number B ($B = 1$ for nucleons and the hyperons Λ, Σ, Ξ), the third component of isospin, I_z, and charge, Q, were linked by the Gell-Mann–Nishijima relation,

$$Q = I_z + (B + S)/2. \tag{3.3}$$

Since the masses of the Σ^+ and Σ^- were not close enough to the mass of the Λ for them to form an isotriplet, a new hyperon, Σ^0, was predicted that would decay into Λ and a γ. Since the Ξ^- decayed weakly into $\Lambda\pi^-$ it was assigned $S = -2$. Using the Gell-Mann–Nishijima equation, we see that the Ξ^- must have $I_z = -1/2$. Thus a Ξ^0 with $I_z = 1/2$ is required. These predictions of Gell-Mann were subsequently verified.

In 1954 the Bevatron started operating with proton energies up to 6 GeV at the Radiation Laboratory in Berkeley. The early emulsion work at the Bevatron concentrated on K^+ (that is, θ^+, χ^+, or κ^+) and τ^+ studies. This work considerably augmented the cosmic-ray data

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on mass equality (**Ref. 3.13**, Ref. 3.14) and lifetime equality (Ref. 3.15, 3.16) between the K^+ and the τ^+. If these were different particles, they had to be a very close doublet in mass with very similar lifetimes as well! Subsequent counter experiments at the Bevatron and Cosmotron (Refs. 3.17, 3.18) gave even closer agreement for the lifetimes of the various K decay modes and the tau.

Just as data from accelerators began to supplant those from cosmic rays, a major effort, the G-Stack (for "giant") experiment, was mounted by the groups from Bristol, Milan, and Padua. A volume of 15 liters of emulsion was flown at a height of 27,000 meters for six hours. The emulsion stack was thick enough to stop many of the particles produced by decays at rest. Tracing microscopic tracks through 250 sheets of emulsion was an enormous task, but the reward was also great: the clear identification of the decays $K_{\mu 2}$, $K_{\pi 2}$ and K_{e3}.

In 1955, W. D. Walker measured two cloud chamber events apparently of the form $\pi^- p \rightarrow K^0 \Lambda$ (Ref. 3.19). One event was consistent with the interpretation that there were no additional unobserved particles. The other, however, was inconsistent with this hypothesis and instead fitted better the supposition that a γ or ν had been produced as well. Walker argued that the best interpretation was that the Λ was a decay product. The deduced mass of the decaying object agreed very well with the known masses of the Σ^+ and Σ^-. It was natural to conclude that the actual process was $\pi^- p \rightarrow K^0 \Sigma^0$, followed by $\Sigma^0 \rightarrow \Lambda \gamma$. Indeed, Walker showed that that hypothesis explained some discrepancies in the events reported earlier by Fowler *et al.*

The discovery of the Ξ^0 did not take place until 1959. Since the Ξ has strangeness -2, its production by pions is quite infrequent: the minimal process would be $\pi^- p \rightarrow K^0 K^0 \Xi^0$. A more effective means is to start with a particle with strangeness -1. This was accomplished by L. Alvarez and co-workers using a hydrogen bubble chamber and a mass-separated beam of K^- mesons of momentum about 1 GeV/c produced by the Bevatron. Using the great analytical power of the bubble chamber technique, they were able to identify an event $K^- p \rightarrow K^0 \Xi^0$ (Ref. 3.20). The K^0 decayed into $\pi^+ \pi^-$. The Ξ^0 decayed into $\Lambda^0 \pi^0$. Both the decay of the K^0 and the decay of the Ξ^0 gave noticeable gaps in the bubble chamber pictures. The Λ^0 was identified by its charged decay mode, $\Lambda \rightarrow p \pi^-$. The last hyperon, Ω^-, was not discovered until 1964, as discussed in Chapter 5.

The bubble chamber was invented by Donald Glaser in 1953. The first chambers used propane and other liquid hydrocarbons. The idea was rapidly adapted by Luis Alvarez and his group who used liquid hydrogen (and later also deuterium) as the working liquid. They also developed methods for building increasingly large chambers. The bubble chamber works by producing a superheated liquid by rapid expansion just before (about 10 ms) the arrival of the particles to be studied. Bubbles are formed when boiling starts around the ions produced by the passage of the charge particles through the liquid. These bubbles are allowed to grow for about 2 ms at which time lights are flashed and the bubbles are photographed. The properties of bubble chambers are ideally suited for use with accelerators. At an accelerator, the arrival time of a particle beam is known. This allows one to expand the chamber before the arrival of the charged particles, which is not possible in cosmic-ray experiments.

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Exercises

3.1 Suppose that in an experiment like that of Leprince-Ringuet and L'héritier a singly charged particle of mass $M >> m_e$ scatters elastically from an electron. Let the incident particle's momentum be p and the scattered electron's (relativistic) energy be E. Further, let χ be the angle the electron makes with the incident particle (which is nearly undeflected). Show that

$$M = p\left[\frac{E + m_e}{E - m_e}\cos^2\chi - 1\right]^{1/2}. \tag{3.4}$$

For the event of Leprince-Ringuet and L'héritier, the cloud chamber was in a magnetic field of about 2450 gauss. The incident particle had a radius of curvature of 700 cm while that of the electron was 1.5 cm. Take $\chi = 20^\circ$ and assume the scattering plane was perpendicular to the magnetic field. Estimate M.

3.2 Using the data from Table 1 of Rochester and Butler, Ref. 3.2, and the current values for the π, K, p, and Λ masses, determine whether their photograph 1 is $K^0 \to \pi^-\pi^+$ or $\Lambda \to p\pi^-$. Are the errors in the measurements small enough to permit a confident choice?

3.3 Suppose a neutral particle decays into a positive of mass m^+ and a negative of mass m^-. Assume the angular distribution in the initial particle's rest frame is isotropic. Let p_z^+ be the component of the positive particle's momentum along the direction of the incident particle measured in the lab and similarly for p_z^-. Define

$$\alpha = \frac{p_z^+ - p_z^-}{p_z^+ + p_z^-}. \tag{3.5}$$

Show that the points (α, p_t), where p_t is the momentum of a decay product perpendicular to the line of flight of the initial particle, lie on an ellipse. Discuss how this could be used to separate $\Lambda \to p\pi^-$ from $K^0 \to \pi^+\pi^-$. See R. W. Thompson in the *Proceedings of the 3rd Rochester Conference*.

3.4 Using the data of Thompson *et al.*, and the mass of the charged pion, determine the mass of the K^0 and the associated uncertainty. Compare with the Q value quoted by these authors.

3.5 Carry out the construction of the Dalitz plot for $\tau \to 3\pi$. Assume the pions are nonrelativistic with energies E_1, E_2, E_3. Let $M_K - 3M_\pi = Q$ and define $\epsilon_i = E_i/Q$. Construct an equilateral triangle with center $x = 0$, $y = 0$ and base along $x = -1/3$. Then each side is of length $2/\sqrt{3}$. Now for each point inside the triangle, let ϵ_3 be the distance to the base, ϵ_1 the distance to the right leg of the triangle and ϵ_2 the distance to the left leg. Using the nonrelativistic approximation, show that the physical points lie inside the circle

$$x^2 + y^2 = 1/9.$$

Make plots showing the contours of equal probability density for the decay of the τ for the two possibilities, $J^P = 1^-$ and $J^P = 1^+$, using the matrix elements given in the text.

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3.6 Consider the decay $K^+ \to \mu^+\pi^0\nu_\mu$. What is the relation between the energy of the muon in the K^+ rest frame and the invariant mass squared of the $\pi^0 - \nu$ system? What is the maximum energy the muon can have, again in the K rest frame? If the energy of the muon is E, what is the range of energies possible for the π^0? Use this and the relation

$$d\Gamma \sim |\mathcal{M}|^2 dE_1 dE_2$$

to determine the muon energy spectrum assuming the matrix element $\mathcal{M}$ is constant. Use the result to evaluate the likelihood that the two events discussed by C. O'Ceallaigh, Ref. 3.4, are $K \to \mu^+\pi^0\nu_\mu$. Assume the neutrino, ν_μ, is massless.

Further Reading

A. Pais gives a first hand account in *Inward Bound*, Oxford University Press, New York, 1986.

For a fine historical review, see the articles by C. Peyrou, R. H. Dalitz, M. Gell-Mann and others in *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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PHYSIQUE NUCLÉAIRE. — *Existence probable d'une particule de masse* 990 m_0 *dans le rayonnement cosmique*. Note (¹) de MM. **Louis Leprince-Ringuet** et **Michel Lhéritier**.

Nous avons pris, au cours de l'année 1943, dans le laboratoire de Largentière (Hautes-Alpes) situé à 1000^m d'altitude, une série de 10000 clichés de trajectoires cosmiques commandées par compteurs. Les rayons, filtrés par 10^{cm} de plomb, traversaient une chambre de Wilson de 75^{cm} de hauteur, placée dans un champ magnétique H de 2500 gauss environ. Nous nous sommes placés dans les conditions expérimentales les plus favorables [discutées précédemment (²), (³), (⁴)] pour profiter au mieux des clichés de collision entre particules pénétrantes et électrons du gaz de la chambre, dans le but de déterminer la masse au repos de la particule incidente.

Nous avons obtenu une dizaine de clichés intéressants. Le plus remarquable représente une collision dans le gaz pour laquelle d'excellentes conditions sont réalisées : le secondaire fait avec le plan médian de la chambre un angle ζ tel que $\operatorname{tang}\zeta = 0{,}32$ et son rayon de courbure projeté (1^{cm},6), ainsi que la flèche dont il s'écarte du primaire sont mesurables avec précision. Le $(H\rho)$ du primaire $= 1{,}7 \times 10^6$ gauss $\times$ cm. La formule de collision élastique donne pour le primaire, qui est positif, la masse au repos

$$\mu_0 = 990 \pm 12\ \% \text{ (limites extrêmes de l'erreur)} \quad (^5).$$

La masse ainsi obtenue peut surprendre. Les indications suivantes, qui donnent des garanties de la validité de la mesure, nous ont poussés à publier ce résultat.

(¹) Les enroulements sont doublés et montés de façon que la somme des ampères-tours produits par le courant des tubes électroniques soit pratiquement annulée à l'état de repos.

(¹) Séance du 17 juin 1944.

(²) L. Leprince-Ringuet, S. Gorodetzky, E. Nageøtte, R. Richard-Foy, *Comptes rendus*, **211**, 1940, p. 382; *Phys. Rev.*, **59**, 1941, p. 460; *Journal de Physique*, **2**, 1941, p. 63.

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(⁴) S. Gorodetzky, *Thèse*, Paris, 1942; *Ann. de Physique*, **19**, 1944, pp. 5-70.

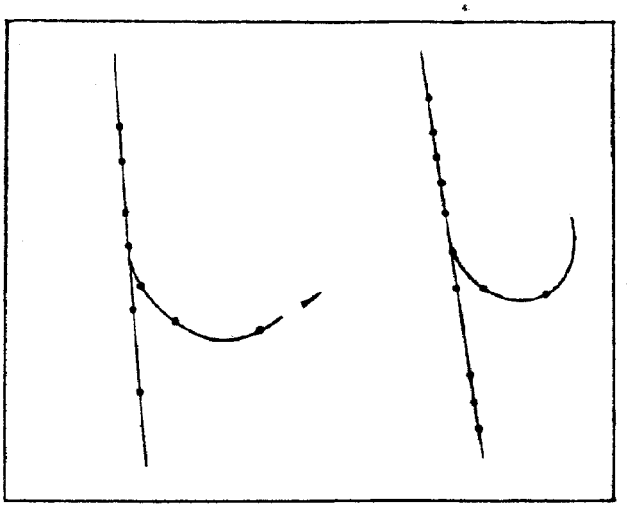
(⁵) Nous n'avons pas tenu compte de l'erreur que peut introduire une courbure naturelle des trajectoires, due à la diffusion coulombienne; cette erreur peut être de l'ordre de 5%.

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1° Il ne peut y avoir, dans l'ensemble de notre expérience, de grossière erreur : en effet nous sommes conduits, pour déduire la masse des données du cliché, à effectuer deux opérations successives : tout d'abord lire sur l'abaque de Richard-Foy (*) la valeur d'une quantité Z fonction seulement des données du *secondaire* et de la valeur du champ; ensuite calculer la masse μ_0 par la relation $\mu_0 = Z(\rho_1/\rho_0)$, ρ_1 étant la projection du rayon de courbure du *primaire*, sur le plan perpendiculaire au champ, et ρ_0 la quantité ρ_0 cm $= 1700/H$ gauss : le primaire n'intervient que dans cette seconde opération.

Or certains clichés, notamment six clichés remarquables, donnent des collisions avec un secondaire se présentant dans de bonnes conditions, mais avec un primaire trop peu courbé pour pouvoir être mesuré. Ces clichés, inutilisables pour fournir une valeur de la masse, sont du plus haut intérêt pour donner une confirmation de la méthode et de la validité de l'expérience. Ils doivent en effet donner un Z voisin de zéro, puisque le rapport ρ_1/ρ_0 est alors parfois supérieur à 10000 et que μ_0 ne peut dépasser plusieurs milliers. On trouve ce résultat sur l'abaque à partir des données mesurées du secondaire, et de la valeur du champ : les limites extrêmes trouvées pour Z encadrent bien la valeur zéro, de façon parfois extrêmement précise. Or ceci n'est possible que si d'une part la collision est élastique, et si d'autre part il n'y a pas d'erreur grave sur les mesures.

2° De grandes précautions ont été prises pour s'assurer du caractère secondaire de l'électron éjecté (notamment stéréoscopie triple) et pour obtenir une restitution dans l'espace donnant les meilleures garanties d'exactitude et de séparation.



Dessin stéréoscopique de la collision.

3° Le cliché donnant la masse 990 se présente particulièrement bien : des erreurs même notables sur la mesure de la flèche, sur celle de l'angle d'éjection

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dans l'espace et sur la valeur du champ affecteraient à peu près linéairement la valeur de la masse, ce qui est le cas le plus favorable. On pourrait supposer, pour expliquer ce résultat, que le secondaire a subi, peu après le choc, une diffusion notable invisible à l'œil; mais ce ne peut être le cas : même si l'on supposait une diffusion brusque de 6 degrés au départ (ce qui serait fort improbable), la valeur de la masse ne serait à modifier que de 80 unités.

4° Signalons enfin que trois autres collisions, observées dans la série de nos clichés, permettent d'encadrer la valeur de la masse du mésoton normal, sans toutefois autoriser, à cause de la valeur élevée du moment réduit ou de l'imprécision sur la flèche, une mesure précise de sa masse.

En résumé, nous possédons une mesure se rapportant à une particule positive de masse $(990 \pm 12\ \%)\, m_0$. On peut remarquer que cette valeur est à peu près quadruple de celle du mésoton normal; une particule ayant une masse moitié de celle du proton (925) entrerait d'ailleurs aussi dans l'intervalle de nos mesures; cela sous réserve que la collision soit élastique, fait que nous ne pouvons naturellement pas affirmer pour le cliché envisagé, mais qui est vérifié pour tous les autres clichés remarquables présentant une collision à primaire peu courbé dans la même série d'expériences, sous réserve également que les charges électriques des particules incidente et heurtée soient celles de l'électron, ce qui est probable; la charge double de l'une des particules est exclue par l'observation de l'ionisation.

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No. 4077 December 20, 1947 NATURE 855

EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE ELEMENTARY PARTICLES

By Dr. G. D. ROCHESTER
AND
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AMONG some fifty counter-controlled cloud-chamber photographs of penetrating showers which we have obtained during the past year as part of an investigation of the nature of penetrating particles occurring in cosmic ray showers under lead, there are two photographs containing forked tracks of a very striking character. These photographs have been selected from five thousand photographs taken in an effective time of operation of 1,500 hours. On the basis of the analysis given below we believe that one of the forked tracks, shown in Fig. 1 (tracks *a* and *b*), represents the spontaneous transformation in the gas of the chamber of a new type of uncharged elementary particle into lighter charged particles, and that the other, shown in Fig. 2 (tracks *a* and *b*), represents similarly the transformation of a new type of charged particle into two light particles, one of which is charged and the other uncharged.

The experimental data for the two forks are given in Table 1; H is the value of the magnetic field, α the angle between the tracks, p and Δp the measured momentum and the estimated error. The signs of the particles are given in the last column of the table, a plus sign indicating that the particle is positive if moving down in the chamber. Careful re-projection of the stereoscopic photographs has shown that each pair of tracks is copunctal. Moreover, both tracks occur in the middle of the chamber in a region of uniform illumination, the presence of background fog surrounding the tracks indicating good condensation conditions.

Though the two forks differ in many important respects, they have at least two essential features in common: first, each consists of a two-pronged fork with the apex in the gas; and secondly, in neither case is there any sign of a track due to a third ionizing particle. Further, very few events at all similar to these forks have been observed in the 3-cm. lead plate, whereas if the forks were due to any type of collision process one would have expected several hundred times as many as in the gas. This argument indicates, therefore, that the tracks cannot be due to a collision process but must be due to some type of spontaneous process for which the probability depends on the distance travelled and not on the amount of matter traversed.

TABLE 1. EXPERIMENTAL DATA

Photo-graph	H (gauss)	α (deg.)	Track	p (eV./c.)	Δp (eV./c.)	Sign
1	3500	66·6	*a*	$3{\cdot}4 \times 10^8$	$1{\cdot}0 \times 10^8$	+
			b	$3{\cdot}5 \times 10^8$	$1{\cdot}5 \times 10^8$	−
2	7200	161·1	*a*	$6{\cdot}0 \times 10^8$	$3{\cdot}0 \times 10^8$	+
			b	$7{\cdot}7 \times 10^8$	$1{\cdot}0 \times 10^8$	+

This conclusion can be supported by detailed arguments. For example, if either forked track were due to the deflexion of a charged particle by collision with a nucleus, the transfer of momentum would be so large as to produce an easily visible recoil track. Then, again, the attempt to account for Fig. 2 by a collision process meets with the difficulty that the incident particle is deflected through 19° in a single collision in the gas and only 2·4° in traversing 3 cm. of lead—a most unlikely event. One specific collision process, that of electron pair production by a high-energy photon in the field of the nucleus, can be excluded on two grounds: the observed angle between the tracks would only be a fraction of a degree, for example, 0·1° for Fig. 1, and a large amount of electronic component should have accompanied the photon, as in each case a lead plate is close above the fork.

We conclude, therefore, that the two forked tracks do not represent collision processes, but do represent spontaneous transformations. They represent a type of process with which we are already familiar in the decay of the meson into an electron and an assumed neutrino, and the presumed decay of the heavy meson recently discovered by Lattes, Occhialini and Powell[1].

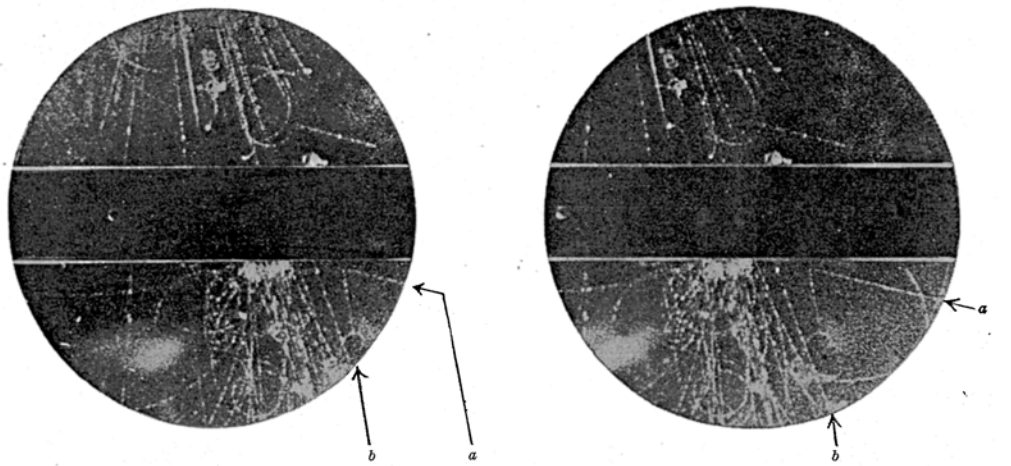


Fig. 1. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (*a b*) IN THE GAS. THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN AN ANTICLOCKWISE DIRECTION

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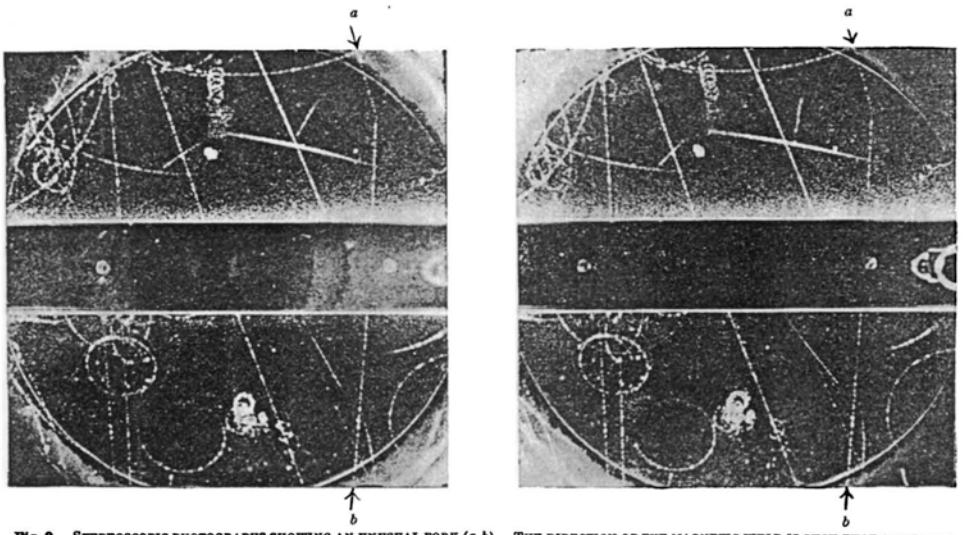


Fig. 2. STEREOSCOPIC PHOTOGRAPHS SHOWING AN UNUSUAL FORK (*a b*). THE DIRECTION OF THE MAGNETIC FIELD IS SUCH THAT A POSITIVE PARTICLE COMING DOWNWARDS IS DEVIATED IN A CLOCKWISE DIRECTION

The Masses of the Incident Particles

Let us assume that a particle of mass M and initial momentum P is transformed spontaneously into two particles of masses m_1 and m_2, momenta p_1 and p_2 at angles of θ and φ with the direction of the incident particle. Then the following relations must hold :

$$\sqrt{M^2c^4+P^2c^2} = \sqrt{m_1^2c^4+p_1^2c^2} + \sqrt{m_2^2c^4+p_2^2c^2} \quad (1)$$

$$P = p_1 \cos\theta + p_2 \cos\varphi \quad (2)$$

$$p_1 \sin\theta = p_2 \sin\varphi. \quad (3)$$

These general relations may be used to obtain the mass of the incident particle as a function of the assumed masses of the secondary particles.

The value of M must be greater than that obtained by taking the rest masses of the secondary particles as small compared with their momenta; thus the minimum value $M_{\min}$ is given by the following equation :

$$M_{\min}c^2 = c\sqrt{(p_1+p_2)^2} - P^2. \quad (4)$$

Applying this equation to the forked track of Fig. 1, after calculating P from the observed values of p_1 and p_2, it is found that $M_{\min}$ is $(770 \pm 200)m$, where m is the mass of the electron. The application of equation (4) to the forked track of Fig. 2, however, after calculating p_2 from the observed values of P and p_1, shows that $M_{\min} = (1{,}700 \pm 150)m$. This value of the mass would require an ionization for the incident particle of twice minimum, which is inconsistent with the observed ionization. We are therefore justified in assuming that the real value of P is greater than the observed value which, as indicated in Table 1, has a large error. If larger values of P are assumed, then $M_{\min}$ is reduced in value. The lowest value of $M_{\min}$ is $(980 \pm 150)m$ if P is $14{\cdot}5 \times 10^8$ eV./c. Beyond this value of P the mass increases slowly with increasing momentum. No choice of incident momentum will bring the mass of the incident particle below 980 m.

In the special case where the incident particle disintegrates transversely into two particles of equal mass m_e, giving a symmetrical fork, equation (1) reduces to the following expression,

$$\frac{M}{m} = \frac{2m_e}{m}\left(1 + \frac{p^2c^2}{m_e^2c^4} \cdot \sin^2\theta\right)^{1/2}, \quad (5)$$

where p is the momentum of each of the secondary particles. Some typical results for different assumed secondary particles, calculated from equation (5), are given in Table 2. On the reasonable assumption that the secondary particles are light or heavy mesons, that is, with masses of $200m$ or $400m$, we find that the incident particle in each photograph has a mass of the order of $1{,}000m$.

TABLE 2. MASS OF INCIDENT PARTICLE AS A FUNCTION OF MASS OF SECONDARY PARTICLE

Photograph	Assumed secondary particle m_e/m	Momentum of observed secondary particle (eV./c.)	Incident particle M/m
1	0	$3{\cdot}5 \times 10^8 \pm 1{\cdot}0 \times 10^8$	770 ± 200
	200	"	870 ± 200
	400	"	1110 ± 150
	1837	"	3750 ± 50
2	0	$7{\cdot}7 \times 10^8 \pm 1{\cdot}0 \times 10^8$	980 ± 150
	200	"	1080 ± 100
	400	"	1280 ± 100
	1837	"	3820 ± 50

Upper values of the masses of the incident particles may also be obtained from the values of the ionization and the momenta. Thus for each of the observed particles in Fig. 1, the ionization is indistinguishable from that of a very fast particle. We conclude, therefore, that $\beta = v/c \geqslant 0{\cdot}7$. Since the momentum of the incident particle may be found from the observed momenta of the secondary particles, we can apply equation (1) to calculate M. In this way we find $M/m \ll 1{,}600$. Again, since the ionization of the incident particle in Fig. 2 is light, $\beta \geqslant 0{\cdot}7$, from which it can be shown that $M/m \ll 1200$. This last result, however, must be taken with

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caution because of the uncertainty in the measured value of the momentum of the incident particle.

One further general comment may be made. This is that the observation of two spontaneous disintegrations in such a small number of penetrating showers suggests that the life-time of the unstable particles is much less than the life-time of the ordinary meson. An approximate value of this life-time may be derived as follows. The probability of an unstable particle of life-time τ_0 decaying in a short distance D is given by

$$p = \frac{D(1 - \beta^2)^{1/2}}{\tau_0 c \beta}. \qquad (6)$$

Since the total number of penetrating particles in the penetrating showers so far observed is certainly less than 50, we must assume that the number of our new unstable particles is unlikely to have been greater than 50. Since one particle of each type has been observed to decay, we can therefore put $p \approx 0{\cdot}02$. Setting $D \approx 30$ cm., and $\beta = 0{\cdot}7$, we find from equation (6) that $\tau_0 = 5{\cdot}0 \times 10^{-8}$ sec.

We shall now discuss possible alternative explanations of the two forks.

Photograph 1. We must examine the alternative possibility of Photograph 1 representing the spontaneous disintegration of a charged particle, coming up from below the chamber, into a charged and an uncharged particle. If we apply the argument which led to equation (4) to this process, it is readily seen that the incident particle would have a minimum mass of 1,280m. Thus the photograph cannot be explained by the decay of a back-scattered ordinary meson. Bearing in mind the general direction of the other particles in the shower, it is thought that assumption of the disintegration of a neutral particle moving downwards into a pair of particles of about equal mass is more probable. Further, it can be stated with some confidence that the observed ionizing particles are unlikely to be protons because the ionization of a proton of momentum $3{\cdot}5 \times 10^8$ eV./c. would be more than four times the observed ionization.

Photograph 2. In this case we must examine the possibility of the photograph representing the spontaneous decay of a neutral particle coming from the right-hand side of the chamber into two charged particles. The result of applying equation (4) to this process is to show that the minimum mass of the neutral particle would be about 3,000m. In view of the fact that the direction of the neutral particle would have to be very different from the direction of the main part of the shower, it is thought that the original assumption of the decay of a charged particle into a charged penetrating particle and an assumed neutral particle is the more probable.

We conclude from all the evidence that Photograph 1 represents the decay of a neutral particle, the mass of which is unlikely to be less than 770m or greater than 1,600m, into the two observed charged particles. Similarly, Photograph 2 represents the disintegration of a charged particle of mass greater than 980m and less than that of a proton into an observed penetrating particle and a neutral particle. It may be noted that no neutral particle of mass 1,000m has yet been observed; a charged particle of mass 990m ± 12 per cent has, however, been observed by Leprince-Ringuet and L'héritier[2].

Peculiar cloud-chamber photographs taken by Jánossy, Rochester and Broadbent[3] and by Daudin[4] may be other examples of Photograph 2.

It is a pleasure to record our thanks to Prof. P. M. S. Blackett for the keen interest he has taken in this investigation and for the benefit of numerous stimulating discussions. We also wish to acknowledge the help given us by Prof. L. Rosenfeld, Mr. J. Hamilton and Mr. H. Y. Tzu of the Department of Theoretical Physics, University of Manchester. We are indebted to Mr. S. K. Runcorn for his assistance in running the cloud chamber in the early stages of the work.

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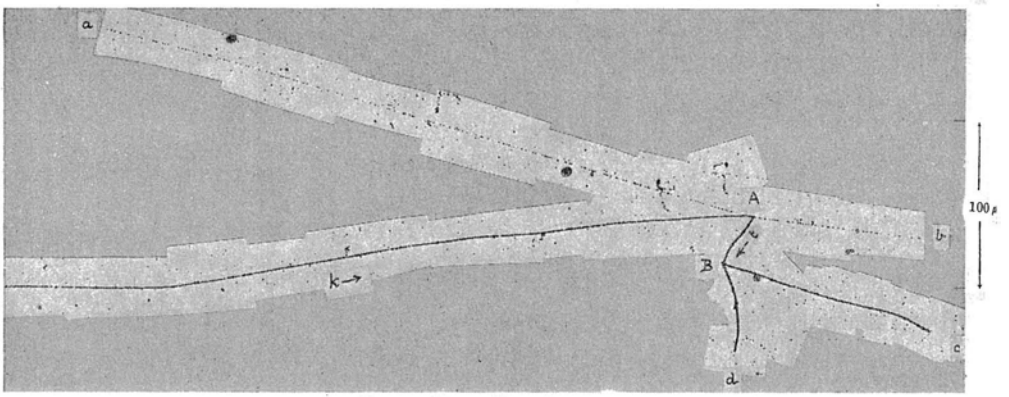
OBSERVATIONS WITH ELECTRON-SENSITIVE PLATES EXPOSED TO COSMIC RADIATION*

By Miss R. BROWN, U. CAMERINI, P. H. FOWLER, H. MUIRHEAD
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H. H. Wills Physical Laboratory, University of Bristol

and D. M. RITSON
Clarendon Laboratory, Oxford

PART 2. FURTHER EVIDENCE FOR THE EXISTENCE OF UNSTABLE CHARGED PARTICLES, OF MASS ~ 1,000 m_e, AND OBSERVATIONS ON THEIR MODE OF DECAY

ONE of the first events found in the examination of electron-sensitive plates exposed at the Jungfraujoch is represented in the mosaic of photomicrographs shown in Fig. 8. There are two centres, *A* and *B*, from which the tracks of charged particles diverge, and these are joined by a common track, *t*. Because of the short duration of the exposure, and the small number of disintegrations occurring in the plate, the chance that the observation corresponds to a fortuitous juxtaposition of the tracks of unrelated events is very small—of the order 1 in 10^7. It is therefore reasonable to exclude it as a serious possibility. Further observations in support of this assumption are presented in a later paragraph.



Observer: Mrs. W. J. van der Merwe
Fig. 8

An inspection of the track *k* shows that the particle producing it approached the centre of disintegration *A*. The range of the particle in the emulsion exceeds 3,000 μ, and there is continuous increase in the grain-density along the track in approaching *A*. Near *A*, the grain-density is indistinguishable from that of particles of charge *e*, recorded in the same plate, near the end of their range.

The evidence for the direction of motion of the particle based on grain-counts is supported by observations on the small-angle deviations in the track due to Coulomb scattering. These deviations are most frequent near *A*, and the scattering is less marked at points remote from it.

From these observations, it is reasonable to conclude that the particle *k* approached the point *A*; that it carried the elementary electronic charge; and that it had reached, or was near, the end of its range at the point *A*. We therefore assume that the particle *k* initiated the train of events represented by the tracks radiating from *A* and *B*. It follows that the particle producing track *t* originated in star *A*, and produced the disintegration *B*. In order to analyse the event, we first attempted to determine the mass of the particle *k*.

* Continued from page 51.

Mass Determinations by Grain-Counts

About a year ago, experiments were made in this Laboratory to determine the ratio, m_π^-/m_μ, of the masses of π- and μ-mesons, by the method of grain-counting[5], and by studying the small-angle scattering of the particles in their passage through the emulsion[4]. The values obtained by the two methods were $m_\pi/m_\mu = 1{\cdot}65 \pm 0{\cdot}11$, and $m_\pi/m_\mu = 1{\cdot}35 \pm 0{\cdot}10$*, respectively. Recent experiments at Berkeley[6] suggest that the true value is $1{\cdot}33 \pm 0{\cdot}02$, a result which throws serious doubt on the reliability of the method based on grain-counts. Because of the advantage of this method, and of the important conclusions which have been based on it, experiments were made to determine the conditions in which reliable results can be obtained.

In the first experiments[5], the two most serious experimental difficulties arose from the fading of the latent image and from the variation of the degree of development with depth. This made it necessary to

* For the following reasons, the limits of error quoted above, in the determination of m_π/m_μ by observations on scattering, are less than those given in ref. 4. Previously, values for the mass of the different types of mesons, classified phenomenologically, were given separately. It is now known, however, that at least the majority of the σ-mesons are π−-particles; and the ρ-mesons, μ+- and μ−-particles. The different results can therefore be combined to give a value for m_π/m_μ with a greater statistical weight.

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An Unusual Example of V^0 Decay*

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THE object of this note is to report in detail a rather unusual V^0 decay recently observed in the new magnetic chamber.[1] Event R-118 is shown in Fig. 1. The V^0 particle, occurring with a penetrating shower, decays after traversing about one-eighth of the illuminated height of the chamber. The decay takes place

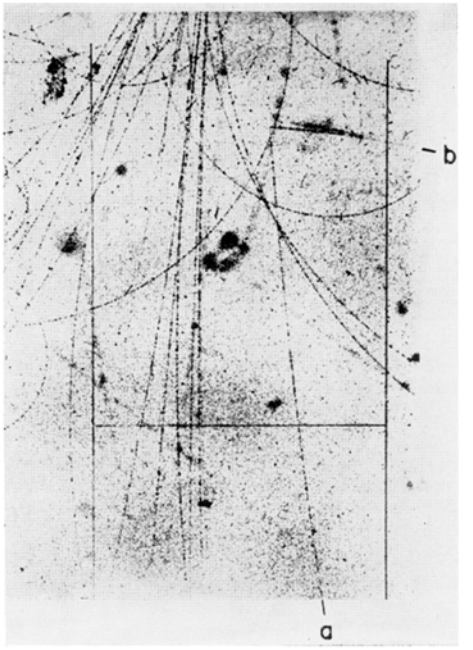


FIG. 1. Event R-118. The upper ⅗ of the chamber is shown. The obscuration of track b, by an unrelated old track, is less in the other two stereoscopic views.

very near the center of the illuminated depth; the positive fragment (track a) is projected almost vertically down, and the negative fragment (track b) almost horizontally to the right.

The track of the positive fragment is 43 cm long and is well illuminated throughout its entire length. The comparator plot for the left eye is shown in Fig. 2. The corrected momentum, derived from the three eyes, is 0.67 ± 0.02 Bev/c, and the ionization is indistinguishable from that of electronic tracks nearby. A proton of this momentum would be heavily ionizing by a factor 2.3, which it is believed would not easily escape detection under these conditions. Thus it is probable that the positive fragment is lighter than a proton, which means that the disintegration is not of the type $V_1^0\rightarrow p+\pi$.

The track of the negative fragment, although relatively short, is highly curved and distinctly heavily ionizing. The track makes an angle of 26° with the plane of the chamber and crosses the front boundary of the illuminated depth near the right side of the chamber, as evidenced by the fading of track b in Fig. 1. The comparator plot for the left eye is shown in Fig. 2. The momentum is 0.094 ± 0.008 Bev/c, and the track is heavily

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ionizing by an estimated factor of 2 or 3. A pion of this momentum would be heavily ionizing by a factor 2.5; and a muon by a factor 1.8; thus it is likely that the negative fragment is a pion or nuon. A τ-meson of this momentum would be heavily ionizing by a factor in the neighborhood of 15 and would not easily escape detection. We thus consider it unlikely that this event represents a decay of the type suggested by the California Institute of Technology group,[2] namely $V_2^0 \rightarrow (\tau^-$ or $\kappa^-) + \pi^+ + 60$ Mev.

The corrected angle between the tracks is $79.2° \pm 0.4°$, the relatively large error arising primarily from the shortness of the negative track. Although the orientation of the event with respect to the associated shower suggests that it represents the decay of a neutral V particle (the angle of decay being so large), the possibility that the event is grossly misinterpreted must not be overlooked. The possibility that the event represents the decay of a charged particle (track b) which enters the chamber from the right can be excluded on energetic grounds since the total energy indicated by track b is considerably less than the kinetic energy of track a. The possibility that the event represents the decay of a charged particle (track a) which enters the chamber from below is a possible but relatively improbable interpretation.

The $Q(\pi, \pi)$ value is 215 ± 7. The next most accurate cases[1] R-32 and R-39 give 212 ± 10 and 216 ± 7, and a recent unpublished event (R-151) gives 219 ± 15. Confirmation of individual $Q(\pi, \pi)$ values in the neighborhood of 214 Mev has not been forthcoming from other groups, and there is certainly no indication therefrom for the existence of either a line or a pronounced maximum in that neighborhood. We are inclined to consider that the values in the neighborhood of 214 determined as described above are incompatible with a value of 170 Mev,[3] limits of 115–185 Mev,[4] or a range of 100–130 Mev,[2] so that the present observations appear to be distinct from those of other investigators.

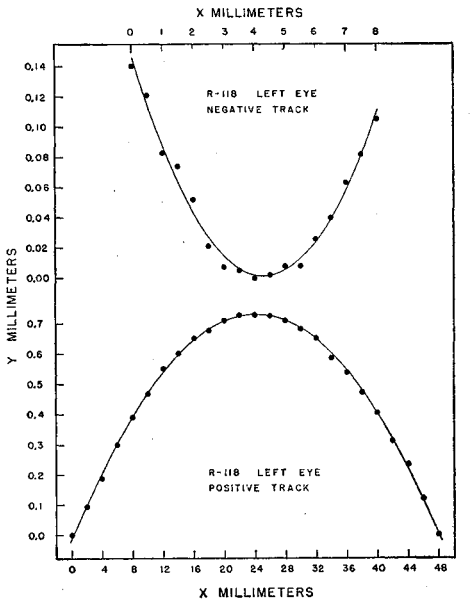


FIG. 2. Comparator plots of R-118 for the left eye. The plots for the other two stereoscopic views are of the same quality.

It may be that the experimental arrangement has biased[5] our observations in favor of a different type[6] of neutral V particle, $V_4^0 \rightarrow (\pi^+$ or $\mu^+) + (\pi^-$ or $\mu^-) + Q$, where $Q(\pi, \pi) = 214 \pm 5$ Mev.[7,8] In view of the limited statistics (7 cases of V_4^0), we cannot, of course, exclude a splitting of the V_4^0 structure in the Q-curve plot,[1] or a three-body decay. The latter might account for part of the differences with the results of other investigators, and for events[1] 328 and R65B.

* Assisted by the U. S. Office of Ordnance Research and by grant of the Frederick Gardner Cottrell Fund of the Research Corporation.

[1] Proceedings of the Third Rochester Conference. See Thompson, Buskirk, Etter, Karzmark, and Rediker, Phys. Rev. **90**, 329 (1953).

[2] Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953).

[3] We are indebted to Dr. Butler for recently informing us that the Manchester data has been remeasured to give $Q(\pi, \pi)$ values in the neighborhood of 170 Mev instead of 122 Mev as previously reported.

[4] We are indebted to Dr. Bridge for sending us a preprint of a forthcoming paper of the Massachusetts Institute of Technology group.

[5] With the new magnetic chamber, we find roughly equal numbers of V_1^0 and V_4^0 (see below).

[6] The Manchester group and the Massachusetts Institute of Technology group use the symbol V_2^0 to indicate the class of all neutral V particles other than $V_1^0 \rightarrow p + \pi$. In that usage, the V_2^0 symbol seems inappropriate here, in view of the large variety of decay schemes in that class which have been reported (see reference 2), but which we have not as yet observed.

[7] In case one or both fragments are muons, slight modification of the Q value would be necessary.

[8] The kinetic energy per pion in the c.m. system would be 107 Mev, very near $E_\pi = 115 \pm 10$ Mev for the χ-decay. See the excellent review paper of D. H. Perkins in the *Proceedings of the Third Annual Rochester Conference on High Energy Physics* (Interscience Publishing Company, New York, 1953).

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PHYSICAL REVIEW VOLUME 93, NUMBER 4 FEBRUARY 15, 1954

Production of Heavy Unstable Particles by Negative Pions*

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(Received November 10, 1953)

In addition to two previously discussed cloud-chamber examples of V-particle production by 1.5-Bev π^- mesons from the Cosmotron, four further examples are discussed here. In two of the new examples a $\Lambda^0(V_1^0)$ and a $\vartheta^0(V_4^0)$ are seen to decay in a geometry indicating that they were produced together in a $\pi^- - p$ collision. A third example is best interpreted as production of a $\Lambda^-(V_1^-)$ together with a $K^+(V_2^+)$ by a π^- colliding with a proton. A fourth example shows a probable Λ^- decaying into a π^- and a neutron with a Q value of about 130 Mev. A cross section of $\sim$1 millibarn for V-particle production is inferred from the number of $\pi^- - p$ collisions observed.

IN a previous letter[1] we have reported two examples of Λ^0 particles[2] produced in hydrogen by negative pions (π^-) of 1.5-Bev kinetic energy. For both examples it was shown that if there were only two resulting particles the second was a K^0 particle of a mass of about 650 Mev. Since, however, the K^0 was not seen to decay it was also possible to balance energies and momenta by assuming two lighter neutral particles (including π^0) instead of one K^0 in addition to the Λ^0.

Observations on heavy unstable particles in cosmic radiation indicate lifetimes as long as 10^{-10} to 10^{-9} second with production cross sections at least 10^{-2} times those for π mesons. These facts can be reconciled theoretically[3] if it is assumed that the particles must be produced doubly (two at a time). Different particles may be produced simultaneously, in addition to pairs of identical ones. It appears that no evidence for double production of such particles, exceeding purely statistical coincidence, has been reported in cosmic radiation although a few examples might perhaps be interpreted in this manner.[4] The two examples of production in hydrogen reported by this group indicate multiple production. This interpretation is uncertain, however, since the K^0 particles are not observed to decay and the computed masses are higher than the value of about 500 Mev most commonly found for K particles.

We now wish to describe three additional cases where double production of heavy unstable particles by 1.5-Bev π^- is indicated with more certainty then in the previous two examples. We shall refer to the previous examples as cases A and B. Case C shows a Λ^0 together with a ϑ^0 probably produced in a heavy nucleus. Case D shows the same combination produced in hydrogen. Case E shows what may well be a Λ^- together with a K^+ with mass of about 500 Mev produced in hydrogen. A few cases of Λ^+ have been observed in cosmic radiation[5,6] but evidence for Λ^- is less certain. In a fourth case, called F, we shall describe an additional example best interpreted as a Λ^-.

Details of the experimental method will be described in a later article. A diffusion cloud chamber filled with 20 atmospheres of hydrogen was exposed to a 1.5-Bev π^- beam produced in a carbon target by the 2.2-Bev circulating proton beam in the Cosmotron. The pions were selected and collimated by the field of the Cosmotron magnet and a channel in the concrete shielding around the machine. The beam thus obtained is quite monoenergetic with a spread probably less than ± 0.1 Bev. The beam was finally deflected by a magnet into a concrete house containing the cloud chamber mounted between the pole faces of a magnet providing an average field of 10 500 gauss. This magnetic field has been calibrated to 1 percent accuracy and its vertical and horizontal components have been mapped throughout the chamber.

The examples to be described were obtained out of a total of 26 000 photographs obtained at a rate of one every 7 to 8 seconds. In addition many examples of V events were found for which no associated V event or nuclear interaction in the gas was observed. Finally, we have observed about 170 pion interactions in hydrogen, most of which lead to single and multiple production of pions. These will be described in a later article.

CASE C: Λ^0 WITH ϑ^0

Figure 1 (case C) shows a photograph of two V events, of which (a) is considered to be a Λ^0, and (b) a ϑ^0. Data which lead to this identification are given in Table I. Row 2 gives the momenta as measured on the 35-mm film by means of a Cooke microscope. The measure-

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **91**, 1287 (1953).

[2] We are using here the nomenclature suggested for V events at the International Congress on Cosmic Radiation, Bagnères-de-Bigorre, France. Accordingly $\Lambda^{0,+,-}\rightarrow$nucleon+pion+$Q_\Lambda$; $K^{0,+,-}$ is any particle whose mass falls between those of pion and proton; for example, $\vartheta^0(\rightarrow\pi^+ + \pi^- + Q_\vartheta)$ is a K^0.

[3] A. Pais, Phys. Rev. **86**, 663 (1952). References to previous work are cited in this article. A. Pais, Proceedings of the Lorentz-Kamerlingh Onnes Conference, Physica (to be published); M. Goldhaber, Phys. Rev. **92**, 1279 (1953); M. Gell-Mann, Phys. Rev. **92**, 833 (1953).

[4] Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953); Fretter, May, and Nakada, Phys. Rev. **89**, 168 (1953); G. D. Rochester and C. C. Butler, Repts. Progr. in Phys. **16**, 364 (1953), give a comprehensive review of cosmic-ray results.

[5] York, Leighton, and Bjornerud, Phys. Rev. **90**, 167 (1953).

[6] International Congress on Cosmic Radiation, Bagnères-de-Bigorre, France (unpublished).

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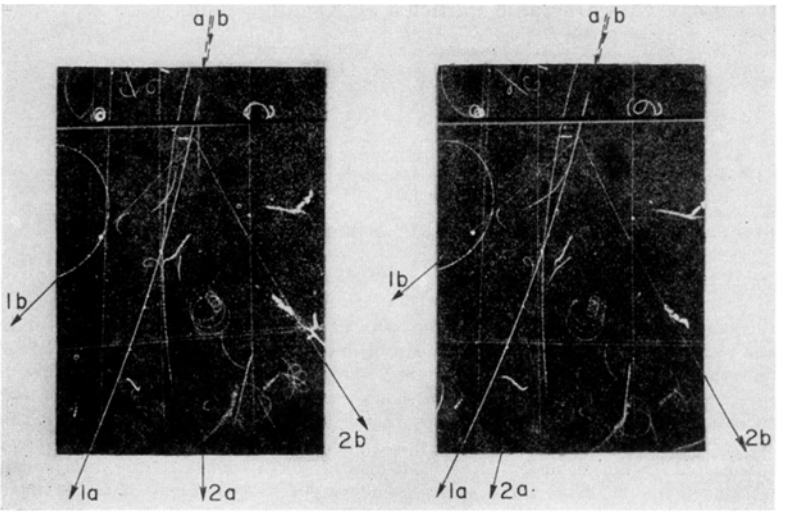


FIG. 1. Case C. Diffusion cloud-chamber photograph of two neutral V particles (a) and (b), whose lines of flight are almost colinear. (a) is believed to be a Λ^0 decaying into a proton (1a) and a negative π meson (2a). Tracks 1a and 2a practically coincide in the right view. (b) is probably a ϑ^0 decaying into π^+ (1b) and π^- (2b).

ments have been corrected for dip angle and space variations of magnetic field and magnification. The mass limits given in row 4 were deduced from measured momenta and estimated ionization densities. Row 5 shows what particle was assumed for further calculation. The angles between tracks in row 6 were obtained from a 3-dimensional reprojecting system as well as by geometrical reconstruction and calculation. The Q value for (a) is, within the given error, consistent with the usually accepted value of 37 Mev for a Λ^0. The Q value for (b) is rather large compared to the best value of 214 Mev given in the literature[7] for a ϑ^0.

From the measured momenta and angles in space for each track one can infer that the lines of flight of the Λ^0 and ϑ^0 practically coincide. From the total number of Λ^0 and ϑ^0 (originating in the walls) found in the 26 000 pictures one concludes that the probability for random association of the two particles in such a geometry is $\sim 10^{-9}$. We therefore should be justified in assuming that the Λ^0 and ϑ^0 were produced in one act. Since no incident particle is visible in the chamber and since the Λ^0 and ϑ^0 travel at an angle of about 24° upwards from the bottom of the chamber, we assume that they were produced in or below the bottom glass plate, though probably not much further down since the pion beam was fairly well collimated. The origin must, of course, lie on the line of intersection of the decay planes of the Λ^0 and ϑ^0. Both particles travel in directions between 0.5° and 1.5° to this line for a range of reasonable choices for the position of the origin.

The following procedure can now be used to determine the Q values more accurately than before. Since we know the directions of the lines of flight of Λ^0 and ϑ^0 with fair certainty we can deduce the momentum of one decay product in each V event from the momentum of the other. As row 2, Table I, shows, the momenta of 1a and 2b are known much better than those of 1b and 2a. We therefore have deduced the momenta of 1b and 2a. For the momenta of 1a and 2b we have chosen their lowest values within the given experimental errors. This choice will result in somewhat lower Q values than calculated above. The new momenta are given in row 8 and the recalculated Q values in row 9. The indicated remaining errors are now mainly due to the mentioned uncertainty in the directions of flight of Λ^0 and ϑ^0. The Q value for the ϑ^0 is still not in good agreement with the usual value of 214 Mev.

From the momenta in row 8 and the given angles one finds the momenta of Λ^0 and ϑ^0 given in row 10. Assuming that the particles were produced in a collision between a π^- and a nucleon and that no additional particle was involved ($\pi^- + p \rightarrow \Lambda^0 + \vartheta^0$) one calculates from the resultant of the momenta of Λ^0 and ϑ^0 that the total energy of incident pion and nucleon must have been 2050±25 Mev before the collision. On the other hand, with the mases of 1119±10 and 546±20 Mev for Λ^0 and ϑ^0, respectively, one finds for the sum of their energies a value of 2068±30 Mev. This value must be equal to the initial energy just calculated, if no other particles are involved in the collision, and one indeed finds agreement. Therefore the Λ^0 and ϑ^0 could have been produced in a $\pi^- - p$ collision, the π^- previously having been scattered upward by 24°, with the required energy. Such repeated interactions could take place in a heavy nucleus. For this interpretation the almost colinear flight of the Λ^0 and ϑ^0 would mean that in the

[7] Thompson, Buskirk, Etter, Karzmark, and Rediker, Phys. Rev. 90, 1122 (1953).

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TABLE I. Measurements and results for case *C*.

	Track	Event a 1a	Event a 2a	Event b 1b	Event b 2b
1	Sign of charge	+	−	+	−
2	Measured momenta (Mev/*c*)	272±8	205±40	451±70	391±15
3	Estimated ionization density	>5×min	<1.5×min	<1.5×min	<1.5×min
4	Mass limit (Mev)	>780	<170	<380	<330
5	Assumed particle	proton	pion	pion	pion
6	Angle between tracks (degrees)	31.1±1		70±1	
7	*Q* values calculated from above data (Mev)	54±20		271±30	
8	Momenta for (2a) and (1b) calculated from direction of line of flight, assuming lowest momenta for (1a) and (2b) (Mev/*c*)	264	189±20	441±15	376
9	*Q* values recalculated (Mev)	49±10		266±20	
10	Momentum of unstable particle (Mev/*c*)	437		673	

center-of-mass system (c.m.s.) of π^- and nucleon the Λ^0 went almost straight backward. The same will be found for the next example to be discussed. From the observed momenta and angles a π^- of the beam colliding with a nucleon could *not* have produced the Λ^0 and ϑ^0 traveling in the observed direction, with simultaneous production of some other particle going downward to balance transverse momenta.

CASE *D*: Λ^0 AND ϑ^0 PRODUCED IN $\pi^- - p$ COLLISION

Figure 2 (case *D*) shows a photograph of a π^- track (marked π^-) disappearing abruptly in the hydrogen, and two nearby *V* events of which (a) is considered to be a Λ^0 and (b) a ϑ^0. Data which lead to this identification are given in Table II. The measured momentum of the incident particle (row 2) agrees well with the momentum of 1630 Mev/*c* for a 1.5-Bev π^-. The other momenta are not well determined, mostly because the tracks are of short length. The longest track (2b), furthermore, seems to show a slight deflection, perhaps due to scattering or to $\pi - \mu$ decay, which makes its momentum also unreliable. The given mass limits (row 4), however, seem to justify the assumed choices for the individual particles (row 5). In particular, since in a collision in hydrogen only one proton was present and since this proton is probably found in 1a, 2b could hardly be another proton in spite of the rather high upper mass limit.

The decay planes of both particles contain the end point of the incident track. The directions of flight of Λ^0 and ϑ^0 and incident π^- appear coplanar, though this is not accurately determined because of the small angle between π^- and ϑ^0 (b). Therefore no additional neutral particle has to be assumed, although calculation shows that kinematically this would be possible. One is therefore justified in assuming the same reaction as in case *C* ($\pi^- + p \rightarrow \Lambda^0 + \vartheta^0$). All pertinent angles are given in rows 6 and 7. From these angles and the momentum of the incident π^- one can calculate the momenta of the decay products directly. The results (row 9) agree with the measured values (row 2) within the errors. With the momenta from row 9, *Q* values have been calculated (row 10). Two experimental errors are given separately with each *Q* value. The first was determined from the probable variation of *Q* with the possible variations of all of the angles (rows 6 and 7) used for the computation. The second error was found from the variation of *Q* with a possible uncertainty of ±100 Mev/*c* for the momentum of the incident π^-. One sees that within the errors both *Q*'s may agree with the usual values of 37 and 214 Mev, respectively, although the *Q* for the ϑ^0 is again rather high and agrees with the value found for case *C*. It should be pointed out that the error for the *Q* for the Λ^0 depends most strongly on the measurement

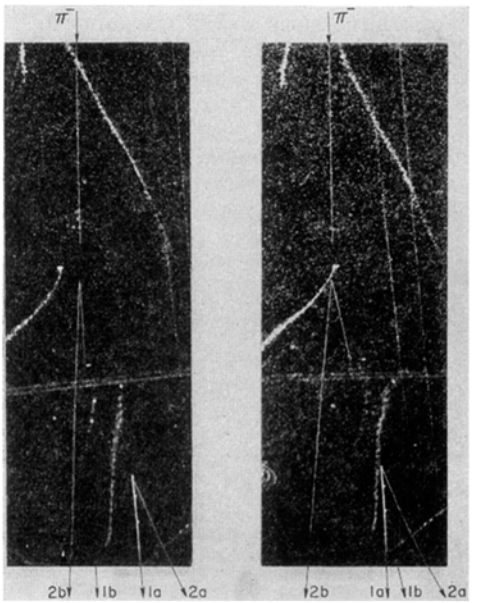


FIG. 2. Case D. Photograph of a 1.5-Bev π^- producing two neutral *V* particles in a collision with a proton. Tracks 1a and 2a, believed to be proton and π^-, respectively, are the decay products of a Λ^0. A ϑ^0 is probably seen to decay into π^+ (1b) and π^- (2b). Because of the rather "foggy" quality of this picture tracks 1b, 2a, and 2b have been retouched for better reproduction.

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TABLE II. Data for case *D*.

		Incident track	Event a 1a	Event a 2a	Event b 1b	Event b 2b
1	Sign of charge	−	+	−	+	−
2	Measured momenta (Mev/c)	1620±160	210^{+210}_{-70}	140^{+300}_{-60}	210^{+210}_{-70}	840±300
3	Estimated ionization density	<1.5×min	>5×min	<1.5×min	<1.5×min	<1.5×min
4	Mass limit (Mev)		>400	<370	<350	<870
5	Assumed particle	pion	proton	pion	pion	pion
6	Angle between incident π^- and direction of flight (degrees)		11.1±1		2.3±0.5	
7	Angle between direction of flight and decay products (degrees)		8.8±1	11.3±1.5	29.3±2	11.0±2
8	Momentum of (a) and (b) calculated from incident momentum and angles (Mev/c)	1630	282		1357	
9	Momenta of decay products from momenta of (a) and (b) and angles (Mev/c)		160	125	400	1027
10	Q values calculated from rows 7 and 9		27±11±3		258±35±21	

of the small angle (2.3°) between incident π^- and ϑ^0 (b). Modifying this angle to make Q_{Λ^0} equal to 37 Mev would reduce Q_{ϑ^0}, which depends on this angle less strongly, to a value of 244 Mev.

From the momenta (row 8) of the Λ^0 and ϑ^0 and their masses of 1097±12 and 538±40 Mev, respectively, one calculates that the kinetic energy of the incident π^- must have been 1.52±0.04 Bev which is quite consistent with the 1.5-Bev beam energy.

CASE *E*: POSSIBLE Λ^- AND K^+ PRODUCED IN $\pi^- - p$ COLLISION

Figure 3 (case *E*) shows a photograph of what on first sight appears to be a π^- scattered forward by a proton with a subsequent decay of the π^-. Closer inspection shows that the momentum of the decay product

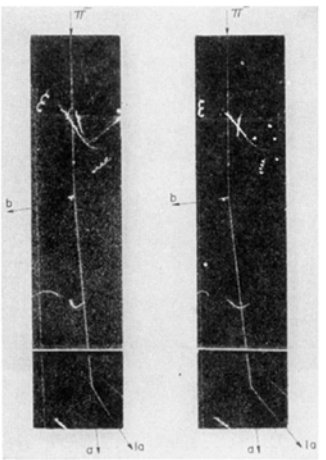


FIG. 3. Case E. Photograph of a $\pi^- - p$ collision event possibly resulting in a Λ^- (a) with a π^- (1a) as a decay product and a K^+ whose decay is not seen.

(1a) and its angle with respect to the track of the decaying particle (a) are much too large for a $\pi-\mu$ or $\mu-\beta$ decay. Therefore (a) must have been a heavy unstable particle.

As far as can be ascertained from the "scattering" event, particle (a) might have been produced at the Cosmotron target or at the cloud chamber wall, and scattered by a proton in the cloud chamber. Certainly the rate of production of heavy mesons would have to be large (~10 percent of that for pions) and their decay lifetime long (~10^{-8} sec) for the beam to contain an appreciable contamination of heavy mesons. No beam particles have shown a decay resembling that of (a). If (a) were produced in the target, it would be quite remarkable that it lives until it reaches the cloud chamber, is scattered, and then decays within the chamber. Such an origin is possible but seems unlikely. If (a) were a particle produced in the wall and scattered in the chamber, it would be remarkable that the incident track has both direction and momentum characteristic of beam tracks. For these reasons we assume that the incident particle is a beam π^- producing a charged unstable particle in a collision with a proton.

Data are given in Table III. Since the tracks are short and the momenta are high, the latter are not well determined. We therefore assume that the incident particle had the beam energy of 1.5 Bev, and compute the momenta of (a) and (b) by assuming that no additional neutral particle was produced. This assumption is very probably justified because (a), (b), and incident track are coplanar. One finds the momentum values given in row 8. If the mass of (a) is given, that of (b) is determined so that their total energies equal that of the incident π^-. In Table IV a number of such consistent values are given. The errors on the mass values of (b) include the uncertainties given for the angle measurements as well as an improbably large uncertainty of ±300 Mev for the energy of the incident π^-. To obtain a mass of 930 Mev (proton) for (b) does not seem to be possible unless (a) is a pion, without making

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TABLE III. Data for case *E*.

		Incident track	Track a	Track 1a	Track b
1	Sign of charge	−	−	−	+
2	Measured momenta (Mev/c)	1800±600	1400±400	>120[a]	−
3	Estimated ionization density	<1.5×min	<1.5×min	<1.5×min	3 to 6×min
4	Mass limit (Mev)		<1500		
5	Assumed particle	pion		pion	
6	Angle between incident track and collision products (degrees)		8±1		79±3
7	Angle between (a) and its decay product (degrees)			36±1	
8	Momenta from incident momentum and angles (Mev/c)	1630	1604		227

[a] Track 1a is slightly distorted. Therefore only a lower limit can be given.

quite unreasonable assumptions for the uncertainties of the measured angles and of the incident momentum.[8] In the cosmic radiation Λ^+ particles have been found[6] with Q values of about 130 Mev, leading to a mass of 1200 Mev. Row 5 of Table IV shows that such a mass for (a) would lead to a mass for (b) which is quite consistent with that usually found for K particles. Case E can therefore be interpreted as the charged counterpart of case C and case D in which Λ^0 and K^0 were produced. For this interpretation the present photograph is an example of the reaction $\pi^-+p\rightarrow\Lambda^-+K^+$.

A calculation has been performed to investigate whether a neutrino (ν) or π^0 could have been produced in addition, which might then change the above conclusions. One finds that only the combinations $[\Lambda^-, K^+, \pi^0]$ or $[\Lambda^-, K^+, \nu]$ are possible (though unlikely because of the observed coplanarity) while the combinations $[\Lambda^+, K^-, \pi^0]$, $[\Lambda^+, K^-, \nu]$, $[p, K^-, \pi^0]$, or $[p, K^-, \nu]$ are kinematically not possible.

From the mass of (b) of 520 Mev and its momentum of 227 Mev/c one finds that (b) should show an ionization density of $\sim$4×min which agrees with the estimated ionization density given in row 3.

Assuming a decay of $\Lambda^-\rightarrow n+\pi^-$, the calculated momentum for 1a of 1604 Mev/c and measured momentum for (b) of $\geqslant$120 Mev/c lead to a Q value $\geqslant$50 Mev. Track 1a may be somewhat distorted so that these figures probably represent lower limits only. If much of the apparent curvature of 1a is due to distortion, the Q value may be as high as 130 Mev, corresponding to a momentum of 440 Mev/c for 1a, as has been assumed in the previous discussion.

[8] For the present discussion it is of particular importance to exclude the possibility that the mass of (b), M_b, could be that of a proton (930 Mev) for the assumption that (a) is a K^- of mass 500 Mev. One finds that $\partial M_b/\partial p_0=8.1$ Mev/(100 Mev/c), where p_0 is the momentum of the incident π^- (so far assumed to be the beam momentum of 1630 Mev/c). Furthermore $\partial M_b/\partial\alpha_a=-11.3$ Mev/degree and $\partial M_b/\partial\alpha_b=-3.7$ Mev/degree, where α_a and α_b are the angles recorded in Table III, row 6, for (a) and (b), respectively. It is very hard to conceive how π^- of momenta >1700 Bev/c could be contained in the beam. With this upper limit and the uncertainties for α_a and α_b given in Table IV one sees that $M_b\leqq$890 Mev if all uncertainties are assumed to act together in a direction to increase M_b. Only by decreasing α_a by 3° and α_b by 9°, for example, could one obtain a value for M_b of 930 Mev. The values for M_a and M_b noted in rows 2 and 3 of Table IV are then not possible without destroying a nucleon.

CASE *F*: EXAMPLE OF A Λ^-

The photograph shown in Fig. 4 (case F) shows another V event which may be interpreted as a Λ^-. The picture shows a negative particle (a) of momentum 1190±170 Mev/c and of estimated ionization density $\leqslant$1.5×min, apparently produced in the wall of the chamber. The angle between (a) and the beam direction is 8°. Particle (a) decays into a negative particle (1a) of momentum 83±3 Mev/c and estimated ionization density 2 to 3×minimum.[9] The mass of the decay product thus lies between 110 and 150 Mev, identifying it as a π^-. The angle between (a) and 1a is 76°. If one additional neutral decay product is assumed one calculates Q values and mass values for (a) as given in Table V. One sees that only the assumption of a neutron (row 1) leads to Q and mass values compatible with those found in cosmic radiation. Particle (a) can also not be identified as a $\tau^-\rightarrow2\pi^0+\pi^-+70$ Mev because 1a alone would have an energy of 230 Mev in the rest system of the τ^-. The assumption in row 4 ($K^-\rightarrow\mu^-+2\nu$) is unlikely because the decay product is most probably

TABLE IV. Consistent masses for particle (a) and particle (b) of case *E*.

	Particle (a)	Mass of (a) (Mev)	Particle (b)	Mass of (b) (Mev)
1	π^-	140	proton	934±6
2	K^-	500	?	860±20
3	?	760	?	760±30
4	$\Lambda^-(Q=37$ Mev)	1107	K^+	570±50
5	$\Lambda^-(Q=130$ Mev)	1200	K^+	520±50

TABLE V. Q values and masses for case F, assuming different masses for the neutral decay product.

	Charged decay product	Neutral decay product	Mass of neutral decay prod. (Mev)	Q for (a) (Mev)	Mass of (a) (Mev)
1	π^-	n	930	130^{+25}_{-15}	1200
2	π^-	π^0	140	430 ±70	710
3	π^-	K^0	500	230±35	870
4	μ^-	2ν	0	>520±80	>620

[9] For the assumption of a Λ^0 traveling backwards the momentum of (a) is much too high.

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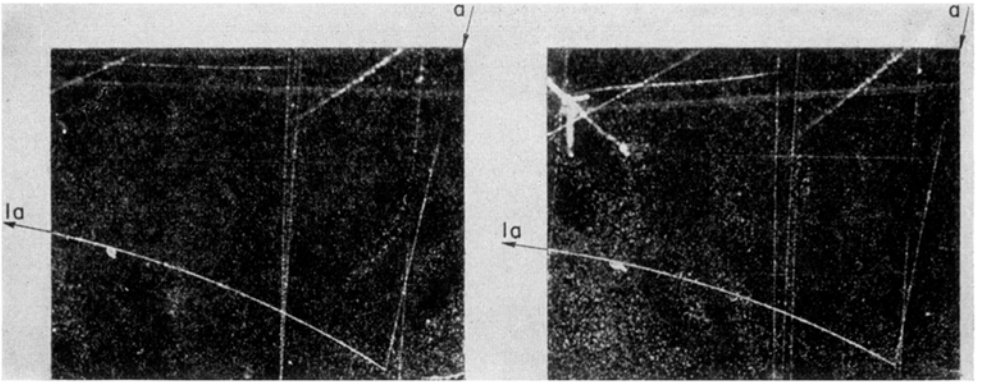


FIG. 4. Case F. Photograph of a negative unstable particle (a) best interpreted as a Λ^-. The decay product (1a) is identified as a π^- from momentum and ionization density.

identified as a π^-. We therefore are left with the conclusion that the present photograph shows the decay of a $\Lambda^- \rightarrow n + \pi^- + Q$, where $Q = 130_{-15}^{+25}$ Mev. The errors on the latter are due to the uncertainty of the measured momentum of (a).

It has been pointed out[10] that if the hypothesis of charge independence applies to $\Lambda^{+,-,0}$, then the Λ^- must have isotopic spin z component $(-3/2)$ with isotopic spin $3/2$, in which case a doubly-charged Λ^{++} should also exist. No Λ^{++} decays have been reported to date, but the number of observed Λ^- and Λ^+ is so small that no significant discrepancy exists. A track which might be interpreted as a Λ^{++} has been reported by Ascoli.[11]

LIFETIMES, CROSS SECTION, AND ANGULAR RELATIONSHIPS

The role played by chance in apparent lifetimes, cross sections, and angular relationships deduced from a small number of cases is very large. Nevertheless the few available observations will be compiled in the following paragraphs.

Table VI shows the lifetimes. All values are consistent with mean lifetimes of 10^{-10} to 3×10^{-10} sec cited in the literature.[4-6]

TABLE VI. Observed lifetimes of all particles in units of 10^{-10} sec.

Particle	*A*	*B*	*C*	*D*	*E*	*F*
Λ^0	0.4	0.3	6	9		
Λ^-					2	3
ϑ^0			2	0.1		
K^0	>4[a]	>3[a]				
K^+					>0.7	

[a] Not taking into account that decay may result in two neutral particles and thus be invisible.

[10] D. C. Peaslee, Phys. Rev. **86**, 127 (1952).
[11] G. Ascoli, Phys. Rev. **90**, 1079 (1953).

For a mean lifetime of 3×10^{-10} sec for the Λ^0 and 1.5×10^{-10} for the ϑ^0, the given cloud-chamber geometry, a π^--beam energy of 1.5 Bev, and isotropic angular distributions (in the c.m.s.) of Λ and K particles one can estimate that 60 percent of the Λ and 50 percent of the K should be seen to decay inside the chamber. One can conclude that for 80 percent of all occurring cases one should see at least one of the two particles decay and for 20 percent of all cases one should see both decaying. (For shorter lifetimes or angular distributions peaked forwards or backwards the probabilities are even larger.) Therefore the 4 cases of unstable particle production in hydrogen (A, B, D, E) observed here may correspond to 5 ± 3 cases that actually happened.[12] This number can be compared with the other 170 $\pi^- - p$ interactions observed, including events with two and four outgoing prongs. Making use of Fermi's statistical theory of meson production[13] and of the isotopic spin formalism, Fermi[14] has calculated the probabilities for the different combinations. One finds that combinations resulting in no outgoing prongs are expected to occur in only 12 percent of all interactions. Therefore our 170 observed cases may correspond to 190 actual interactions. The total interaction cross section has been found to be 34 ± 3 millibarns.[15] Therefore the cross section for heavy unstable particle production by 1.5-Bev π^- in hydrogen is $\sim$1 millibarn.

Table VII gives the angles between the decay planes of the particles and their production planes (the plane formed by the incident track and the line of flight of the unstable particle.) The absence of large angles for the Λ particles is surprising and might be taken as an indication for a large spin for these particles. In fact the

[12] Decays of Λ^0 and ϑ^0 into neutral particles cannot be observed in this experiment and are not taken into account here.
[13] E. Fermi, Progr. Theoret. Phys. (Japan) **5**, 570 (1950).
[14] E. Fermi (private communication).
[15] Cool, Madansky, and Piccioni, Phys. Rev. **93**, 637 (1954).

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separation between the decay and production planes seems smaller than would be expected unless the spin is taken to be unreasonably large.

Table VIII shows the angles between incident π^- and direction of emission of Λ^0 in the c.m.s. Again the result is surprising because of the absence of angles near 90° for which the solid angle is largest. The solid angle between 170° and 180° amounts to only 1.5 percent of the hemisphere, yet both C and D fall into this region. This may indicate that large angular momentum states are involved in the production of these particles, which might be consistent with the possibility

TABLE VII. Angles between decay plane and production plane.

Particle	A	B	C	D	E
Λ^0	5°±5°	30°±20°	18°±7°	27°±10°	7°±5°
Λ^-					
ϑ^0			60°±6°	70°±5°	

of a large spin of the Λ^0. Since $\lambda_0 \approx 2\times10^{-14}$ cm in the c.m.s. for a π^- of 1.5-Bev laboratory energy, angular momentum states up to $L=6$ may be possible.

SUMMARY

These examples of the production of heavy unstable particles in $\pi^- - p$ collisions have been shown to be consistent with a double production process,

$$\pi^- + p \rightarrow \Lambda + K,$$

occurring with a cross section of about 1 millibarn for 1.5-Bev π^-. Further work is required to determine whether production is *always* double in these and nucleon-nucleon collisions.

In four cases the Λ is a Λ^0, and in two of these the K^0 is observed to decay and can be considered to be a ϑ^0, although the Q values of about 260 Mev are not quite consistent with the cosmic-ray value of 214 Mev. One case is interpreted as a Λ^-, and an additional charged decay originating outside the chamber is thought to be a Λ^- with Q value of 130 Mev.

The data suggest an angular correlation between Λ-decay planes and production planes, which may mean that Λ particles have large spin, and a preferred backward (or forward) emission in the c.m.s., which may mean that Λ particles are produced in states of high angular momentum. Many more data are needed to determine such angular relationships.

We wish to express our thanks to the many members of the Cosmotron Department whose efforts have created the opportunity for this work and whose cooperation is enabling us to pursue it. Our thanks are also due to the other members of the cloud-chamber group without whose support this work could not be continued.

TABLE VIII. Angle between incident π^- and direction of emission of $\Lambda^{0,-}$ in c.m.s.

Particle	A	B	C	D	E
Λ^0	141°	125°	177°	174°	
Λ^-					30°

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Bevatron *K*-Mesons*

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(Received May 9, 1955)

TO facilitate the search for K-mesons from the Bevatron, two of us (L.T.K. and D.H.S.) have suggested the use of a strong-focusing spectrometer (Fig. 1),[1] consisting of a magnetic quadrupole focusing lens[2] followed by an analyzing magnet. Particles of any desired momentum can be brought to a focus, forming an image of the target at a point behind the analyzing magnet. Emulsion stacks are placed at this point. With this arrangement we have found examples of four types of heavy mesons first established in cosmic-ray work.[3] Particles of different mass can be separated according to their ranges in emulsion. For particles of momentum 360 Mev/c, the range of K's is 4.6 times the range of the protons, and pions pass through the emulsion stack at minimum ionization.

A stack of 107 Ilford G.5600-μ pellicles,[4] 3.5 in. by 3.5 in., has been exposed so that 114-Mev K-particles stopped in the center of the stack. The proper time of flight for such particles from the target to the emulsion is about 10^{-8} sec.

This stack has been scanned in a swath across the direction of the meson flux for tracks lying in the plane of the emulsion whose ionization is visibly greater than minimum. Particles stopping in the stack (beyond the position of the swath) have masses less than 1200 m_e. Particles that go all the way through the stack have masses less than 800 m_e.

The tracks are followed until they stop and the endings are examined for decays. To date 300 decays have been observed. Twenty of these are π^+ mesons whose unique decay into three charged pions is readily identifiable. Among the others, all of which decay into one lightly ionizing secondary, only those with a secondary that is flat or with an ionization obviously higher than minimum have been categorized. Three examples have been found of what is assumed to be the alternate decay of the π into one charged and two neutral pions, with the pion stopping in the emulsion stack. Two events decay into low-energy muons (less than 55 Mev) and are presumably examples of the κ or $K_{\mu 3}$.

To establish the existence of the $K_{\pi 2}(\theta^+,\chi^+)$ or of the $K_{\mu 2}$ mesons, either very large emulsions are needed to stop the long-range secondary or else very accurate measurements of the multiple scattering and the ionization must be made. Measurements on four fortuitously flat secondaries at a distance of 5 cm from the decay point revealed that three of the primaries were $K_{\pi 2}$'s and one presumably a $K_{\mu 2}$, as determined by the tentative identification of the secondary as a high-energy muon. Excellent calibration on grain count is available from the π mesons of known energy traversing the same region of the emulsions. From the number of K-mesons found here compared to the number found at about 25 cm from the target,[5] it is unlikely that the mean life of any of the K's seen is less than 3×10^{-9} sec.

In the initial exposure, the momentum resolution as determined from the proton ranges allows a mass determination to $\pm 40\, m_e$ on each K-meson. With a few exceptions, all particles with lightly ionizing secondaries fall within a distribution of this width centered about 20 m_e below the average for τ mesons plotted separately (Fig. 2). In a subsequent exposure the momentum resolution has been improved. The scattered points on the high-mass side of the main distribution may be due to particles that suffered inelastic collisions, or scattered off the channel. A

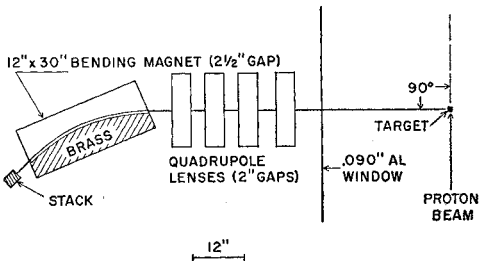


FIG. 1. Strong-focusing spectrometer.

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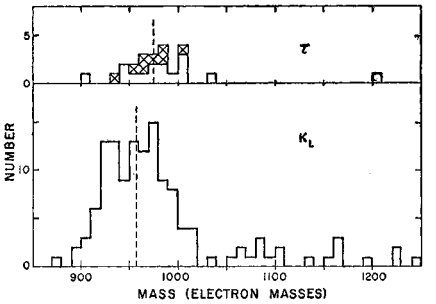


FIG. 2. Mass distributions: Upper histogram represents τ mesons. Crossed squares refer to τ's found nonsystematically. Lower histogram is made up of particles decaying into a single lightly ionizing secondary.

comparison of the measured τ meson mass of (974 ± 6) m_e with the accepted value[3] of $966\,m_e$ indicates a possible systematic error.

This work was done with the encouragement and guidance of Professor Chaim Richman. Most of the scanning was performed by Mrs. Beverly Baldridge, Miss Irene d'Arche, Mrs. Marilynn Harbert, Mrs. Edith Goodwin, and Miss Kathryn Palmer.

It is with pleasure that we acknowledge the help and advice in nuclear emulsion techniques given us by Professor Powell's group at Bristol. The assistance of the Bevatron crew, under the direction of Dr. Edward J. Lofgren, and their skillful operation of the machine are greatly appreciated.

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
† National Science Foundation Predoctoral Fellow.
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[4] Birge, Kerth, Richman, Stork, and Whetstone, University of California Radiation Laboratory Report No. UCRL-2690, September, 1954 (unpublished).
[5] Proceedings of the 5th Rochester Conference (to be published).

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