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Pion-Pair Production in a Nuclear Emulsion

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A positive and a negative π-meson pair of tracks with energies of 17.94 and 18.65 Mev, respectively, are observed to originate in an emulsion without any other associated ionizing particles. It is shown that the event probably did not originate from a nuclear collision. Among the mechanisms considered are materialization from a photon, the decay of a theta-meson, and decay of a (previously postulated) zeta meson. The Q-value of the event, computed as a 2-body decay is 27.9 Mev. If it is a two-body decay the mass of the parent particle is about 600 m_e. This event is also consistent with the decay of a neutral tau meson into a neutral pion and two charged pions for which the total kinetic energy of the charged mesons could vary between 0 and about 80 Mev.

IN our studies on the emission of slow mesons from nuclear disruptions produced by cosmic radiation,[1] one event has been observed in which only the tracks of a positive and a negative meson diverge from a common point in the recording medium. Both particles terminate their range within the confines of a single 1500-micron layer of Ilford G5 emulsion. One of the particles is captured near the end of its range and produces a 2-pronged star, the other exhibits the typical π-μ-e decay processes characteristic of a π^+ meson. Examination of the common point of origin shows complete absence of any associated recoil or delta-ray tracks (Fig. 1). The preparation was sensitive to fast singly charged particles at the minimum of ionization (15 developed blobs per 100 microns). Had any relativistic particles of this character been associated with the event their tracks would be clearly evident, as the origin is located 271 microns below the air interface of the processed gelatin and is accessible to examination by oil immersion objectives of 1.3 numerical aperture.

The event might have originated in a collision of a high-energy neutron ($\geq$700 Mev) with a surface neutron producing the pion-pair and ejecting the uncharged target nucleon. The residual nucleus may then have only a small excitation, of the order of 5 Mev, and may reach stability by either γ ray or neutron emission. While it is possible for the proposed collision to produce two slow π mesons and an absence of recoil, it is to be expected that in the c.m. system of the colliding neutrons that both mesons would have to be projected almost backward and with a velocity closely related to the c.m. velocity of the neutrons. This circumstance might occur with a probability, estimated by Dalitz,[2] of about 1 in 10^4 in a process whose total cross section is at the most about 10^{-27} cm^2.

An alternative mechanism is the simple creation of a positive and negative meson pair by materialization of a photon near the Coulomb field of a nucleus. One difficulty with this novel process is that the difference between the momentum of the photon ($\gtrsim$350 Mev/c) and the total momentum of the π mesons (148 Mev/c) would have to be absorbed by the nucleus. Assuming that the latter escaped distruption in absorbing more than 200 Mev/c momentum, its resulting recoil energy would be about 0.3 Mev even if the nucleus was as massive as silver, yet no recoil is observed. At best, the cross section for this hypothetical process would be $\lesssim 10^{-32}$ cm^2. Because of the large momentum transfer, the process would have to occur very close to or within the nucleus, and direct nuclear meson-production processes should predominate.[3]

The event could originate from the two-body decay of an uncharged K-meson. By employing the data in Table I, the mass of the parent particle X has been estimated from the relationship:

$$X^2=2m^2+2p_1p_2\left[\left\{1+\left(\frac{m}{p_1}\right)^2\right\}^{\frac{1}{2}}\left\{1+\left(\frac{m}{p_2}\right)^2\right\}^{\frac{1}{2}}-\cos\varphi\right],$$

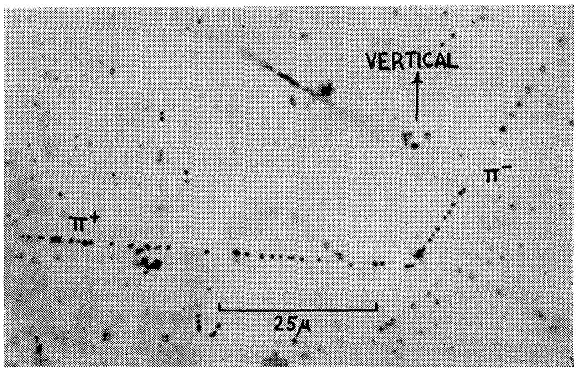

FIG. 1. Photomicrograph showing the origin of the pion pair. The angle between the tracks is 120°. Both tracks terminate in a 1500-micron emulsion layer, and can be identified as positive and negative π mesons by phenomenological behavior at the end of their range.

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[1] H. Yagoda, Phys. Rev. 87, 753 (1950); 85, 891 (1952); 95, 648 (1954).

[2] R. H. Dalitz (private communication).

[3] In this connection our observations on the emission of two or more slow mesons per nuclear evaporation are of interest. Among 18 stars, only 2 exhibit a positive and a negative π-meson track, and in one event both mesons are positive. In the 15 other examples both mesons are of negative sign. These stars invariably exhibit a large number of black and gray prongs indicative of the disruption of heavy nuclei. The slow mesons are, with but one exception, wide-angle members of a large shower of relativistic particles.

TABLE I. Properties of the pion-pair.

Meson track	π^-	π^+
Range in microns	6890±300	6440±300
Kinetic energy, Mev[a]	18.65±0.67	17.94±0.65
Momentum, Mev/c	73.0 ±1.4	74.5 ±1.4
Initial dip, tan β	0.133	$\sim$0
Angle between tracks in emulsion plane	120±1°	
Spatial angle	119.8±1°	
Q-value for 2-body decay[b]	27.85±0.76 Mev	

[a] Based on range-energy tables for nuclear emulsions by Fay, Gottstein, and Hain, Nuovo cimento **12**, Suppl. No. 2, 234 (1954). Errors in energy were estimated by combining as root mean squares the errors in range measurement and those introduced by straggling (2.5 percent of E_π).

[b] The error in the Q-value was estimated by the method described by Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953).

where m refers to the average pion mass, taken as 273 m_e, and p_1 and p_2 are the momenta of the meson particles. The mass of the K-meson is thus estimated at 600 m_e and the Q-value of the decay process at 27.9±0.8 Mev. These values are not reconcilable with either the θ^0-meson ($M \sim 1000\ m_e$, $Q = 214$ Mev) or the once postulated[4] neutral zeta meson with a Q-value of about 2 Mev.

The pion pair may have originated from a three-body decay of a neutral K-meson, $K^0 \rightarrow \pi^+ + \pi^- +$neutral particle. Then, as shown in the appendix, the kinetic energy Q of the charged pions (measured in their c.m. system) may be between zero and $M_{K^0} - m_+ - m_- - m_0$, where m_0 is the mass of the neutral particle. In a τ^0-decay, for example, where the third particle is a neutral pion, Q must lie between 0 and 80 Mev, assuming a τ^0 mass equal to that of the charged tau meson. This event is therefore not incompatible with interpretation as a τ^0-decay. Several cloud-chamber pictures of "anomalous θ^0-decays" exist, which if interpreted as originating from a two-body decay process, provide, on the basis of the charged members, apparent Q-values ranging between 30 to 55 Mev.[5] The present example may possibly belong to this category.

The event was found in 60 cc of emulsion flown in the absence of appreciable surrounding matter for 8.2 hr at λ55°N at an average elevation of 95 000 ft. A total of 1180 π-μ decays and 1740 σ-star endings were traced back to their points of origin within the confines of each 1500-micron thick layer. Of these 102 π^+-mesons and 320 π^--mesons originated in stars. The feedback scanning mechanism resulted in the detection of one coplanar tau-meson decay, a mesonic-decay of an excited triton,[6] and a small group of π^- mesons originating from one-prong stars.[7]

Pion-pair production may be more frequent than these observations would indicate as recognition is dependent on both particles terminating their range. This is particularly true, if as in the present example, both mesons emerge with equal velocity. The gain densities about the point of origin are then identical, and in following back one of the meson tracks, the origin of the pair would be interpreted as a large-angle scatter, unless a sufficient length of the second member recorded to indicate a pronounced increase in gain density.

Opportunity is taken to thank the members of the Office of Naval Research Skyhook Project for the high-altitude balloon exposure. Appreciation is expressed to Howard Smith for assistance in the development and scanning of the emulsion ensemble. The writer is particularly indebted to R. H. Dalitz for a discussion of potential mechanisms for the origin of the pion pair.

APPENDIX A. THREE-PARTICLE DECAY OF A NEUTRAL PARTICLE[2]

Consider the disintegration of a neutral particle of mass M into two charged particles of masses m_+, m_- and a neutral particle of mass m_0. In the system in which the particle M is initially at rest, suppose that the disintegration products have momenta p_+, p_-, p_0, and total energies E_+, E_-, E_0. Then conservation of momentum and energy are expressed by the equations (taking $c=1$)

$$p_+ + p_- + p_0 = 0, \qquad (1)$$

$$E_+ + E_- + E_0 = M. \qquad (2)$$

Consider now the quantity $(E_+ + E_-)^2 - (p_+ + p_-)^2$, which has the same value in all reference systems. Its value in the rest system of particle M is

$$\begin{aligned}(E_+ + E_-)^2 - (p_+ + p_-)^2 &= (M - E_0)^2 - p_0^2, \\ &= M^2 + m_0^2 - 2ME_0. \qquad (3)\end{aligned}$$

In the c.m. system of the two charged particles, their total momentum is zero. If one designates their total energies by ϵ_+ and ϵ_-, then $\epsilon_+ + \epsilon_- = m_+ + m_- + Q$. In this expression, Q represents the sum of the kinetic energies of the two charged particles in their c.m. system and is identical with the apparent Q-value computed on the assumption of a two-particle decay. In this system, (3) has the value $(\epsilon_+ + \epsilon_-)^2$, and

$$Q = (M^2 + m_0^2 - 2ME_0)^{\frac{1}{2}} - m_+ - m_-. \qquad (4)$$

The value of Q therefore depends only on the kinetic energy in the M-rest system acquired by the neutral decay particle. Its maximum value, $Q_{\max} = M - m_+ - m_- - m_0$, is assumed when $E_0 = m_0$, and the minimum value $Q = 0$ corresponds to the maximum value of E_0,

$$(E_0)_{\max} = [M^2 + m_0^2 - (m_+ + m_-)^2]/2M. \qquad (5)$$

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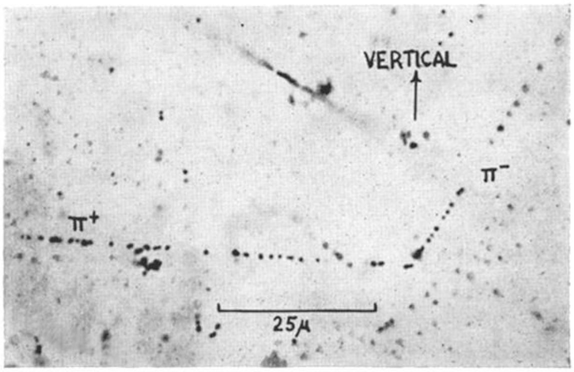
[4] Danysz, Lock, and Yekutieli, Nature **169**, 364 (1952).

[5] Unpublished observations by the California and Princeton University cloud chamber groups. See V. A. J. van Lint, Duke University Natural Science Foundation Cosmic Ray Conference, Durham, North Carolina, 1954 (unpublished), p. II-40.

[6] H. Yagoda, Phys. Rev. (to be published).

[7] When these events are analyzed on the assumption that they originated from the decay of a Λ^0-particle, one event yields a Q-value of 35.7 Mev, and six events have $16 < Q < 24$ Mev. Results on a transverse momentum analysis of the latter will be described elsewhere.



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