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Publication Date

1956-02-29

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Radiation Laboratory

BERKELEY, CALIFORNIA

UCRL-3321

UNIVERSITY OF CALIFORNIA

Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

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Printed for the U. S. Atomic Energy Commission

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ABSTRACT

An event is described that is interpreted as evidence for the simultaneous production of a θ^o and a $\overline{\theta}^o$ according to the scheme of Gell-Mann and Pais. This interpretation assumes the production of a normal θ^o and a K^o with no associated hyperon, where the θ^o is observed and the K^o is inferred from the rule of associated production of heavy unstable particles. The event was obtained by exposing a high-pressure diffusion cloud chamber to a 4.5-Bev/c π^--meson beam from the Bevatron. The event is most reasonably interpreted as

$$\pi^- + p \rightarrow \pi^- + p + \theta^o + (\text{neutral}) .$$

Energy and momentum conservation are satisfied by an undetected neutral particle having a mass of 502^{+91}_{-124} Mev. This is consistent with the associated production of a θ^o and a $\overline{\theta}^o$ according to the scheme of Gell-Mann and Pais. Details are given and alternative interpretations are discussed.

*Also at the University of San Francisco.

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During an investigation of the interactions of 4.5-Bev/c π^- mesons with protons,[1] an interesting event involving the production and decay of a θ^o was observed. Most of the previously reported[2] examples of production of heavy unstable particles in π^--p collisions were interpreted as due to the associated production of a K meson and a hyperon. An exception is the event obtained by Ceccarelli, Grilli, Merlin, Salandin, and Sechi[3] in the G-stack which is interpreted as

$$\pi^- + p \rightarrow K^+ + K^- + n .$$

The event to be described also is not consistent with the associated production of a K meson and a hyperon and is most readily explained as the production of two neutral K particles.

The general experimental arrangement is shown in Fig. 1. The π^- mesons were produced by circulating protons of 5.7 Bev striking a carbon target inside the Bevatron. Mesons emitted in the forward direction underwent momentum analysis by deflections of 17.6° in the magnetic field of the Bevatron and 10.8° in an external analyzing magnet. A 4-foot-long steel collimator with a 6-inch-wide gap was inserted between the Bevatron and the analyzing magnet. Beyond a concrete shielding wall the meson beam entered a diffusion cloud chamber which was 65 feet from the target. The chamber

*Also at the University of San Francisco.

[1] Maenchen, Powell, Saphir, and Wright, Phys. Rev. 99, 1619 (1955).

[2] Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. 91, 1287 (1953); Phys. Rev. 93, 861 (1954); and Phys. Rev. 98, 121 (1955).
W. D. Walker, Phys. Rev. 98, 1407 (1955); W. D. Shephard and W. D. Walker, Phys. Rev. 100, 1264 (1955).

[3] Ceccarelli, Grilli, Merlin, Salandin, and Sechi, Nuovo Cimento 2, 828 (1955).

(which has been described previously[4]) was filled with hydrogen gas at 36 atmospheres and operated in a pulsed magnetic field of 21 500 gauss. Curvature measurements on a sample of beam tracks in the center of the chamber, where the event occurred, give a momentum of 4.49 Bev/c with a standard deviation of 0.28 Bev/c. This agrees with the momentum expected from the beam geometry.

A photograph of the region near the origin of the event is shown in Fig. 2. Measurements of the event are summarized in Table I. Track 1 is identified as a proton or possibly as a Σ^+ by its momentum and ionization. This identification locates the only nucleon present and thereby reduces significantly the number of possible processes. Track 2 is negative and is identified as a π^- or possibly a K^-. Track 3, the positive leg of the V^o, is identified as a light particle and is assumed to be a π^+. Track 4, the negative leg of the V^o, is assumed to be a π^-. The Q value of the V^o (Tracks 3 and 4) is 221.6 ± 7.7 Mev (standard error), and its proper lifetime is only 2×10^{-12} sec. This Q value is in good agreement with the well-known θ^o Q value of 214 Mev. The small dot seen near the origin of the event in Fig. 2 is actually slightly displaced from it and is not associated with the production event. It is probably a delta ray from Track 1.

Table I

Basic data on tracks of Fig. 2

Track	Charge	Length (cm)	Measured momentum (Mev/c)	Estimated ionization	Particle
0	-	4.9	4500 ± 350[a]	1.0	π^- (K^-)
1	+	22.2	585 ± 20	~2.5	p (Σ^+)
2	-	23.1	638 ± 20	1.0	π^- (K^-)
3	+	17.2	227 ± 7	~1.0	π^+
4	-	23.3	2254 ± 118	1.0	π^-

[a] This momentum is that of the pion beam.

[4] Elliott, Maenchen, Moulthrop, Oswald, Powell, and Wright, Rev. Sci. Instr. 26, 696 (1955).

Since all the momenta are well measured, we can calculate the mass M_n of an assumed neutral particle or the effective mass of a combination of neutral particles that is needed to account for the missing energy and momentum. The missing energy E_n depends on the various possible choices of mass for the visible particles; the neutral mass $M_n = \sqrt{E_n^2 - p_n^2}$ will thus depend on these choices. These various interpretations and the resulting M_n are summarized in Table II.

Two values of M_n are given for each reaction. The first, $M_{n(1)}$, is the value obtained from the measurements in Table I. The second, $M_{n(2)}$, is the value obtained by decreasing the momentum of Track 4 by 3.5%. This adjustment was made in order to bring the Q value of the visible θ^o decay into agreement with the value to be expected if the θ^o mass were equal to 493.4 Mev, the τ^+ mass. Only this momentum was adjusted, because it contributes nearly all the uncertainty in Q.

Table II

Various interpretations of the event shown in Fig. 2. M_n is the effective mass corresponding to the missing energy and momentum. $M_{n(1)}$ was calculated from the momenta in Table I. $M_{n(2)}$ was calculated in the same way, but with the restriction that the Q value of the θ^o particle must be 214.2 Mev. Imaginary values of M_n indicate more missing momentum than missing energy. The errors on M_n are about 1.5 standard errors.

	Reaction	$M_{n(1)}$ (Mev)	$M_{n(2)}$ (Mev)
	Track: 0 → 1, 2, 3,4		
Case A	$\pi^- + p \rightarrow p + \pi^- + \theta^o + M_n$	438^{+178}_{-272}	502^{+136}_{-186}
Case B	$\pi^- + p \rightarrow \Sigma^+ + \pi^- + \theta^o + M_n$	$i(519^{+40}_{-58})$	$i(487^{+27}_{-39})$
Case C	$\pi^- + p \rightarrow p + K^- + \theta^o + M_n$	$i(375^{+78}_{-260})$	$i(322^{+68}_{-226})$
Case D	$K^- + p \rightarrow p + \pi^- + \bar{\theta}^o + M_n$	500^{+172}_{-272}	561^{+132}_{-164}

The errors listed in Table I correspond to about 1.5 standard errors, and include estimated gas distortion in the cloud chamber as well as measurement uncertainties. The latter were estimated from the internal consistency of four sets of measurements of the event, which indicated that both for angles and for curvatures there is one chance in ten that the true value lies outside the errors used. The gas distortion was estimated by measuring curvatures of beam tracks at one of the times when the magnetic field was turned off briefly (about 45 minutes before this event occurred). The distortion was found to be less than 0.04 mm, which corresponds to a radius of curvature of about 100 meters for a 20-cm track. The agreement between the measured and the expected momentum of beam particles also indicated little gas distortion. The momentum and angle errors were combined in quadrature to obtain the uncertainties on M_n listed in Table II. The adjusted value of the momentum of Track 4 was not allowed to vary in the computation of the errors in $M_{n(2)}$. Higher derivatives were taken into account, and the resulting errors also correspond to 1.5 standard errors. The value of M_n mentioned in the abstract, however, corresponds to $M_{n(2)}$ in Reaction A, and its error has been reduced to corredpond to one standard error.

It is of interest to consider the reactions listed in Table II from the point of view of the scheme of Gell-Mann and Pais[5] for the classification of heavy unstable particles. In this theory the usually observed θ^o is part of an isotopic spin doublet, $\theta^o\ \theta^+$, with "strangeness" S = +1; its antiparticle, the $\overline{\theta}^o$, is part of the doublet $\overline{\theta}^o\ \theta^-$ with S = -1. The Λ and Σ hyperons are assigned S = -1. Selection rules for production processes result from conservation of the strangeness quantum number in all strong interactions. Hence a θ^o or a θ^+ may be produced[6] together with a $\overline{\theta}^o$, θ^-, Λ^o or Σ, but a $\overline{\theta}^o$ or a θ^- may be produced only with a θ^o or a θ^+.

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[5] M. Gell-Mann, Phys. Rev. 92, 833 (1953); M. Gell-Mann and A. Pais, Proceedings of the 1954 Glasgow Conference on Nuclear and Meson Physics (Pergamon Press, London, 1955); M. Gell-Mann, Pisa Conference, June 1955 (unpublished).

[6] The τ meson may have the same doublet arrangement as the θ, and could replace it in these production rules. We mention only the θ here although we cannot differentiate between a θ^o and a τ^o as the missing neutral particle.

The most reasonable interpretation of the event is Reaction A:

$$\pi^- + p \rightarrow p + \pi^- + \theta^o + \text{(neutral)}$$

The neutral particle has a mass of about 500 Mev and can be either a neutral K meson or two or three neutral pions. The latter interpretation violates the rule of associated production of heavy unstable particles. If the associated production rule is valid, then the neutral particle is a K meson. This means that in the Gell-Mann scheme, either it or the observed V^o must have S = -1 and be a $\overline{\theta}^o$.[6] The neutral particle left the sensitive region of the chamber in a proper time of about 0.8×10^{-10} sec.

As shown by the imaginary mass values in Table II, both Reactions B and C may be ruled out, since they result in more missing momentum than missing energy and thus cannot be balanced by any real particle.

In Reaction D we consider the rather unlikely possibility that our pion beam may have a small contamination of K mesons. Such an energetic K^- is kinematically possible, and its proper time of flight from the target to the cloud chamber is about 10^{-8} sec. In this case the missing neutral particle presumably consists of two or three neutral pions. One may note that the incident K^- has strangeness -1. In order to conserve strangeness the V^o whose decay is observed must have S = -1 and therefore must be a $\overline{\theta}^o$. Thus with either Reaction A or D we require the presence of a nuetral K meson with S = -1.

We have considered only two other possible interpretations. One is that Prongs 1 and 2 are due to a very rapid Λ^o decay. This may be ruled out because the Q value of such a decay would be 225 Mev. The other possibility is that Prong 1 is a proton from a rapid decay of $\Sigma^+ \rightarrow p + \pi^o$ which had a sufficiently small angle of decay to escape observation. The track was examined carefully, and at many points along the track the minimum detectable angle was estimated and transformed to the center-of-mass system of the Σ^+. Assuming the decay to be isotropic in the center-of-mass system, one finds that less than 4% of such decays could have escaped observation. The actual probability of this interpretation is somewhat smaller than this limit because roughly half of these undetectable decays would require momenta for the Σ^+ that would not fit the kinematics of the original event.

The possibility that this event is due to a collision with a carbon or oxygen nucleus is considered extremely small. Methyl alcohol, which was the condensable vapor in the cloud chamber, constituted about 0.1% of the gas molecules at the beam level. Carbon or oxygen stars should be recognizable as such because of the net positive charge of the event of 5 or 7, and because of the typical highly ionizing low-momentum prongs. The dot near the origin of this event is too displaced and too rounded to be a recoil blob. The few alcohol stars observed were easily recognized.

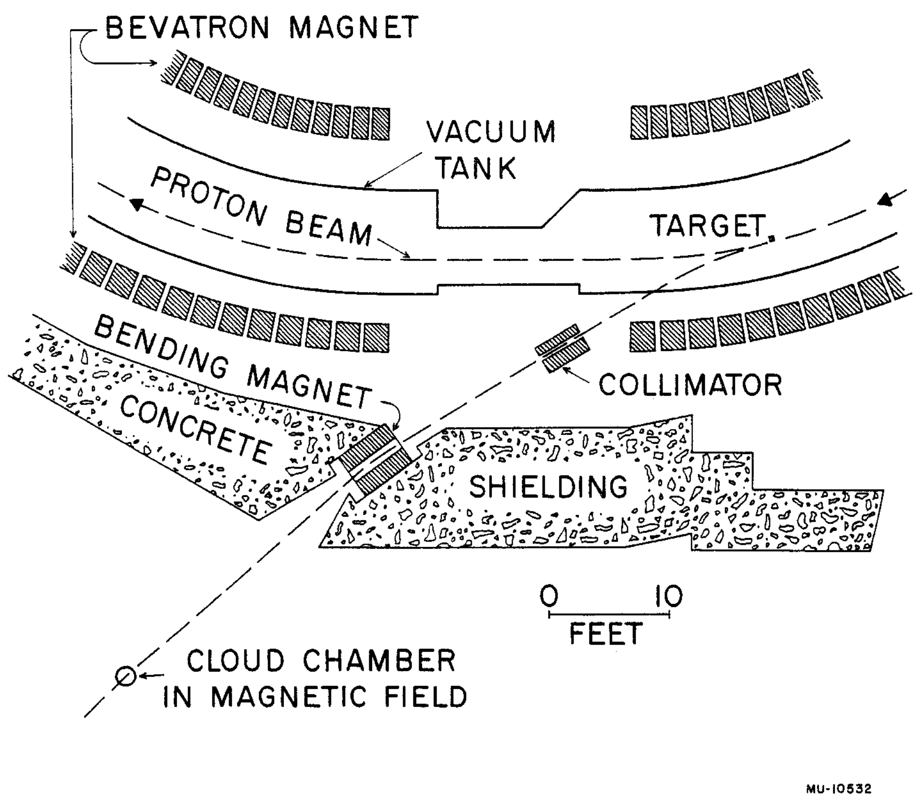
We wish to thank Mr. Howard S. White for programing and processing some of the calculations on an IBM 650 computer. We are indebted to Dr. Edward J. Lofgren and the Bevatron staff for their excellent cooperation.

This work was performed under the auspices of the U. S. Atomic Energy Commission.

Figure Captions

Fig. 1. Experimental arrangement of the 4.5-Bev/c π^- beam.

Fig. 2. Photograph of the region near the origin of the event. The most likely interpretation is that Track 0 is the incident 4.5-Bev/c π^- meson, Track 1 is a proton, Track 2 is a π^- meson, and Tracks 3 and 4 are pions from the θ^0 decay.


BEVATRON MAGNET
VACUUM
TANK
PROTON BEAM
TARGET
BENDING MAGNET
CONCRETE
COLLIMATOR
SHIELDING
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FEET
CLOUD CHAMBER
IN MAGNETIC FIELD
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Fig. 1

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Fig. 2