Production of K Mesons and Hyperons in Hydrogen by 1.95-Bev Protons*

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A search has been made for K mesons and hyperons produced by a well-collimated beam of 1.95-Bev protons in a hydrogen-filled diffusion chamber. One case of associated production was observed, which is interpreted as $p+p\rightarrow\Lambda^0+K^++p$. In a total track length of 2.4×10^5 g/cm² of hydrogen, no other hyperons or K mesons were observed to be produced. It is concluded that the cross section for production of K mesons and hyperons is probably less than 0.4 mb.

INTRODUCTION

THE production of heavy unstable particles in free proton-proton collisions was investigated by exposing a hydrogen-filled diffusion cloud chamber to the 1.95-Bev proton pencil beam at the Cosmotron. The method of producing such an external beam at the Cosmotron has been described in an earlier article which reported a similar pencil beam experiment at an energy of 3 Bev.[1] References to previous work in this subject are cited in that article. By comparing the results of the present experiment, which is at an incident energy slightly above the energy threshold for associated production of hyperons and heavy mesons, with the experiment at 3 Bev, it was hoped to obtain a qualitative appraisal of the excitation function for the production of heavy unstable particles in free proton-proton collisions.

Briefly summarized, the experimental technique is as follows: the external proton beam is collimated and focused to narrow, pencil-like proportions and is passed once every 30 seconds through the sensitive region of the Brookhaven magnet diffusion chamber.[2] The width of this beam is about 1 cm and the average intensity about 500 protons per pulse. Heavy unstable particles produced in proton-proton collisions in the hydrogen gas of the chamber are detected by observing their decay in the 5-cm deep sensitive region of the chamber. Because of the masking effect of the pencil beam and the limited extent of the sensitive region, only a fraction of the V particles produced are detected.

7600 traversals of the pencil beam through the chamber were photographed and one definite case of heavy unstable particle production was observed. In this event both hyperon and K meson are identified, and this case of associated production in free proton-proton collision is reported here in detail. Tentative conclusions are drawn about the production cross section, based upon the observation of this one event and a calculated estimate of the efficiency for detecting V particles produced in the gas.

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[1] Cool, Morris, Rau, Thorndike, and Whittemore, Phys. Rev. **108**, 1048 (1957).
[2] The construction and operation of this chamber have been described by Fowler, Shutt, Thorndike, and Whittemore, Rev. Sci. Instr. **25**, 996 (1954).

ASSOCIATED PRODUCTION EVENT

In order to establish a neutral unstable particle as having been produced in a free proton-proton interaction, it was required that its line of flight, calculated from the spatial orientation and momenta of its decay products, intersect the region in the chamber through which the pencil beam passed, and that it also have a common origin with at least one track emerging from the beam in that region. The latter requirement was necessary in order to make it more nearly certain that the unstable particle actually was produced in an interaction in the gas and was not produced by high-energy background incident upon the steel walls of the chamber.

In 7600 pictures, three events were interpreted as decays of heavy unstable particles. All of these were neutral particles, but only one of them was definitely associated with other tracks emerging from the beam. Of the other two neutral particles, one was identified as Λ^0 by the kinematics of its decay products, and the other was consistent with either Λ^0 or θ^0. Neither of these two particles is associated with any other track emerging from the pencil beam. Moreover, their calculated lines of flight intersect the center of the beam only 4 cm and 2 cm, respectively, from the front steel wall of the chamber, indicating that they were probably produced by background particles incident upon the front steel wall.

The definite case of associated production referred to above is shown in Fig. 1. Two positively charged particles, c and d, emerge from an interaction at the edge of the pencil beam, and a neutral particle decays about 10 cm away. The line of flight of the neutral particle, calculated from the measured momenta and space angles of its decay products, a and b, passes within 0.1 ± 0.3 cm of the intersection of c and d. The errors quoted here and those to follow are the maximum uncertainty, not the probable error, in the stated quantities. Momentum is conserved by the four tracks, but because of the errors in measurement, the presence of a neutral particle with momentum <0.150

Bev/c cannot be ruled out. The measured momenta and ionization densities are given in Table I.

The upper limit placed on the ionization estimate of d is supported by noting that it is less dense than a 0.440-Bev/c proton track, located at the same height, 2 cm away, whose ionization should be $3\frac{1}{2}$ times minimum. Further, the upper mass limit of 600 Mev obtained from the momentum and ionization values is in agreement with the mass limit obtained from the measurement of a relatively energetic electron ejected by d. This electron is ejected at an angle greater than 54° and has a range greater than 2.4×10^{-3} g/cm² in hydrogen, which corresponds to a kinetic energy greater than 0.059 Mev. To conserve energy and momentum in the collision process, particle d must have a mass less than 650 Mev.

In terms of known particles, the possible interpretations of this event consistent with the incident kinetic energy and conservation of strangeness, heavy particles, and charge are

$$p+p\rightarrow\Lambda^0+K^++p, \quad (1)$$

$$p+p\rightarrow\Sigma^0+K^++p, \quad (2)$$

$$p+p\rightarrow\Sigma^++K^0+p. \quad (3)$$

The production of a π meson as an additional particle in reactions (1)–(3) is not possible since the incident energy is below the energy threshold for such a process.

In reaction (3), the maximum momentum which the K^0 could have is 0.810 Bev/c. However, the momentum of the observed neutral particle, p_N, calculated from

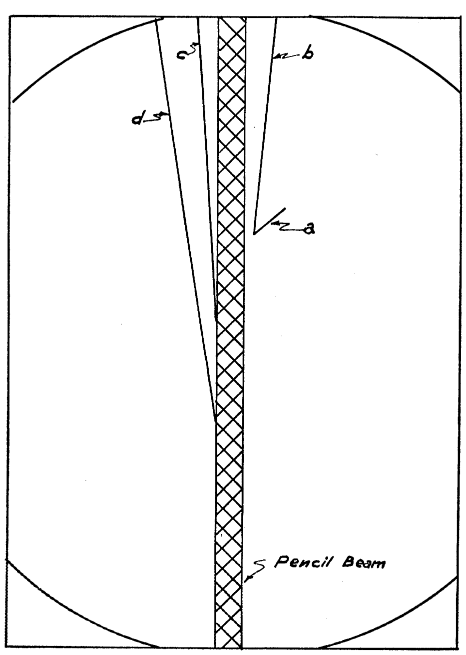

FIG. 1. Drawing of event interpreted as $p+p\rightarrow\Lambda^0+K^++p$. Pencil-beam protons enter chamber from bottom of picture. Tracks a and b are pion and proton from the Λ^0 decay, track c is the proton, and d is the K^+ particle.

TABLE I. Momentum and ionization data for event described in Fig. 1.

Particle	a	b	c	d
Sign	−	+	+	+
Length (cm)	3	11	22	22
Measured momentum (Bev/c)	0.120 ± 0.02	$0.975_{-0.10}^{+0.13}$	1.38 ± 0.05	0.270 ± 0.008
Ionization	$\sim2\times$min	$<1.5\times$min	$<1.5\times$min	2–3 $\times$min
Mass limit from momentum and ionization (Bev)	...	<1.10	<1.4	$0.38<m_d<0.60$
Mass limit from knock-on electron (Bev)	...	...	...	$m_d<0.65$

the momenta of its decay products is 1.06 ± 0.12 Bev/c. This incompatibility, together with the mass limit placed on particle d, makes it impossible to fit the observed event with reaction (3).

The observations do not fit Σ^0 production [reaction (2)] very well. In the center-of-mass system, the total energy of d identified as a K^+ meson, U^*, is 0.539 ± 0.004 Bev, and the total energy of c identified as a proton, U_p^*, is 0.984 ± 0.008 Bev. Since the available energy (including rest-mass energy) in the center-of-mass system for protons of 1.950 ± 0.020 Bev kinetic energy incident upon hydrogen is 2.680 ± 0.010 Bev, the energy left to a third particle is $2.680-U_K^*-U_p^*=1.157\pm0.022$ Bev. This agrees with the computed energy of the Λ^0 ($U_0^*=1.133\pm0.007$ in the center-of-mass system), but not with 1.197 ± 0.004 Bev, the energy needed if the third particle is to be a Σ^0 as in reaction (2).

If the reaction (1) is assumed, the Q value of the neutral particle, when it is identified as a Λ^0, is 38 ± 15 Mev. The uncertainty in the momentum of the neutral particle can be reduced by computing p_N from the accepted Q value of a Λ^0 and the angles between the line of flight of the neutral particle and its decay products. This gives $p_N=1.06\pm0.03$ Bev/c. Upon using this value for p_N, if the upper mass limit on particle d is ignored and it is identified as a proton, the mass of particle c must be imaginary in order to satisfy conservation of energy. If c is identified as a proton, then conservation of energy leads to a mass of 560_{-90}^{+80} Mev for d. This is in agreement with the accepted mass of the K^+ meson (494 Mev) which is the only known mass that would be compatible with the mass limits set on d by the ionization-momentum measurement and energetic knock-on electron. Thus, the observed event is consistent only[3] with reaction (1): $p+p\rightarrow\Lambda^0+K^++p$.

To our knowledge, this is the first case of unstable-particle production in free proton-proton interactions

[3] There is an extremely slight possibility that the reaction is $p+n\rightarrow\Lambda^0+K^++n$ which occurred within a carbon or oxygen nucleus in the alcohol vapor, and that the resulting neutron became a proton by charge exchange within the nucleus. However, there are 160 times as many free protons as neutrons within the chamber. Also, the fact that transverse momentum of the particles in this event balances within 45 Mev/c makes this interpretation even less likely.

TABLE II. Estimated limits to production cross sections of heavy unstable particles in proton-proton collisions.

Reaction products	Detection probability	No. of events identified[a]	Probable upper limit to cross section[b]	Probable lower limit to cross section[b]
Λ^0+K^++p	0.12	1	0.38 mb	0.0006 mb
Σ^0+K^++p	0.12	0	0.27 mb	...
Σ^++K^0+p	0.14	0	0.23 mb	...
Σ^++K^++n	0.06	0	0.55 mb	...

[a] In a total path of 2.4×10^5 g/cm^2 of hydrogen.
[b] The probable upper limit is here computed to be that cross section which would yield the observed number of events or fewer with a probability of 0.01 according to Poisson statistics. The lower limit would yield the observed number of events or more with a probability of 0.01.

in which both the K meson and hyperon appear to have been conclusively identified.

PRODUCTION CROSS SECTION

In order to estimate the production cross section it is necessary to establish the efficiency for detecting unstable particles produced in interactions in the gas. For an unstable particle to be detected in the diffusion chamber used in this experiment, it must decay in a portion of the sensitive region which is visible in both stereoscopic views, and at least one of its decay products must be charged. The dimensions of the chamber are such that only V particles with lifetimes of the order of 10^{-10} second have an appreciable probability of decaying in the sensitive region. Thus in the four production reactions consistent with the conventional conservation laws,

$$p+p\rightarrow\Lambda^0+K^++p, \tag{4}$$

$$p+p\rightarrow\Sigma^0+K^++p, \tag{5}$$

$$p+p\rightarrow\Sigma^++K^0+p, \tag{6}$$

$$p+p\rightarrow\Sigma^++K^++n, \tag{7}$$

only the Σ^+, Σ^0, Λ^0, and $\theta_1{}^0$-component of the K^0 have a substantial probability of being detected when produced. These probabilities have been estimated by a Monte Carlo process. One hundred of each of the above particles were considered to be produced at points uniformly distributed throughout the region through which the pencil beam passed. It was assumed that the angular distribution of these particles is isotropic in the center-of-mass system, and that their momentum distribution corresponds to Fermi's statistical theory. The average probability for the Σ^+, Σ^0, Λ^0, and K° to decay in a visible portion of the sensitive region was thus calculated to be 0.06, 0.20, 0.20, and 0.21, respectively. The scanning efficiency was assumed to be 90%, which is reasonable in view of the low background in the pictures and the fact that each picture was scanned twice—once by a physicist and once by an experienced scanner.

On the basis of present evidence,[4] one third of the Λ^0's have been assumed to decay to neutral particles which are not detected in this experiment. Also, half of the K^0's are expected to be too long-lived to decay in the chamber. It was further assumed that if either of the two unstable particles produced in a single production reaction is observed, then the reaction will be identified. The resulting estimated efficiencies for detecting the reactions (4)–(7) are, respectively, 0.12, 0.12, 0.14, and 0.06.

The average intensity in the 7600 pictures was 500 protons per picture. If one takes the effective path length of each proton traversing the chamber to be 30 cm, and the density of the hydrogen in the chamber to be 2.1×10^{-3} g/cm^3, the result is a total path in hydrogen of 2.4×10^5 g/cm^2. Based on the one observed event which was identified as reaction (4), and assuming that the observable events obey Poisson statistics, probable limits on the cross sections for reactions (4) to (7) have been computed and are listed in Table II.

It should be observed that if the distribution of unstable particles is not isotropic but peaked in the forward and backward directions, the likelihood will be decreased that an unstable particle should emerge from the beam before decaying. In this case, the cross-section limits presented in Table II would be too low.

The above considerations indicate that it would require an improbable statistical fluctuation, or an angular distribution sharply peaked in the forward direction, in order for the results of this experiment to be consistent with a proton-proton production cross section for known unstable particles greater than about 0.4 mb at 1.95-Bev energy. This conclusion is consistent with the work of others[1,5] who have studied the proton-proton production of unstable particles at 3 Bev.

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[4] Eisler, Plano, Samios, Schwartz, and Steinberger, Nuovo cimento **5**, 1700 (1957).
[5] Baumel, Harris, Orear, and Taylor, Phys. Rev. **108**, 1322 (1957).