π^+-p Interactions Producing Σ^+-K^+ in a Propane Bubble Chamber*†

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Seven cases of production of Σ^+-K^+ by 1.0-Bev π^+-p interactions have been identified in the Yale propane bubble chamber. In six of these cases, the Σ^+ direction was forward in the center-of-momentum system. The cross section derived from these is 0.08 mb. The decay of the Σ^+ is equally divided between the pion and proton decay modes.

EXTENSIVE observations[1] have been made of associated production by negative pions of approximately 1-Bev energy colliding with protons. The corresponding production by positive pions in the same energy region is less well known and is of considerable interest for the study of the charge dependence of the associated production mechanism. In the case of positive pions, only the single process $\pi^++p\rightarrow\Sigma^++K^+$ can occur at 1 Bev of energy. Following is an account of events observed in the Yale 33-cm propane bubble chamber, interpreted as $\pi^++p\rightarrow\Sigma^++K^+$, at an energy of 1 Bev.

I. APPARATUS AND BEAM ARRANGEMENTS

The Yale propane chamber is $13\frac{1}{2}$ in.$\times6\frac{1}{2}$ in.$\times4\frac{1}{2}$ in., operated in a magnetic field of about 8000 gauss. It is similar in construction and based upon the design of the chamber described by Oswald, Fowler, and Powell.[2] An unusual feature of the Yale chamber is that its temperature is controlled by hot oil circulating rapidly through a jacket adjacent to the chamber walls. This arrangement provided a short term temperature stability of the order of 0.01°C, and the temperature could be controlled within 0.1°C over an extended period. The chamber was mounted in a horizontal magnetic field between two pole pieces of the electromagnet. The beam, which was parallel to the 33-cm length of the chamber, entered the chamber through a 1 in.$\times$3 in. window containing 4 g/cm^2 of stainless steel.

The Yale chamber was one of four bubble chambers operated simultaneously in pion beams from the same target at the Cosmotron. A diagram of the arrangement and details of the beam layout are given by Erwin and Kopp.[3] The design of the beam was similar to that of previous high-energy π^+ beams[4,5] at the Cosmotron. The external 3.0-Bev proton beam from the Cosmotron was made to strike a polyethylene target 1 in. thick, 8 in. high, and 18 in. in the beam direction. The pions were selected at 7° to the target, and the pion beam was momentum-analyzed twice, once before and once after the primary Cosmotron shielding. In another concrete shield near the chamber, the beam was collimated to $\frac{3}{4}$ in.$\times$3 in. by a brass collimator 36 in. long. A strong-focusing quadrupole magnet pair with 12-inch aperture was used just after the target to focus the pions at the chamber. Measurement of particle trajectories, by observing the deflection of a current-carrying wire, indicated a momentum resolution of $\pm2\%$.

ANALYSIS AND CONCLUSIONS

The total track length of pion tracks which passed through the thin window in this experiment was measured to be 1.1×10^6 g/cm^2 of propane. This figure was obtained by counting the number of beam tracks in a uniformly distributed sample of pictures. This beam is a mixture of pion and proton tracks, with a small percentage of muons and electrons. To ascertain the cross section for production of Σ^+-K$^+$ by pions, it is necessary to determine the fraction of beam which consists of pions. There is considerable uncertainty in this fraction, and it is difficult to determine from the pictures. The pion fraction in the Yale chamber has been measured by three different methods, each applied to a sample taken at a different part of the series of pictures.

One method used is based upon the higher bubble density of proton tracks compared to meson tracks at the beam momentum of 1.15 Bev/c. Instead of counting individual bubbles, gaps between bubbles which were greater than a certain arbitrarily selected minimum length were counted.[6] At the same time, the amount by which each counted gap length exceeded the minimum gap length was measured, these amounts were totalled, and divided into the number of counted gaps. The result equals the average number of bubbles per

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[1] Report of the *1958 Annual International Conference on High-Energy Physics at* CERN, edited by B. Ferretti (CERN Scientific Information Service, Geneva, 1958), p. 148. This paper supplants preliminary results reported there by the Yale Group.
[2] L. O. Oswald, Rev. Sci. Instr. **28**, 80 (1957).
[3] A. Erwin and J. Kopp, Phys. Rev. **115**, 669 (1959).
[4] R. Cool, O. Piccioni, and D. Clark, Phys. Rev. **103**, 1082 (1956).
[5] J. L. Brown, D. A. Glaser, D. I. Meyer, M. L. Perl, and J. Van der Velde, Phys. Rev. **107**, 906 (1957).
[6] W. J. Willis, E. C. Fowler, and D. C. Rahm, Phys. Rev. **108**, 1046 (1957). Blinov, Krestnikov, and Lomanov, J. Exptl. Theoret. Phys. U.S.S.R. **31**, 762 (1956) [translation: Soviet Phys.-JETP 4, 661 (1957)].

TABLE I. Kinematics of observed π^+-p interactions producing Σ^+-K^+.

Event No.	Lab angle of Σ^+	Lab angle of K^+	Lab π momentum (Mev/c)	Angle of Σ^+ (cm.)	Σ^+-decay mode
92319	15°	26°	1130	105°	p
92629[a]	4.5	44	1180	20	π
00335[a]	7	38	1120	36	π
01396[b]	10.5	32	1100	67	p or π
22623	15.5	35	1160	84	p
33349	14.5	46	1220	77	π
34844	8	31	1090	31	p

[a] In these cases, the K decayed also, stopping in the chamber.
[b] The pion which produced this event did not pass through the thin window of the chamber.

unit track length assuming that bubbles are randomly distributed along the track. The arbitrarily selected minimum gap length must be chosen to be larger than the minimum resolvable distance between bubbles. This method avoids errors due to clogging of bubbles. The procedure was applied to a sample of 66 beam tracks taken from adjacent pictures with uniform temperature conditions in the chamber. The resulting histogram of gap densities was interpreted to be caused by two groups of different bubble density. The meson fraction obtained in this manner was 0.40±0.07. The ratio of the mean proton bubble density to the mean meson bubble density was 1.5.

A second method of measuring the meson fraction used the fact that protons of this momentum cannot produce a δ ray of range greater than 2 cm, whereas a meson traversing the chamber has a readily calculable chance, (about 20%) of doing so. A count of δ rays for a sample of 428 tracks yielded a meson fraction of 0.60±0.07.

A third method, based upon the number of identified p-p elastic events (16) in a sample of 2000 tracks, gives a meson fraction of 0.50±0.08.

Averaging these results gives a meson fraction of 0.50. Although the muon contamination was not measured, observations[4] of similar beams have found it to be about 8%. The pion fraction in this beam is therefore considered to be 0.46.

The possible events of the type $\pi^+ + p \rightarrow \Sigma^+ + K^+$ were first selected by the requirement that they be coplanar within 4° and that the production angles of the Σ^+ and K^+ be not clearly inconsistent with the reaction, assuming the pion momentum to be between 1.05 and 1.25 Bev/c. Forty-one possible events were selected in this manner.

These events were checked in detail for validity on the basis of their production angles. Since the production of Σ^+ and K^+ is a two-body process, all other kinematical quantities are determined by these two parameters. The track densities and curvatures of the secondary tracks, as well as the decay angle from the Σ^+, were required to be consistent with the values calculated from the production angles assuming the reaction $\pi^+ + p \rightarrow \Sigma^+ + K^+$.

Of the events screened, seven satisfied all the above criteria for $\pi^+ + p \rightarrow \Sigma^+ + K^+$. In two of these, the K particle stops in the chamber and decays. These events are summarized in Table I. In six of the seven cases, the Σ^+ direction in the center-of-momentum system lies in the forward hemisphere. The average pion momentum is 1.15 Bev/c, in good agreement with the expected value.

To determine the cross section for Σ^+-K^+ events, the efficiency of detection, as well as the number of spurious hydrogen-like events produced by interactions in carbon, must be evaluated. The chance of missing a Σ^+ decay because of too small a decay angle or too short primary track, is about 33%. Combining this chance with a measured scanning efficiency of 86%, yields an over-all detection efficiency of 58%. The estimated fraction of spurious events produced by carbon interactions is 11%. From these data, the calculated cross section, based upon the six events produced by pions through the thin window, is 0.08 mb. In addition to statistical uncertainty in the cross section caused by the small number of observed events, there are estimated uncertainties of 15% in detection efficiency, 10% in beam flux, and 15% in beam composition.

This value for the cross section is lower than, but not inconsistent with the values found by others.[3,5]

APPENDIX

The estimate of the number of spurious hydrogen-like Σ-K production events due to carbon interactions was obtained by evaluating the following three independent factors. (1) Because of interactions as the pion beam passes through the carbon nucleus, the average pion flux seen by a proton within the nucleus is lower than that incident upon a proton outside the nucleus[7]; (2) There is a chance that either the K or the Σ^+ particle will interact within the carbon nucleus before it emerges; and (3) The Fermi momentum of a proton in carbon often produces a noncoplanar event or an apparent value for the incident pion momentum which is clearly untenable.

The average pion flux inside the carbon nucleus was calculated to be 54% of the value incident upon the nucleus for a Gaussian distribution of nucleons and 52% for a uniform distribution, assuming in each case an rms radius of 2.4 fermis. Since the actual nucleonic distribution seems to lie between these extremes,[8] 53% appears to be an accurate value for this average flux.

The average chance that both Σ^+ and K^+ particle emerge from the carbon nucleus without further interaction was crudely estimated at 33%, assuming that

[7] The existence of this factor was pointed out to us by H. D. Taft.

[8] J. H. Fregeau and R. Hofstadter, Phys. Rev. 99, 1503 (1955).

the Σ^+-nucleon cross section is 45 mb and the K^+-nucleon cross section is 15 mb, and assuming each to travel one nuclear radius before emerging from the carbon nucleus.

The effect of Fermi momentum of the carbon proton was evaluated by assuming that 80 Mev/c of transverse momentum would lead to a clearly noncoplanar interaction, and that 100 Mev/c along the pion direction would lead to an apparent incident momentum that is clearly incorrect. Assuming the Gaussian distribution of proton momenta given by Cladis, Hess, and Moyer,[9] one then finds that a carbon event has only a 28% chance of not being rejected because of its proton motion.

[9] J. B. Cladis, W. N. Hess, and B. J. Moyer, Phys. Rev. 87, 425 (1952).

Multiplying these three attenuation factors by the ratio of carbon to hydrogen protons present in the propane, one obtains the figure of 11% contamination by spurious events from the carbon.

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Small-Angle Proton Scattering at 3 Bev*

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The differential cross section for elastic scattering of 3-Bev protons has been measured with targets of hydrogen, carbon, copper, and lead over the angular range 0.5 to 4 degrees in the laboratory coordinate system. Within our limits of error, no evidence was found of Coulomb-nuclear interference with hydrogen, while with carbon there is indication of a real component of the nuclear scattering amplitude associated with a repulsive force. It is inferred from the extrapolated nuclear scattering cross section at zero degrees that appreciable scattering results form spin dependent forces with hydrogen but not with carbon. A derived value of the rms radius for p-p scattering exceeds that found in electron-proton scattering by a factor $\sqrt{2}$.

INTRODUCTION

THE purpose of this experiment was to measure directly the absolute values of some nuclear differential elastic-scattering cross sections $\sigma_e(\theta)$[1] for protons of 3-Bev energy, particularly at small angles where the Coulomb and nuclear elastic scattering are of comparable magnitude and the possibility exists of appreciable interference between the two. Since the Coulomb scattering amplitude is known, this gives information about the real and imaginary components of the nuclear scattering amplitude $f_n(\theta)$. At lower energies the effect is well known; for example, for 96-Mev protons on C and Al there is considerable destructive interference.[2] More generally, the differential cross sections at various energies furnish the data from which the parameters of any assumed nuclear potential must be calculated.

In the Bev energy range, the Coulomb and nuclear elastic scattering are of comparable magnitude at very small angles; these may be estimated crudely as follows. The point charge Coulomb scattering of protons at small angles θ in the laboratory system is given approximately by

$$\sigma_C(\theta)=4Z^2r_e^2(mc^2/pv)^2/\theta^4 \text{ cm}^2/\text{sr}, \quad (1)$$

where Z is the nuclear charge, $r_e=2.82\times10^{-13}$ cm, mc^2 is the electron self-energy, and p and v are the momentum and velocity of the incident proton in the laboratory system. The nuclear elastic scattering is mostly diffraction scattering resulting from absorption processes, principally meson production. Hence the forward scattering amplitude is approximately that due to a "black disk" of radius R cm:

$$\sigma_e(0)=\tfrac{1}{4}k^2R^4 \text{ cm}^2/\text{sr}, \quad (2)$$

where k is the propagation constant of the incident

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[1] We use the following notation for various cross sections: $\sigma_e(\theta)$ for the nuclear elastic differential scattering, $\sigma_C(\theta)$ for the Coulomb *point-charge* differential scattering, $\sigma(\theta)$ for the total effective elastic differential scattering, σ_e for the total nuclear elastic scattering, σ_a for the total nuclear absorption, and $\sigma_t=\sigma_e+\sigma_a$ for the total nuclear cross section.

[2] G. Gerstein, J. Niederer, and K. Strauch, Phys. Rev. 108, 427 (1957).