particles to stars initiated by K^- mesons is much too high to be accounted for by production of neutral K mesons in the emulsion. This time is long compared to the lifetime of the decay $\theta^0 \rightarrow \pi^+ + \pi^-$, attributed in the scheme of Gell-Mann and Pais[9] to the θ_1. The θ_2, with a possibly longer life, has then a component which is $\bar{\theta}^0$ and would interact as a particle of negative strangeness. It could alternatively be a $\bar{\tau}^0$ which causes these events, if the τ meson is a different particle from the θ meson.[10]

[9] M. Gell-Mann and A. Pais, Phys. Rev. **97**, 1387 (1955). The decay of particles produced in the $\bar{\theta}^0$ mode have been observed by Alvarez *et al.*, reference 4.

[10] G. A. Snow, Phys. Rev. **103**, 1111 (1956).

Similar events have been described by the Wisconsin group.[11]

We would like to express our appreciation to Dr. M. M. Shapiro for exposing the emulsion, to Professor E. J. Lofgren and the Bevatron staff for arranging the exposure, to F. W. O'Dell and B. Stiller for their aid in processing the emulsion, and to Mrs. G. Rones, Mrs. J. D. Leek, and E. Witterholt for their invaluable assistance in scanning the plates. We would also like to thank the Berkeley bubble-chamber group and the Wisconsin and Brookhaven emulsion groups for sending us their data prior to publication.

[11] Fry, Schneps, and Swami, Phys. Rev. **103**, 1904 (1956).

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Scattering of K^+ Mesons by Protons*

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The scattering of 20- to 90-Mev K^+ mesons by protons has been investigated by using a propane bubble chamber. On the basis of 32 events, a total cross section of 9.4 ± 1.7 mb is obtained. The experimental angular distribution is not isotropic.

INTRODUCTION

THIS paper describes a study of the elastic scattering of positive K mesons by hydrogen nuclei at kinetic energies of less than 100 Mev. The experiment was carried out in the University of Michigan 12-inch propane bubble chamber using K^+ mesons from a specially purified beam at the Cosmotron of the Brookhaven National Laboratory.

The study of the scattering of K mesons on nucleons is of basic importance to the elucidation of the nature of K meson-nucleon interaction. One may hope eventually to obtain the same type of information from K meson-nucleon scattering experiments as has been obtained from π meson-nucleon scattering experiments. A step toward this goal is the study of the elastic scattering of positive K mesons on protons at sufficiently low energy so as to drastically restrict the number of angular momentum states involved in the interaction. The information which is required is the total and differential scattering cross sections over a range of K-meson kinetic energies.

Previous to this work all K^+ meson-proton scattering data was collected in nuclear emulsions.[1,2] While the use of emulsions has the advantage of not requiring a particularly pure K^+ beam, the scanning for K^+-proton scatterings is extremely laborious. The low kinetic energy of the K^+ meson also makes the use of counters difficult. However, a propane bubble chamber of reasonable size is suitable for this experiment, because for these low-energy scatterings both the scattered K^+ meson and the recoil proton stop in the chamber. Moreover, the speed of scanning in a bubble chamber is much greater than in an emulsion, and the separation of carbon from hydrogen scatterings is direct at these low energies. The present experiment was undertaken for these reasons with a propane bubble chamber.

* This work was supported in part by the U. S. Atomic Energy Commission.

[1] N. N. Biswas *et al.*, Nuovo cimento **3**, 1481 (1956).

[2] M. Ceccarelli (private communication of a collection of data from Göttingen, Padua, Berkeley, Bristol, Dublin, and Rochester).

EXPERIMENTAL APPARATUS

K^+ mesons were obtained by allowing the external beam of the Cosmotron to bombard a 3-inch-thick copper target. Because of the large number of π^+ mesons of a given momentum produced with the K^+ mesons, it was necessary to find some means of separating the two kinds of particles. For example, for 3-Bev protons producing mesons of momentum around 400 Mev/c, this ratio of π^+/K^+ at the target is about 100 in the forward hemisphere. Allowing a reasonable distance for momentum analysis, in which distance a large fraction of the K^+ mesons decay, one K^+ meson could have been accepted in about every 40 pictures

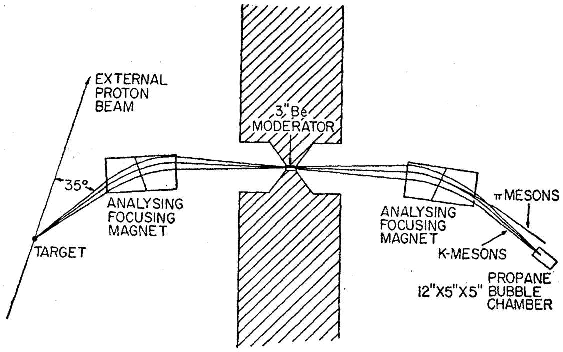

FIG. 1. The external proton beam from the Cosmotron strikes a 1.5-inch-thick copper target. A mixed beam of K and π mesons and protons is momentum-analyzed and focused, their energy degraded in Be, then reanalyzed and focused to obtain a mass separation.

without the accompanying π^+ mesons being so numerous so as to prevent the scanning of the pictures. Protons of the correct momentum have such a short range that they are stopped in the chamber wall and cause no trouble.

The method used to separate the two types of mesons consisted of a magnet to momentum-analyze the beam, followed by a moderator of Be which reduces the K^+ momentum more than that of the π^+, and a second magnet to reanalyze the beam. The system is shown in Fig. 1. In order to attain reasonable K^+-meson intensities, it was necessary to incorporate some focusing in the system. To keep the distances short so that not too many K^+ mesons would decay, momentum analysis was combined with strong focusing in a single magnet.[3] By using a large gradient, both horizontal and vertical focusing were attained with an object-to-image distance of 3 meters for each magnet. The beam of particles focused and analyzed at the chamber was 2.5 cm high by 5 cm wide. A figure of merit for the separation is that the π^+/K^+ ratio at the chamber is a factor of 50

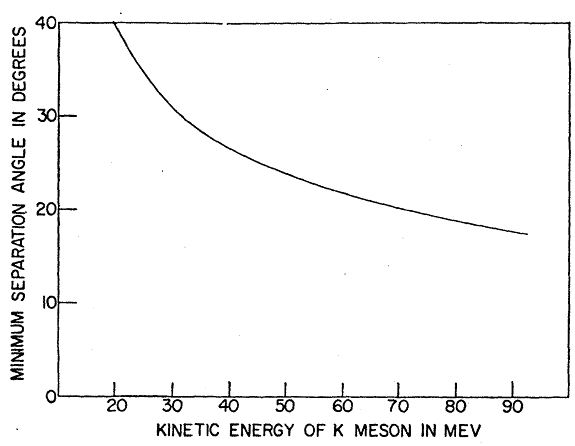

FIG. 2. Hydrogen and carbon events can be distinguished by the recoil in the hydrogen case. The minimum laboratory scattering angle at which this recoil is visible is shown as a function of the kinetic energy of the incoming K meson.

[3] R. M. Sternheimer, Rev. Sci. Instr. 24, 573 (1953).

smaller than it would be if the Be were removed and the magnet readjusted for the unseparated beam. With this system about one K^+ meson entered the chamber in every 6 pictures.

The University of Michigan propane bubble chamber has a sensitive volume of 12 by 12 by 30 cm, and was operated at 52.8°C. The K^+ mesons enter the chamber with an energy of about 100 Mev, and the stopping power is sufficiently high so that they come to rest in the chamber and decay. Stereographic pictures were taken at five-second intervals using 70-mm film.

METHOD OF ANALYSIS AND RESULTS

About 25 000 pictures were taken, of which 20 400 pictures were scanned. The remainder were not scanned because of excess beam intensity, no beam being present, or damage in the developing process. The large size of the pictures made it possible to scan with the naked eye directly from the film. The scanning was done by looking along the edge of the picture where K^+ mesons entered the chamber. Tracks having the appropriate number of bubbles per cm were then followed. A decay into a lightly ionizing particle or the characteristic τ^+ decay would then identify the K^+ meson. No attempt was made to distinguish the various decay modes except that of the τ^+. In a few percent of the tracks, where absolute bubble density was not sufficient to distinguish K mesons from π or μ mesons, the criteria involving multiple scattering of the track and rate of change of bubble density along the track were used. Occasionally a K^+ meson would be found by a general area-scanning of the pictures which was done after the above procedure was completed. Finally all tracks which were counted as K mesons were required to enter the chamber within perscribed angles and to have a length equal to at least half the chamber length if they did not scatter in the chamber. The total cross section was corrected for this second requirement which eliminates a known small fraction of K mesons which decay in flight.

3507 K^+ mesons were found, including 189 τ^+ mesons, giving a ratio of the number of τ^+ mesons to the total number of K mesons of 5.4%. This ratio agrees well with other published τ^+ to K^+ ratios and is a direct verification that the method of identification of K^+ mesons was correct.

The separation of K-meson scatterings on hydrogen from those on carbon depends upon the presence of a recoil track in the former case. In the elastic scattering on carbon of K mesons with kinetic energies in the range of this experiment, the velocity of the recoiling carbon nucleus is always much too low to produce a visible track. However, the elastic scattering on free protons gives a visible proton recoil track, if the scattering angle of the K meson is above a minimum angle which depends on the energy. This minimum angle, as shown on Fig. 2, varies from 33° at 30 Mev to 17° at 90 Mev. The minimum angle is sufficiently small so that there is only a small fraction of the solid angle about the forward direction where the separation of hydrogen from carbon events cannot be made.

All entering tracks which satisfied the bubble density criteria were scanned for scatterings. Since the minimum scattering angle for hydrogen-carbon separation is much larger than the minimum discernable scattering angle, all measurable hydrogen scatterings, that is, all scatterings with a visible recoil, were detected. Scatterings without visible recoils were noted, but will not be discussed in this paper. Measurements from the stereographic photographs provide the angles of the scattered and recoil tracks with respect to the incoming tracks. If either of these tracks stop in the chamber, the range is also known, or if they leave the chamber a minimum range is determined. Since K mesons have almost nonrelativistic energies, the relation between the scattering angle and the recoil angle is almost energy independent. These angles combined with the requirement of coplanarity are the first test as to the genuineness of a K meson-proton collision. When the ranges can also be measured, the kinematics is considerably overdetermined and the genuineness of the event can be ensured.

34 events were found in which the recoil track and scattered track stopped in the chamber and the scattered track had the characteristic K-meson decay. 32 of these events were shown by all of the aforementioned criteria to be K meson-proton scatterings. Of the remaining 2 events, one involved a K meson of less than 20 Mev and could not be satisfactorily analyzed. The other event was an inelastic K meson-carbon scattering, which could be separated from K meson-proton scatterings since the binding energy of the carbon nucleus is important at these low energies.

The chamber was sufficiently large so that no recoil track could leave the chamber, but at the higher energies some of the K mesons which are scattered by protons through certain angles should leave the chamber before decaying, if the K meson is traveling near a chamber wall. While this should not often occur, an extensive search was made for such events, by measuring all scattered incoming tracks which obeyed the bubble density criteria but did not decay in the chamber. To decrease the possibility of such bias, the bubble density criteria were relaxed to include probable π-meson tracks, if the track was too short positively to identify the nature of the incoming particle. One possible K meson-proton scattering was found in 56 such events. However, the recoil proton track was too short to be measured accurately and the nature of the event was not clear.

The distribution of the K meson-proton scattering angles in the laboratory system is shown in Fig. 3. The minimum angles for hydrogen-carbon separation are also shown; line A indicating that angle for 30 Mev and line B that angle for 90 Mev. On the basis of the analysis of the aforementioned 56 events, no more than two or three events have been missed in the range of laboratory angles of 30° to 60° in which the K meson could decay outside of the chamber after scattering on

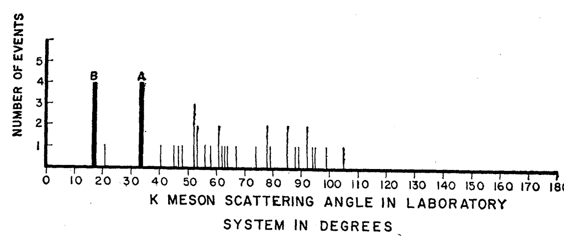

FIG. 3. The distribution of events in the laboratory system. Lines A and B correspond to the minimum angle at which hydrogen recoils can be detected for 30-Mev and 90-Mev K mesons, respectively.

a proton. The small number of events in the backward hemisphere of the laboratory system is believed to be representative of the true angular distribution because a special effort was made not to miss these possibly obscure events. The distribution of the K meson-proton scattering angles in the center-of-mass system is shown in Fig. 4 divided into six groups. The center-of-mass angles of 50° and 26° correspond to the minimum angles for carbon-hydrogen separation for 30-Mev and 90-Mev mesons, respectively.

CONCLUSIONS

The total cross section for the scattering of K^+ mesons on protons is 9.4 mb averaged over the meson kinetic energy range of 20 to 90 Mev. The statistical mean square deviation is 1.7 mb and systematic errors are expected to be of about this magnitude. The number of events is too small to obtain a definite relationship between total cross section and energy, but Fig. 5 indicates that the total cross section may increase with energy in this range.

The differential cross section averaged over the meson kinetic-energy range of 20 to 90 Mev can be derived from Fig. 4. Unfortunately the number of events is not large enough to permit a meaningful determination

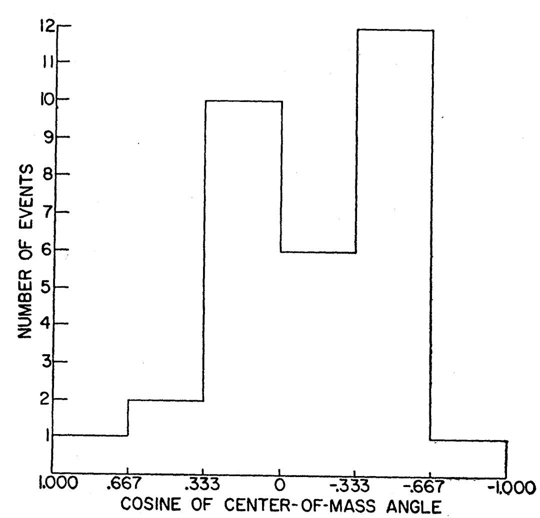

FIG. 4. The center-of-mass distribution of K meson-proton scattering in terms of equal solid angle intervals.

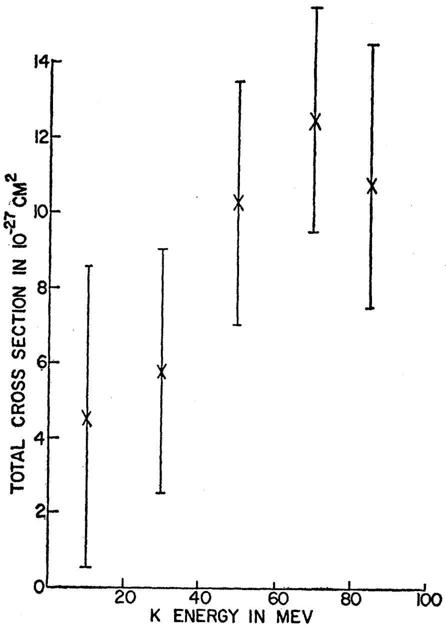

FIG. 5. The total cross section for K meson-proton scattering as a function of the K-meson kinetic energy.

of the parameters in Eq. (1).

$$d\sigma/d(\cos\theta) = 2\pi\lambda\!\!\!^{-2}(A+B\cos\theta+C\cos^2\theta+D\cos^3\theta+E\cos^4\theta). \quad (1)$$

The inclusion of the $\cos^3\theta$ and $\cos^4\theta$ terms in Eq. (1) are necessary because most of the events are at an energy where d-wave effects may be expected. If it is assumed that only s and p waves are involved in the scattering, then Eq. (2) can be fitted by least squares to obtain best values of A, B, and C.

$$d\sigma/d(\cos\theta) = 2\pi\lambda\!\!\!^{-2}(A+B\cos\theta+C\cos^2\theta). \quad (2)$$

There are, however, some general restrictions on the values of A, B, and C from the requirement that the differential cross section, Eq. (2), cannot be negative. This leads to the following restrictions

$$A+B+C\geq 0, \quad (3)$$

$$A-B+C\geq 0. \quad (4)$$

There is a stricter condition on the sum of A, B, and C if the polarization density matrix of the incoming meson beam and of the target protons has only diagonal elements, namely,

$$A+B+C\geq (\sigma/4\pi\lambda\!\!\!^{-2})^2, \quad (5)$$

where σ is the total cross section.

Table I lists the values of the coefficients, A, B, and C for the unrestricted least-squares fitting, for the least-squares fitting subject to Eq. (3) and Eq. (5), and for the assumption that only s waves are involved. These values are for a value of $\lambda\!\!\!^{-2}$ averaged over the 32 events. This last column gives the probability based on the χ^2 test for the experimental distribution to be produced by each set of coefficients. The first section in Fig. 4 is not used in this test.

TABLE I. The least-squares fit of the experimental data with various restrictions, and the χ^2 probability that these coefficients agree with the experimental data.

Restriction	A	B	C	χ^2 probability
None	0.201	−0.050	−0.245	5%
$A+B+C\geq 0$	0.171	−0.017	−0.154	1.5%
Eq. (5)	0.166	−0.012	−0.139	1%
Only s-wave	0.120	0	0	0.1%

From Table I it is clear that the probability is very small of the experimental distribution coming from either of the restricted sets of coefficients. Therefore, if it is assumed that there have been no substantial systematic errors, it can be concluded that the data cannot be interpreted with only s and p waves. It is believed that the systematic errors are not so substantial as to negate this conclusion, but only a repetition of the experiment can confirm this belief. The presence of d waves would not be surprising. The use of only low-energy events in the angular distribution is not possible because the statistics are too small to permit a division into energy ranges and still give meaningful angular distributions.

Emulsion data which have been published[1] give a higher total cross section and different angular distribution than has been found in this bubble chamber work. But unpublished additions[2] to the published emulsion results have considerably modified those results and brought the total cross section closer to the bubble chamber value.

The results of this experiment indicate both the great need for a substantial increase in K^+ meson-proton scattering statistics and the fruitfulness of the bubble chamber approach to this problem. Therefore we are now working toward the repetition of this experiment in a larger bubble chamber, with an improved K-meson beam. In this way it is hoped that statistics can be increased and bias problems considerably reduced.

We wish to thank Dr. Gustave Zorn for his close collaboration in the design of the separation system and Mr. John L. Brown for his help in the taking of data. We also wish to thank Dr. George Collins, Dr. William Moore, and the staff of the Cosmotron Department for their aid, encouragement, and patience.

Note added in proof.—A compilation containing most of the observed K^+ hydrogen scatterings in nuclear emulsions has been published by Ceolin, Cresti, Dallaporta, Grilli, Gueiriero, Merlin, Saladin, and Zago, Nuovo cimento V, 402 (1957). They find a total cross section of 14.6±3.3 mb. The differential cross section is small in the backward direction in agreement with our results. The emulsion data give many events in the forward hemisphere in contrast to our more backward peak. Our bubble chamber results have an experimental bias against very small scattering angles, so the results cannot be compared in the most forward directions.