

Investigation into the Elastic Scattering of Σ^\pm Hyperons on Hydrogen*

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An investigation has been made into the elastic scattering of Σ hyperons on hydrogen. The experiment was based on a sample of 12 000 Σ particles formed in a propane bubble chamber by the interactions of 1.15-Bev/c K^- mesons. A total track length of 210 meters in the energy range 100 to 700 Mev has been examined.

Ten examples were found of the reaction $\Sigma^+ + p \rightarrow \Sigma^+ + p$, and six of the reaction $\Sigma^- + p \rightarrow \Sigma^- + p$. The estimates of the cross sections for the two processes are, respectively, 38_{-14}^{+18} mb and 10_{-4}^{+6} mb. The scattering angle distributions in the c.m. system appear isotropic for the Σ^+ particles, and peaked forward for the Σ^- particles. The results are discussed in relation to various theoretical predictions, and, in particular, some evidence is found favoring the Gammel-Thaler method of treating the triplet odd-parity nucleon-nucleon potential.

INTRODUCTION

THE following reactions are expected between Σ^\pm particles and protons:

$$\Sigma^+ + p \rightarrow \Sigma^+ + p, \quad (1)$$

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

$$\Sigma^- + p \rightarrow \Sigma^0 + n, \quad (3)$$

$$\Sigma^- + p \rightarrow \Lambda^0 + n. \quad (4)$$

Additional processes become available above the threshold for pion production.

To date, only eight examples of interactions in flight on hydrogen have been reported, three being elastic and five inelastic.^{1,2} The reason for the lack of experimental data is to be found in the extreme difficulty of accumulating substantial amounts of track length for such short-lived particles. As an illustration one may point out that the Σ^- and Σ^+ hyperons formed in this experiment, by the interactions of 1.15-Bev/c K^- mesons, travel average distances of only 3.2 cm and 1.6 cm, respectively.

The investigation reported here offers some improvement in the experimental position through a study of 12 000 Σ^\pm hyperons created in a propane bubble chamber. The presence of carbon nuclei poses certain problems of analysis, particularly with respect to Reactions (3) and (4), for which there is generally no information on the energy and line of flight of the neutron. Consequently, our investigation is limited to studying examples of Reactions (1) and (2) occurring on hydrogen, and further consideration will not be given to the inelastic processes.

SCANNING PROCEDURE

The 30-inch propane bubble chamber,³ operating in a magnetic field of 13 kilogauss, was exposed to the

1.15-Bev/c K^- -meson beam at the Bevatron. A total of 100 000 pictures was taken, there being about one K^- -meson interaction per picture.

The scanning procedure for finding Σ -hyperon scatterings consisted of following all tracks from K^- stars in order to locate those giving a secondary star of two prongs. The two prongs were then examined closely for "kinks," i.e., sudden changes of direction. These kinks can be caused by a particle scattering from a carbon nucleus without giving a visible recoil, as well as by a particle decaying.

As one needs adequate lengths of track for angular measurements, events were not accepted unless the Σ particle had at least 3 mm of track both before and after the scattering. Because one expects a diminished efficiency for detecting very-small-angle scattering, a cutoff value for the proton's range had to be adopted. It was required that the proton's track be longer than 2 mm.

Some types of event could be immediately rejected, from observations on the scanning table, as not being Σ -hyperon scattering on hydrogen. For example, if both prongs were seen to lie on the same side of the incoming primary track, transverse momenta could clearly not be balanced. Often when one of the tracks was sufficiently long for curvature and ionization measurements to be made, the particle could be identified as being a pion instead of the expected Σ particle or proton. Many events could be ruled out because the K^- star emitted a Λ^0 hyperon or \bar{K}^0 meson, making it unlikely that it should have emitted a Σ particle also.

About 60 events could not be rejected on such general grounds and consequently were measured on digitized microscopes and the resulting data processed by an IBM 704 computer.

ANALYSIS OF THE EVENTS

All together, 16 examples of Σ -hyperon scatterings on hydrogen were identified by the analysis programs.

For an event to be acceptable it had to satisfy certain criteria. Within experimental error, the forward momentum, transverse momentum, and energy of the

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¹ Luis W. Alvarez, Report to the Ninth Annual International Conference on High-Energy Physics, Kiev, 1959 (unpublished).

² F. C. Gilbert and R. S. White, Phys. Rev. **107**, 1685 (1957).

³ W. M. Powell, W. B. Fowler, and L. O. Oswald, Rev. Sci. Instr. **29**, 874 (1958).

TABLE I. Details of the Σ scatterings on hydrogen.

Event number	Decay mode	Lengths		χ (deg)	θ' (deg)	P (Mev/c)	θ' (deg)	P (Mev/c)	θ^* (deg)
		L_b (cm)	L_a (cm)						
005244	Σ^-	3.5	4.3	1.0 ± 1.0	13.7 ± 1.9	820_{-120}^{+160a}	15.8	845	38
033796	Σ^-	2.4	4.5	2.3 ± 2.3	12.8 ± 2.6	1370 ± 40^b	12.1	1385	31
044271	Σ^-	3.6	12.9	0.6 ± 2.0	29.2 ± 0.7	810 ± 30^a	29.4	830	71
055253	Σ^-	3.4	3.1	1.0 ± 3.0	14.7 ± 0.7	910_{-280}^{+500a}	15.3	915	37
084372	Σ^-	0.4	1.2	4.0 ± 12.5	29.5 ± 6.0	1600 ± 450^c	35.5	1180	88
100987	Σ^-	1.6	1.8	3.7 ± 3.0	33.2 ± 3.7	870 ± 90^c	28.4	785	68
019347	Σ^+	0.5	0.8	7.5 ± 16.5	39.0 ± 2.0	730_{-150}^{+250a}	39.0	705	94
033797	Σ^+	0.8	2.0	1.2 ± 1.3	22.1 ± 1.6	1250 ± 70^b	22.0	1220	57
039553	Σ^+	2.3	2.0	1.4 ± 1.5	26.3 ± 4.0	620 ± 110^a	26.6	565	62
044477	Σ^+	0.7	0.5	2.0 ± 4.5	47.6 ± 14.0	720 ± 140^a	46.5	705	117
082443	Σ^+	3.8	2.0	0.5 ± 1.0	50.5 ± 0.8	1330 ± 40^b	49.8	1330	136
083729	Σ^+	4.2	1.0	3.0 ± 2.0	53.2 ± 3.7	1060 ± 100^a	46.5	1020	118
099038	Σ^+	1.5	0.7	10.0 ± 6.5	15.6 ± 3.8	1500 ± 120^c	19.8	1520	51
079651	Σ^+	1.8	1.4	1.0 ± 5.0	6.7 ± 6.0	1000_{-100}^{+400c}	8.5	1000	21
086283	Σ^+	3.9	0.3	0.5 ± 3.0	29.4 ± 3.8	760 ± 40^a	32.8	775	78
091847	Σ^+	0.4	1.3	8.0 ± 7.5	40.0 ± 6.3	1250_{-300}^{+500a}	40.8	1125	104

^a Momentum determination from P_p and θ_p .

^b Momentum determination from K^-H interaction.

^c Momentum determination from P' and θ' .

system had to be conserved and the tracks had to be coplanar. These conditions can be expressed through the equations

$$F_1 = P' \cos \theta' + P_p \cos \theta_p - P, \quad (5)$$

$$F_2 = P' \sin \theta' - P_p \sin \theta_p, \quad (6)$$

$$F_3 = E' + E_p - E - M_p, \quad (7)$$

$$F_4 = \begin{vmatrix} l & m & n \\ l' & m' & n' \\ l_p & m_p & n_p \end{vmatrix}. \quad (8)$$

The F 's are required to be zero. P and P' are the momenta of the hyperon before and after the scatter; P_p is the momentum of the proton; θ' is the scattering angle of the hyperon and θ_p is the angle the proton makes with the incoming track; E , E' , and E_p are the total energies, and M_p the mass of the proton; the l 's, m 's, and n 's are the direction cosines of the three tracks.

To investigate whether a particular event satisfies these conditions, one may make use of nine parameters: P , P' , P_p , α , α' , α_p , β , β' , and β_p , where the α 's and β 's are the dip and azimuthal angles of the tracks. These variables are denoted by x_i , with $1 \leq i \leq 9$. For all events, measurements are available for the α 's and β 's, although, of course, for exceedingly short tracks these have large errors. Similarly one may always obtain a value for P_p from magnetic curvature, and for about half the cases from range also. The values of P and P' present something of a problem in that the shortness of the Σ tracks generally does not allow direct estimates from magnetic curvature. P' can, however, be determined from the kinematics of the Σ decay by measuring the momentum of the secondary particle and the decay angle. The primary momentum, P , can only be estimated in the approximately 20% of cases for which the hyperon was formed in a K^- interaction with hydrogen

according to the process

$$K^- + p \rightarrow \Sigma^\pm + \pi^\mp. \quad (9)$$

From the known energy of the K^- beam, the angles of the hyperon and pion, and the momentum of the pion, one may find the momentum of the Σ particle.

It should be noted that the existence of four equations allows as many as three of the variables to be unknown and the event still fully determined.

If an event is found satisfactorily to meet all the conditions within the limits of experimental error, it is then submitted to a constraints program to determine the best fit to the parameters. The procedure^{4,5} is to adjust the parameters by a method of successive iteration until the F 's are zero and the quantity M is minimized. M is defined by

$$M(x_i, \alpha_\lambda) = \sum_{i=1}^9 \frac{(x_i - x_i^m)^2}{\Delta_i^2} + 2 \sum_{\lambda=1}^4 \alpha_\lambda F_\lambda(x_i), \quad (10)$$

where Δ_i is the error on x_i , x_i^m is the actual measured value of x_i , and the α_λ 's are additional variables (Lagrangian multipliers) introduced in order to simplify the solution of the equations. Putting the F 's equal to zero and minimizing M effectively minimizes the first term on the right.

Details of the 16 Σ scatterings are shown in Table I. It is seen that six were scatterings of Σ^- and ten of Σ^+ particles. Seven of the positive hyperons decayed into charged pions and the remaining three into protons. L_b and L_a are the lengths of the hyperon track before and after the event; ψ is the angle of noncoplanarity, i.e., the angle the incoming track makes with the plane

⁴ Horace D. Taft, University of California Radiation Laboratory Engineering Note, 4320-60 M7, 1957 (unpublished).

⁵ Frank T. Solmitz, University of California Radiation Laboratory Engineering Note, 4320-60 M6, 1957 (unpublished).

containing the scattered particle and the recoil proton. Next follows the measured value of the scattering angle, θ' . The momentum P of the incoming Σ particle can be estimated in three ways, either by using (a) P_p and θ_p , or (b) the kinematics of the K^- star if this interaction occurred with hydrogen, or (c) P' and θ' . The table gives the more accurate estimate of P for each event and indicates whether it was calculated from (a), (b), or (c). In the final three columns are the constrained values of θ' , P , and θ^* (the c.m. system scattering angle).

Two photographs are reproduced to illustrate the appearance of the Σ scatterings. Figure 1 shows a K^- interaction producing a Σ^+ hyperon and a π^- meson. The hyperon is scattered through a large angle by a hydrogen nucleus and decays into a π^+ meson. The decay pion is also seen to interact. Figure 2 shows a K^- interaction producing a Σ^- hyperon, a π^+ meson, and a proton. The hyperon scatters on hydrogen before decaying into a π^- meson.

To conclude the discussion of the analysis, mention must be made of two difficulties that were encountered. The first concerns pions and protons that scatter first off hydrogen and then again off carbon. The second

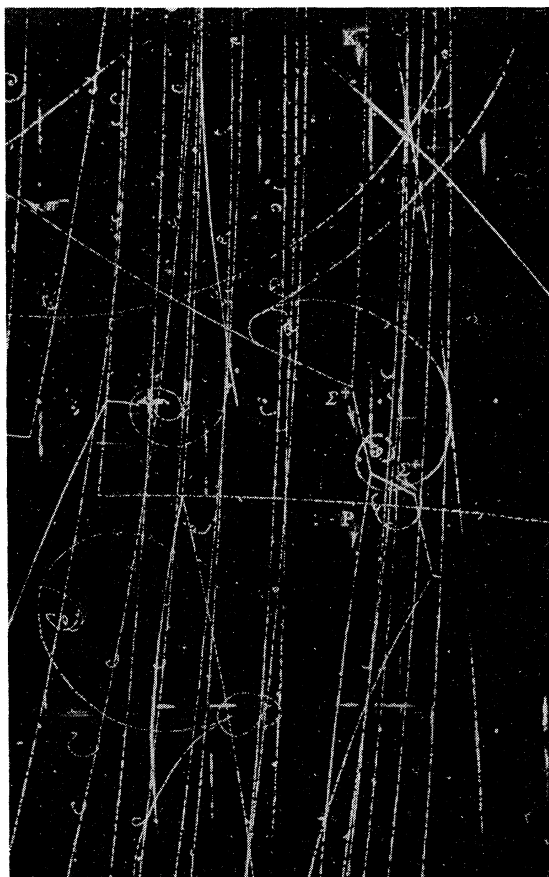


FIG. 1. Event 082443. A K^- interaction produces a Σ^+ hyperon and a π^- meson. The hyperon undergoes a large-angle scattering off hydrogen and decays into a pion. The pion subsequently interacts.

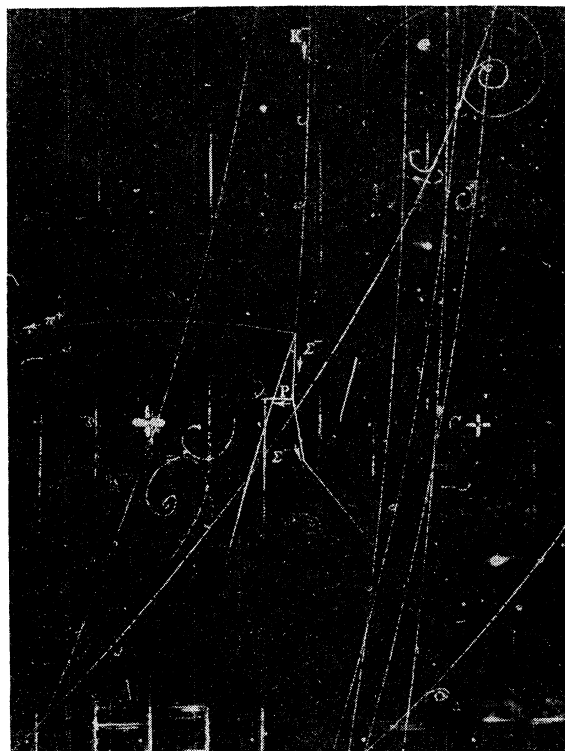


FIG. 2. Event 055253. A K^- interaction produces a Σ^- hyperon, a π^+ meson, and a proton. The hyperon scatters off hydrogen and decays into a pion.

interaction can sometimes be mistaken for a Σ decay, and consequently the hydrogen scattering may be thought to have involved a Σ hyperon. The pions do not present much of a problem in this respect as it is exceedingly difficult to reconcile the kinematics of the hydrogen scattering and of the " Σ_{π^\pm} decay"; also, in some cases there should have been a visible change of ionization at the " Σ_{π^\pm} decay." However, the discrimination between proton-carbon scatterings and Σ_{p^+} decays is not always straightforward. This is because a proton-carbon scattering analyzed on the assumption that it is a Σ_{p^+} decay often gives a Σ particle of momentum similar to that of the proton. The value of the momentum calculated from the kinematics of the hydrogen scattering does not, therefore, provide a sensitive test for many events. However, if the scattering angle (in the c.m. system) of the hydrogen interaction is large (viz., $\theta^* \geq 70^\circ$), a discrimination may be made on the basis of the value found for θ_p , there being a sufficiently large difference for the two interpretations. There was a total of nine possible p - p or Σ^+-p scatterings. From the kinematics, two of these events were unambiguously identified as Σ^+-p (the final two events in the table), and four as p - p scatterings. The remaining three could have had either interpretation. However, one of the possible Σ^+ particles "lived" ten mean lives and the other one nine, making them virtually certain to be protons. The other possible

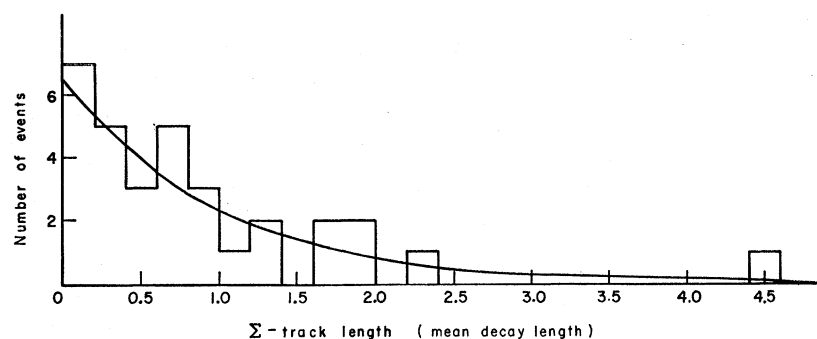


FIG. 3. Distribution of Σ -track lengths before and after the scattering.

Σ^+ particle lived 1.3 mean lives, and is event number 079651 in the table. For this event one has to calculate the relative probability that a particle of such a "lifetime" might have either interpretation. A study has been made of the relative frequencies of Σ_p^+ decays and p -carbon scattering as a function of distance from the K^- star. The results are described in the section on the evaluation of the total Σ -track length. It follows from this work that the kink in question has a 60% probability of being a Σ_p^+ decay and a 40% chance of being a p -C event. However, one may argue further by noting that the p -C scatterings that occur very close to the parent K^- star are generally caused by low-energy evaporation protons. The particle in question has a very high energy and one that is, in fact, characteristic of Σ hyperons. The probability for a true Σ^+-p scattering is thus considerably greater than 60% and consequently the event has been included in the table.

The second analysis difficulty encountered concerns the carbon contamination. This problem is considered in the next section.

CARBON CONTAMINATION

A Σ particle may interact with a carbon nucleus, emitting a single proton, and be mistakenly thought to have interacted with hydrogen. Generally the kinematics of the scattered particle and emitted proton do not satisfy the necessary criteria. However, it is to be expected that some events will conform to the requirements within experimental error and thus be accepted as genuine events.

The general procedure for estimating the number of "quasi-hydrogen" events is as follows. A variable is chosen, such as the angle between the incident and scattered particle. The corresponding angle that the proton should make to the incident particle is calculated and compared with the observed value. The deviation from the expected value is then plotted. This distribution usually shows a large peak corresponding to events with the correct angle, and a long tail representing background carbon events. An extrapolation of the tail into the region of the peak gives an estimate of the number of carbon events that give angular measurements indistinguishable from true hydrogen events. Various authors have used this method and

obtained comparable results for both π^-p and $p-p$ scattering.⁶⁻⁹

Unfortunately, to be able to adopt the procedure one must have a large number of events; this procedure is therefore inapplicable to our experiment. Hence, our approach has had to be one of inferring from another experiment (one that did involve large quantities of data) the contamination that would appear appropriate in our case.

We use the results of the π^- elastic-scattering experiment of Shonle,⁹ which was performed in the same bubble chamber as was used in the work described here. From a study of about 3000 pions in the energy range 610 to 750 Mev it was found that carbon events having the correct angular configuration, within experimental error, represented 10% of the true hydrogen events. This figure, however, cannot be applied directly to our work owing to the difference between the accuracies with which angular measurements were made in the two experiments. These accuracies depend both on the track lengths available for measurement, and on the sizes of the angles themselves. As the tracks of the Σ particles are considerably shorter than those of the pions, the accuracy is poorer for our study and the carbon contamination correspondingly greater.

For the same angles at which the proton was emitted in the Σ^- scatterings, the average error would have been 1.5 deg had the incident particle been a pion, rather than the actual 2.7 deg that was found; i.e., our error is 1.8 times that of Shonle. For the angles involved in the Σ^+ scatterings, the error would have been 1.0 deg for pion scattering rather than the 2.8 deg measured. Including all the background events found by Shonle up to 1.8 times his acceptance limit in the Σ^- case and up to 2.8 times the limit in the Σ^+ case, we arrive at estimated carbon contaminations of $16 \pm 5\%$ for the Σ^- scatterings and $23 \pm 7\%$ for the Σ^+ scatterings.

⁶ M. Chrétien, J. Leitner, N. P. Samios, M. Schwartz, and J. Steinberger, Phys. Rev. **108**, 383 (1957).

⁷ L. O. Roellig and D. A. Glaser, Phys. Rev. **116**, 1001 (1959).

⁸ I. A. Pless, Phys. Rev. **104**, 205 (1956).

⁹ John I. Shonle, thesis, University of California Radiation Laboratory Report UCRL-9362, 1960 (unpublished).

THE SCANNING EFFICIENCY

From the outset of the experiment it was realized that because of the exceedingly small yield of events expected, it would not be easy to estimate the scanning efficiency. With this in mind, it was decided that the K^- stars should be looked at *solely* for Σ -hyperon scatterings, and that the scan should not include searches for additional phenomena. By limiting the scope of the experiment in this way, it was felt, the risk of missing scatterings would be minimized.

Among the events less readily observed are those in which one of the tracks is exceedingly short. If there were a bias from such a cause, it could be demonstrated by plotting the distribution of Σ -track lengths, before and after the scattering, in terms of mean decay lengths (ignoring the first 3 mm for the cutoff criterion). A departure from the expected exponential variation would be observed at short distances. Figure 3 shows, however, that there is no evidence for this form of bias. The 2-mm cutoff for the proton has also been found to be conservative in that several possible events were found and rejected for having a proton range shorter than this minimum length.

A second class of events that could be missed is one in which the scattering planes were nearly vertical (the cameras being above the event). Figure 4 shows the distribution of the angle ϕ between the scattering and vertical planes. The distribution is satisfactorily isotropic above 10 deg, whereas there is some indication of a bias below this angle. Although the statistics are exceedingly poor and the lack of events between 0 and 10 deg could be merely coincidental, we shall assume that the effect is real and take the scanning efficiency to be 89% with respect to this form of bias.

To determine the general efficiency for finding those events with angle $\phi > 10$ deg, a complete rescanning of all the photographs would have been desirable but was clearly impractical. Instead, a selective rescanning was made involving some 5000 photographs, the pictures being chosen so as to contain the 16 events previously located. The two persons involved in the scanning each rescanned the sample. One successfully relocated all 16 events, whereas the other found all but one. No new examples were discovered. It is concluded that the general efficiency is 97%.

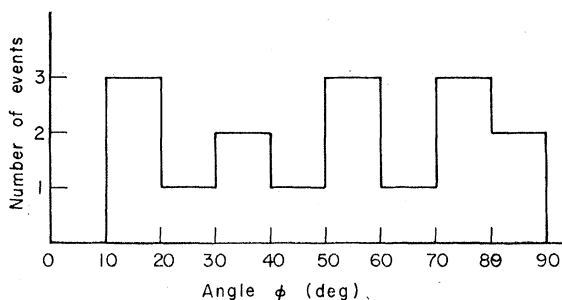


FIG. 4. The distribution of the angle ϕ between the scattering and vertical planes.

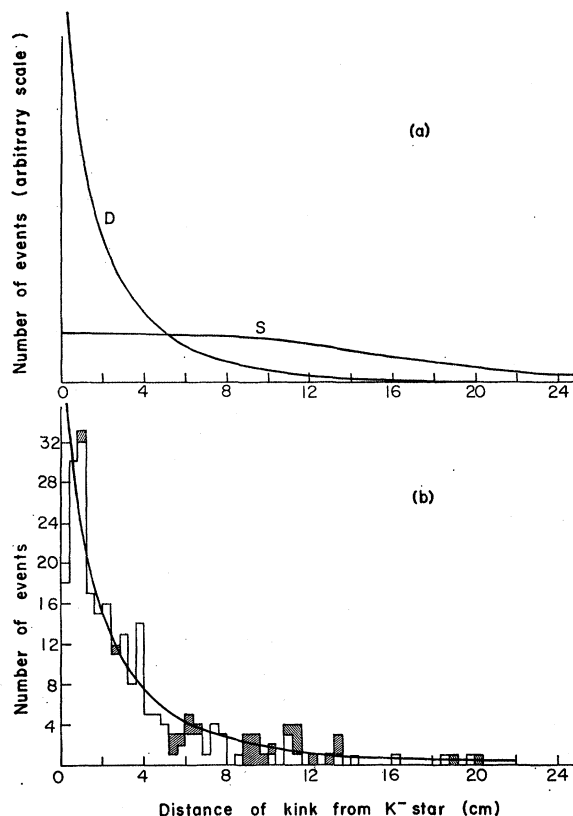


FIG. 5. Distribution of the distance between the K^- star and the kink for Σ^- decays. The S and D curves show the expected shapes of the distributions due to π^- -carbon scatterings and Σ^- decays, respectively. The curve fitted to the histogram is a combination of S and D suitably normalized.

Combining this value with the result found for the biases associated with the angle ϕ , one obtains an overall scanning efficiency of about 85%.

ESTIMATION OF THE TOTAL Σ^\pm -TRACK LENGTH

As a preliminary to deriving the elastic-scattering cross sections, one must know the total number of Σ hyperons observed and their track lengths. It has been pointed out that not all kinks are examples of decays. The aim, therefore, must be to separate out those events which are pion and proton scatterings on carbon. The method adopted is a statistical one based on the distribution of the track length between the K^- star and the kink. The shape of this distribution depends critically upon the relative proportions of true hyperon decays to carbon scatterings. Because of the short lifetimes of the Σ particles, kinks due to decays occur predominantly close to the K^- star and hence have very small primary tracks; those due to scatterings, on the other hand, are spread out approximately uniformly over the available track length. The first step, therefore, is to obtain the expected shape of the distribution of kinks due to scatterings and then to

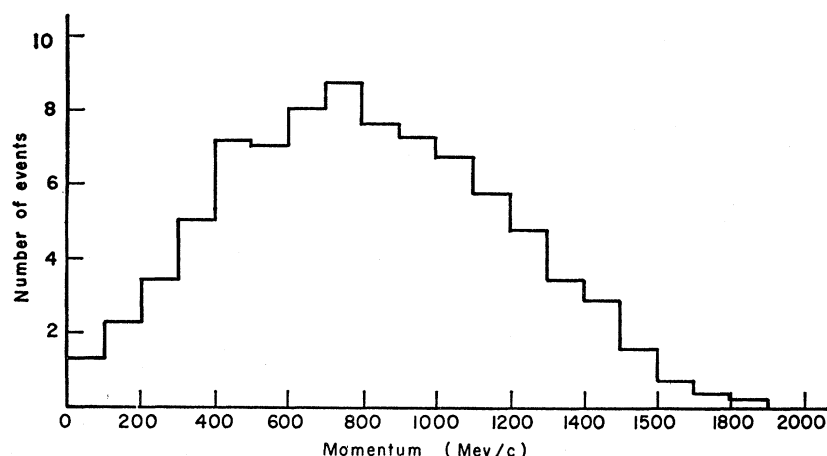


FIG. 6. Momentum spectrum of the Σ^\pm particles.

derive the expected shape of the distribution for Σ decays. Finally, one combines these two curves, suitably normalized, to give the best fit to the observed distribution. The normalized Σ -decay curve then gives all the necessary information concerning the numbers of Σ particles and their track lengths.

We illustrate the method with reference to Σ^- particles; the same arguments apply identically to the Σ^+ particles.

The form of the curve due to scatterings can be easily derived. One measures the track length after the kink as well as before, and adds the two to obtain the total track length. A histogram is constructed showing the number of tracks with a total length equal to or exceeding any given value. On the assumption that a particle has an equal chance of scattering anywhere along its track, this histogram represents also the shape of the distribution of kinks due to scatterings. The graph for negative particles is given as curve *S* of Fig. 5(a), with the ordinate being in arbitrary units.

The validity of the assumption that kinks are uniformly distributed was tested by observing kinks in tracks from those K^- stars emitting Λ^0 hyperons. The presence of the Λ^0 hyperon indicated that such kinks were indeed scatterings and not Σ decays. The number of kinks occurring at a given distance from the K^- star was satisfactorily found to be proportional to the number of particles having a total length equal to or greater than this distance.

The distribution of kinks arising from decays is somewhat more difficult to derive because a knowledge of the momentum spectrum of the Σ particles is necessary. The momenta cannot generally be obtained from magnetic-curvature measurements on the Σ tracks themselves, for they are too short. Consequently, one must resort to the kinematics of their subsequent decay. The momentum of the decay product as measured by its curvature or range, when taken together with the decay angle, provides an estimate of the momentum of the Σ particle. Samples of 42 Σ^+ and 43 Σ^- particles were investigated in this way and, as they

gave essentially similar spectra, the results are combined in Fig. 6. The events are weighted according to the accuracy with which their momenta were determined. Some error is incurred because of the presence of unrecognized scatterings, but, using the results given later, one finds that these amount to no more than about five events out of the total of 85. Assuming a lifetime of $(1.59 \pm 0.1) \times 10^{-10}$ sec for the Σ^- particle,¹ one obtains the decay curve appropriate to negative hyperons with this momentum spectrum. The result is shown as graph *D* in Fig. 5(a).

The curves we have derived in Fig. 5(a) are seen to be very different from each other. Curve *S* shows the distribution for an arbitrary number of kinks arising from scatterings; curve *D* shows the distribution for the same number of kinks due to decays. They have now to be combined in suitable proportions to give the best fit to the experimentally observed distribution.

Figure 5(b) gives this experimentally obtained histogram for a sample of 242 kinks in negative tracks. In some cases, usually when the primary track was long, it was possible from measurements on the track to prove that the event was a scattering of a π^- meson. There are 26 such events in the sample and these are shown crosshatched, leaving 216 events of an indeterminate nature containing decays and scatterings. A feature of the graph is the deficiency of events with short tracks, resulting from the scanning bias against lengths less than 0.3 cm. The resultant curve is built up from a combination of 32 events belonging to the *S* curve and 229 events ascribed to the *D* curve. These figures indicate that only six of the 216 indeterminate events were actually scatterings and that 19 Σ^- decays were missed in the scanning. It follows that the observation of a kink in a negative track, that cannot be readily rejected as a scattering, corresponds to the presence of 1.06 true Σ^- decays (i.e., 229/216).

Next one needs the corresponding length of Σ^- track. One must take into account the criterion that ignores for scattering purposes the first and final 0.3 cm of the track. A total of 0.6 cm has to be subtracted from all

the Σ tracks, therefore those tracks having less than 0.6 cm contribute nothing. From the normalized D curve, it is found that the 216 kinks yield a total of 567 cm. One kink, therefore, corresponds to 2.62 ± 0.18 cm of Σ^- track. The error quoted arises largely from the uncertainty in the Σ^- hyperon lifetime, which governs the shape of the D curve.

The final step is to estimate the total number of kinks observed throughout the experiment. For this purpose, a random sample of 5500 pictures was selected. On the basis of a scan of these photographs it was determined that, for negative tracks, the total number of kinks observed throughout the experiment was 5840 ± 350 . Consequently, there must be 6200 ± 350 Σ^- particles (i.e., 5840×1.06) and a total Σ^- -track length available for scattering of 153 ± 14 meters (i.e., 5840×2.62 cm).

The treatment of the Σ^+ hyperons is exactly analogous except that the particles are separated according to their decay mode. This is because Σ^+ hyperons decaying into charged pions need to be distinguished from pion scatterings, whereas decays into protons are confused with proton scatterings. The lifetime used for the Σ^+ particle is $(0.8 \pm 0.1) \times 10^{-10}$ sec.¹ Figure 7(a) shows the S and D curves for events that could be Σ_π^+ decays or scatterings of π^+ mesons. The experimental histogram in Fig. 7(b) contains 15 recognized scatterings (cross-hatched) and 114 indeterminate kinks. The resultant graph is obtained by assuming 116 events for the D -curve component and 21 events for the S curve. From the graph it is estimated that one indeterminate kink is equivalent to 1.02 true Σ_π^+ decays (i.e., $116/114$) and 1.01 ± 0.14 cm of Σ^+ track available for scattering. The estimated total number of kinks is 3080 ± 250 , as found from the sample of 5500 pictures. Therefore, the total number of Σ_π^+ decays is 3150 ± 250 , (i.e., 3080×1.02), and the Σ^+ -track length is 31.0 ± 6.5 meters (i.e., 3080×1.01).

Figure 8(a) gives the S and D curves for events that are Σ_p^+ decays or proton scatterings. There are six recognized scatterings and 102 indeterminate kinks. The resultant graph is composed of 91 decays and 27 scatterings. One kink is then equivalent to 0.90 true Σ_p^+ decays and 0.88 ± 0.12 cm of Σ^+ track. The total number of kinks is estimated to be 3030 ± 250 . It follows that the number of true Σ_p^+ decays is 2750 ± 250 (i.e., 3030×0.90) and the Σ^+ -track length is 27.0 ± 5.5 meters.

The results for both Σ^- and Σ^+ hyperons are summarized in Table II.

TABLE II. Summary of the total Σ -track length observed.

Particle	Estimated total number of particle	Total track length (meters)
Σ^-	6200 ± 350	153 ± 14
Σ^+	5900 ± 350	58 ± 8
Total Σ^\pm	$12\ 100 \pm 500$	211 ± 16

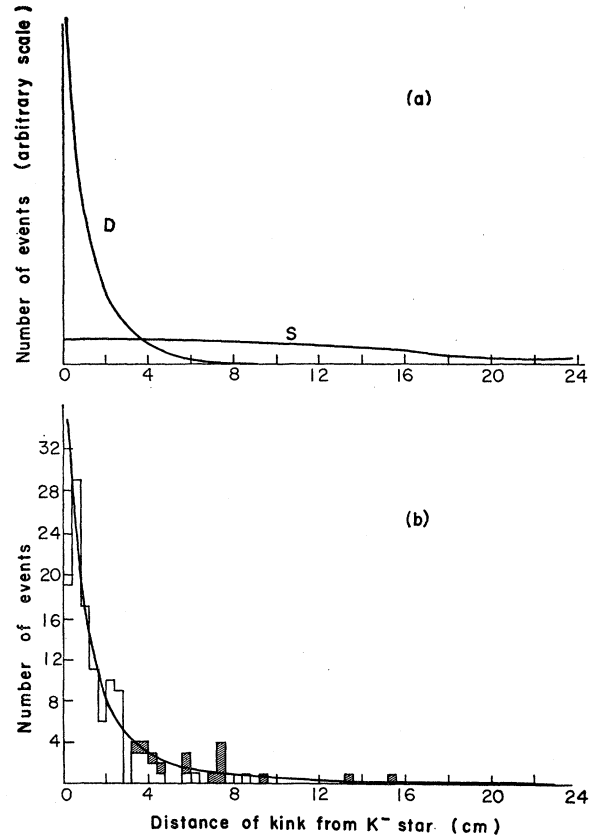


FIG. 7. Distribution of the distance between the K^- star and the kink for Σ_π^+ decays.

Finally, it is of interest to note how the track length is divided between the various regions of hyperon energy. This information is provided in Fig. 9. Plotted on the graph for comparison are the values of the primary momenta for the 16 Σ -hyperon scatterings. With the available statistics one cannot, of course, say anything as yet concerning the variation of the cross sections with energy.

THE CROSS SECTIONS

Six Σ^- and ten Σ^+ scatterings have been observed in 153 ± 14 m and 58 ± 8 m of track, respectively. The carbon contamination has been estimated to be $16 \pm 5\%$ and $23 \pm 7\%$ for the two cases, and the scanning efficiency approximately 85%.

It remains to determine the effect of the small-angle scatterings that were not accepted because the recoil proton had a range less than 2 mm. This correction affects the number of events in the angular range 0 to 25 deg in the c.m. system.

If the angular distribution were isotropic, one would correct by adding 5% to the cross section (i.e., the proportion of the solid angle contained between 0 and 25 deg). As there are equal numbers of Σ^+ events in the forward and backward hemispheres, isotropy will be

assumed for the Σ^+ scatterings and the 5% correction employed.

For the Σ^- events, however, there is evidence of a peaking; all events lie in the forward hemisphere. With so few events it is difficult to make a meaningful extrapolation of the distribution to small angles. To assume the distribution to be as strongly peaked as that for π - p scattering would give a contribution to the cross section of about 25% from the small angles.⁷ On the other hand, we have seen that the assumption of isotropy would place a lower limit on the contribution of 5%. We shall arbitrarily choose a value of $15 \pm 10\%$, where the error limits enclose both the aforementioned cases.

If the density of propane is taken to be 0.415 g/cm^3 , the cross section for Σ^+ scattering becomes

$$\sigma^{(+)} = 38_{-14}^{+18} \text{ mb}, \quad (10)$$

and that for Σ^- scattering

$$\sigma^{(-)} = 10_{-4}^{+6} \text{ mb}. \quad (11)$$

There is at present very little experimental work with which to compare these results. Dallaporta and Ferrari studied the ratio of Λ^0 particles to Σ^\pm particles emitted from K^- interactions at rest in emulsion and in hy-

drogen.¹⁰ They concluded that the inelastic reactions converting Σ hyperons into Λ^0 hyperons had to be large to account for the comparatively small number of Σ^\pm particles emerging from the heavy emulsion nuclei. This conclusion has been confirmed by the European K^- -Stack Collaboration, which found the probability that a Σ particle, created in the primary K^- reaction, would be absorbed on its way out of the parent nucleus was approximately 45%.¹¹ This was determined by comparing the numbers of pions emitted with and without accompanying Σ particles. The Alvarez group found five examples of inelastic Σ^- interactions on hydrogen and only two elastic scattering events; comparison clearly shows that the inelastic processes compete very strongly.¹ This strong competition may be the reason for the rather small value of the elastic cross section $\sigma^{(-)}$, found in this experiment.

With regard to interactions in flight of Σ particles on complex nuclei, a few isolated examples of inelastic reactions have been found in nuclear emulsions.^{12,13} A certain amount of data is also available, through the European K^- -Stack Collaboration, concerning elastic scatterings. From charge independence one may deduce that the Σ^+-p and Σ^--n potentials are identical, as are the Σ^--p and Σ^+-n . In the presence of equal numbers of protons and neutrons, therefore, the Σ^+ and Σ^- hyperons should be scattered equally. However, in the heavy emulsion nuclei, Ag and Br, there is an excess of neutrons, so that any observed difference between the Σ^+ and Σ^- scatterings on nuclei can be attributed to the difference in the Σ^+-n and Σ^--n potentials. Our results indicate that Σ^+-p cross section is larger than that for Σ^--p , and hence Σ^--n scattering is more important than Σ^+-n . It follows that Σ^- hyperons should be scattered from heavy nuclei to a greater extent than Σ^+ particles. The K^- -Stack Collaboration finds eleven Σ^- and one Σ^+ scattering greater than 10° .¹³

Scant though the data may be, one can nevertheless conclude that the various sources providing experimental evidence on Σ^\pm interactions give consistent results.

DISCUSSION

The hyperon-nucleon forces can be transmitted by the exchange of pions or K mesons. Exchanging an odd number of K mesons transfers strangeness and gives rise to an "exchange" force. On the other hand, if only pions are involved, or even numbers of K mesons, the forces are "ordinary."

Theoretical predictions concerning hyperon-nucleon

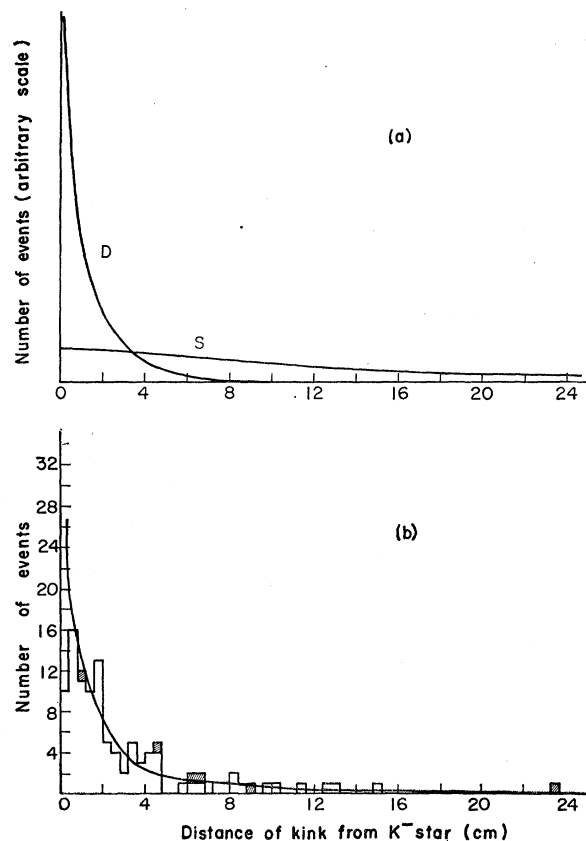


FIG. 8. Distribution of the distance between the K^- star and the kink for Σ_p^+ decays.

¹⁰ N. Dallaporta and F. Ferrari, *Nuovo cimento* **5**, 742 (1957).

¹¹ European K^- -Stack Collaboration, Part 1, *Nuovo cimento* **13**, 690 (1959).

¹² W. F. Fry, J. Schneps, G. A. Snow, and M. S. Swami, *Phys. Rev.* **100**, 939 (1955); R. G. Glasser, N. Seeman, and G. A. Snow, *Phys. Rev.* **107**, 277 (1957); R. D. Hill, F. T. Gardner, and J. E. Crew, *Nuovo cimento* **2**, 824 (1955).

¹³ European K^- -Stack Collaboration, Part 3, *Nuovo cimento* **15**, 873 (1960).

scattering have been based upon the global symmetry hypothesis,¹⁴ which postulates a strong universal pion-baryon coupling and only moderately strong K -meson interactions. In order to couple the Λ and Σ hyperons to the pion field in the same manner as the nucleons are coupled, these hyperons are reorganized into two doublets, thus giving a total of four baryon doublets:

$$\begin{aligned} N_1 &= \begin{pmatrix} p \\ n \end{pmatrix}, & N_3 &= \begin{pmatrix} Z^0 \\ \Sigma^- \end{pmatrix}, \\ N_2 &= \begin{pmatrix} \Sigma^+ \\ Y^0 \end{pmatrix}, & N_4 &= \begin{pmatrix} \Xi^0 \\ \Xi^- \end{pmatrix}, \end{aligned} \quad (12)$$

where

$$Y^0 = (\Lambda^0 - \Sigma^0)/\sqrt{2}, \quad \text{and} \quad Z^0 = (\Lambda^0 + \Sigma^0)/\sqrt{2}. \quad (13)$$

Global symmetry requires the pion-baryon coupling constants to be equal:

$$G_1 = G_2 = G_3 = G_4. \quad (14)$$

The hypothesis can, of course, hold only to the approximation that the Σ^0 - Λ^0 mass difference can be ignored. This assumption affects the calculation of the hyperon-nucleon potentials by less than 10%.¹⁵

It is readily seen that, in principle, one should be able to predict the hyperon-nucleon potentials from the experimentally observed nucleon-nucleon scattering data. In particular, the Σ^+ - p interaction should be identical to that of the p - p system, apart from the restrictions of the Pauli exclusion principle. The latter has the effect of forbidding the 3S state for the p - p system but not for the Σ^+ - p case. One must use, therefore, the triplet odd-parity nucleon-nucleon potential to derive the 3S potential for the Σ^+ - p system. Unfortunately, the triplet nucleon-nucleon potential is not at all well determined at short distances, and unambiguous prediction of the Y - N potentials from experimental N - N scattering data is not possible at present.

Bryan, de Swart, Marshak, and Signell¹⁶ have calculated the Σ^+ - p interaction, using the semiphenomenological Signell-Marshak potential.¹⁷ This SM potential gives an excellent fit to the p - p scattering data up to 150 Mev. For the Σ^+ - p interaction a difficulty was encountered in that the central part of the triplet even potential was found to be so strong at short distances that it led to a ($^3S_1 + ^3D_1$) state of the Σ^+ - p system bound by more than 200 Mev. No such state has been found experimentally, and consequently this central triplet potential had to be cut off. The radius

chosen for the cutoff was such as to make the binding energy zero for the Σ^+ - p system in the triplet state. One result of the calculation is its prediction of a strong forward peaking for the Σ^+ -scattering angle in the c.m. system. Curve SM in Fig. 10 shows the distribution for Σ^+ hyperons having a laboratory-system kinetic energy of 150 Mev.

Ferrari and Fonda¹⁸ have made a similar calculation, using the Gammel-Thaler potential.¹⁹ This GT potential, while also giving an excellent fit to the N - N scattering data, differs markedly from the SM potential in its treatment of the central part of the triplet interaction. Instead of the strong attraction at short distances, the GT potential requires a repulsion. Ferrari and Fonda found that the strong forward peaking of the Σ^+ -scattering angle is not reproduced when the GT potential is used; one obtains the almost isotropic distribution of curve GT_{SP} in Fig. 10. The calculation was made by using S and P waves, and for comparison we show the result obtained for the SM potential using only these waves: curve SM_{SP}.

The striking difference between the predictions for the SM and GT potentials leads to the suggestion that a study of Σ^+ - p scattering may provide information concerning the behavior of the triplet odd-parity N - N potential.

In our experiment we found five Σ^+ events for which the c.m. scattering angle lay in the forward hemisphere, and an additional five for which it was backward. There is one other Σ^+ event, found by Gilbert and White,² and this had an angle of 125 deg. The forward:backward ratio, therefore, becomes 5:6. Although the statistics are exceedingly poor as yet, they nevertheless

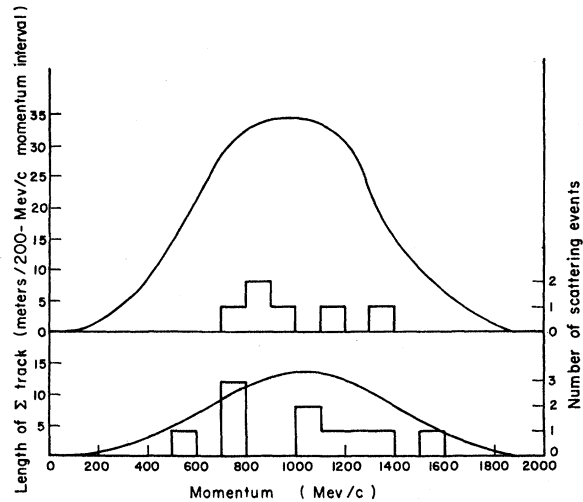


FIG. 9. Distribution of the track length observed for each momentum interval. The upper curve refers to Σ^- and the lower to Σ^+ particles. For comparison, two histograms are also given showing the energies of the 16 hyperons that scattered.

¹⁴ M. Gell-Mann, Phys. Rev. **106**, 1296 (1957); J. Schwinger, Ann. Phys. **2**, 407 (1957); E. P. Wigner, Proc. Natl. Acad. Sci. U. S. **38**, 449 (1952).

¹⁵ R. H. Dalitz, 1958 Annual International Conference on High-Energy Physics, CERN, edited by B. Ferretti (CERN Scientific Information Service, Geneva, 1958), p. 187.

¹⁶ R. A. Bryan, J. J. de Swart, R. E. Marshak, and P. S. Signell, Phys. Rev. Letters **1**, 70 (1958).

¹⁷ P. S. Signell and R. E. Marshak, Phys. Rev. **109**, 1229 (1958).

¹⁸ F. Ferrari and L. Fonda, Phys. Rev. **114**, 874 (1959).

¹⁹ J. L. Gammel and R. M. Thaler, Phys. Rev. **107**, 1337 (1957).

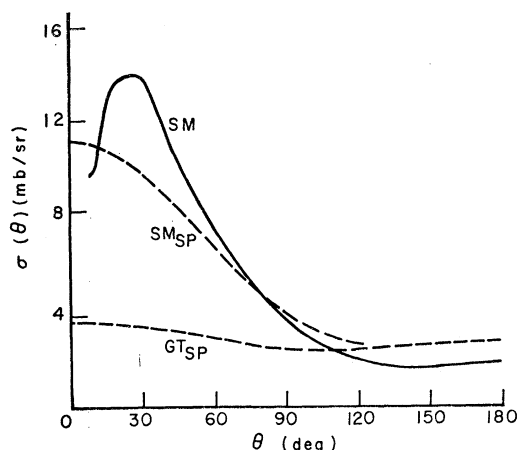


FIG. 10. Theoretical distributions of the c.m. scattering angle for Σ^+ particles having a laboratory-system kinetic energy of 150 Mev. Curves SM_{SP} and GT_{SP} were obtained from the Signell-Marshak and Gammel-Thaler potentials using S and P waves only, and curve SM from the Signell-Marshak potential using all phase shifts.

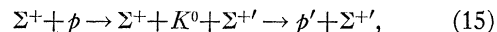
lend some measure of support to the approximately isotropic distribution required by the GT potential, rather than the 2:1 forward peaking indicated by the curve SM_{SP} or the 3:1 ratio required for curve SM .

Whereas the general features of the scattering-angle distributions are not expected to vary appreciably as a function of the energy of the Σ particle, the value for the elastic cross section does change. This makes it difficult to compare the predictions for the cross section with the experimental value of 38_{-14}^{+18} mb. Calculations with the GT and SM potentials have been made only up to 150 Mev, whereas the track length examined in this experiment refers to a mean hyperon energy of about 350 Mev. The GT potential leads to a cross section of 33 mb and the SM to one of 65 mb at 150 Mev. As both cross sections are decreasing as a function of increasing energy, it is difficult to conclude strongly that our value favors either one.

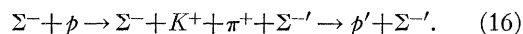
Lichtenberg and Ross²⁰ have made a comprehensive investigation into hyperon-nucleon reactions, using the Brueckner-Watson potential.²¹ Considering S waves only, they found the Σ^+-p elastic cross section to be approximately twice that for Σ^--p elastic scattering. This conclusion is qualitatively confirmed by the experimentally observed difference between the two cross sections.

As previously stated, these results depend upon the validity of global symmetry. An interesting suggestion has been made by Markov²² concerning the possible

effects on Σ^+-p scattering of a strong interaction through the K -meson field. If the Σ^+-p interaction is transmitted by the process



one arrives at a typical exchange reaction and expects the Σ^+ particle to have a tendency to travel backwards in the c.m. system after the scattering. The situation is different for the Σ^--p scattering, in which it would be necessary to exchange both a K^+ and a π^+ meson:



A study of the Σ^+-p angular distribution could perhaps provide an indication of the relative importance of π - and K -meson interactions. This is particularly interesting in the light of the present data, which suggest a significant difference between the Σ^+-p and Σ^--p c.m. angular distributions. The six Σ^- events found in this experiment, together with the two found by the Alvarez group,¹ all lie in the forward hemisphere, giving an 8:0 forward peaking. This is to be contrasted to the 5:6 ratio for the Σ^+-p scattering.

CONCLUSION

Ten Σ^+ and six Σ^- particles have been observed to scatter elastically from hydrogen. These events lead to cross sections of 38_{-14}^{+18} mb for Reaction (1) and 10_{-4}^{+6} mb for Reaction (2). The Σ^- hyperons show a forward peaking of the scattering angle in the c.m. system, whereas the Σ^+ hyperons give an essentially isotropic distribution. The results have been compared to various theoretical predictions. In particular, it was concluded that if the observed isotropy for Σ^+ scattering is confirmed later by better statistics, and if the global symmetry hypothesis is substantially correct in its description of $Y-N$ interactions, the evidence favors the Gammel-Thaler method of treating the triplet odd-parity $N-N$ potential, i.e., this potential should be represented by a repulsion at short distances.

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²⁰ D. B. Lichtenberg and M. H. Ross, Phys. Rev. **107**, 1714 (1957).

²¹ K. A. Brueckner and K. M. Watson, Phys. Rev. **92**, 1023 (1953).

²² M. A. Markov, Lecture, Joint Institute for Nuclear Research, Moscow, AEC-tr-3591 (unpublished) (translation by U. S. Atomic Energy Commission Technical Information Service, Washington, D. C., 1957).

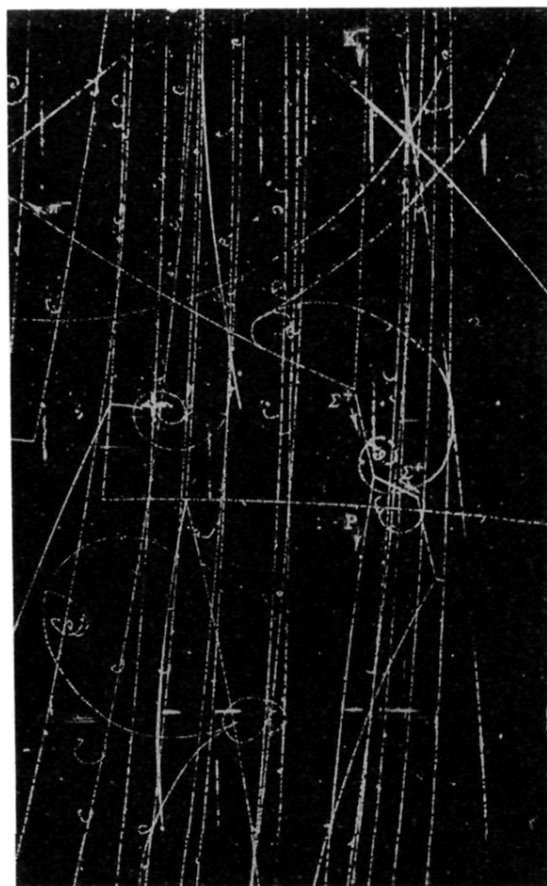


FIG. 1. Event 082443. A K^- interaction produces a Σ^+ hyperon and a π^- meson. The hyperon undergoes a large-angle scattering off hydrogen and decays into a pion. The pion subsequently interacts.

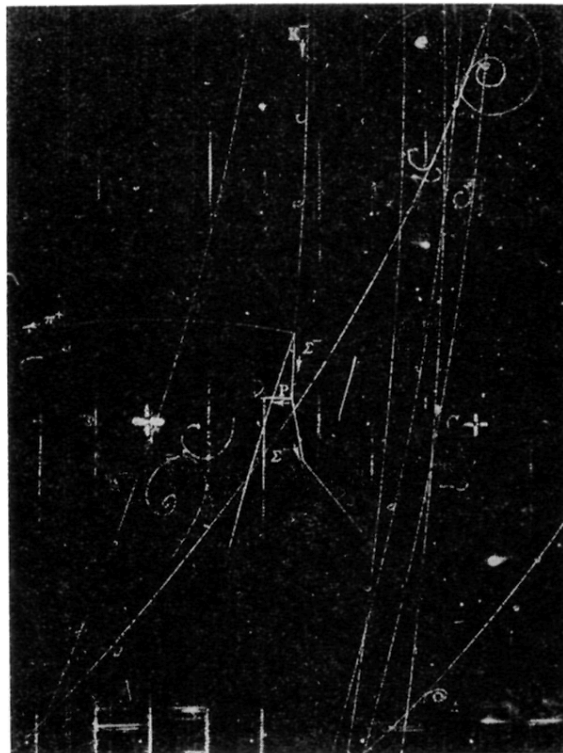


FIG. 2. Event 055253. A K^- interaction produces a Σ^- hyperon, a π^+ meson, and a proton. The hyperon scatters off hydrogen and decays into a pion.