Capture of Negative K Particles by Bound and Free Protons in Emulsion*

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Data are presented from the captures of negative K particles by bound and free protons in nuclear emulsion. Only those captures in which a charged π meson and one additional charged particle are emitted are included in the study. A model is presented for K^--particle capture on bound protons in which the external energies of the emitted Σ hyperons and π mesons are modified from the values for captures on free protons by the internal proton momenta and the Coulomb and nuclear potentials. The model is used to explain the observed Σ^+- and Σ^--hyperon and π^-- and π^+-meson energy distributions. A Coulomb potential of 10 ± 3 Mev is estimated from the relative positions of the high-energy ends of the Σ^+- and Σ^--hyperon energy distributions. This value suggests that most of these captures were on the heavy elements of the emulsion. This potential reduces the ratio of Σ^- to Σ^+ hyperons, which escape the nucleus, from the value of 2 measured on free protons to the value 0.83 ± 0.25 for protons bound in emulsion nuclei. The sum of the binding energies of the last proton in the capture nucleus and the excitation energy of the residual nucleus has a distribution which is peaked at about 20 Mev. Conservation of energy and charge are applied to the identification of the Σ hyperons that end without making a visible star. The prong distribution for stars made by Σ^--hyperon captures in emulsion nuclei can be interpreted as a composite of two distributions: one, a line spectrum of zero-prong events, when the Λ^0 or Σ^0 hyperon and neutron escape; the other, a spectrum of many-prong events, when the Λ^0 or Σ^0 hyperon or neutron (or both) are absorbed. The number of Σ^- hyperons that were captured to give stars of zero or one prong is 0.65 ± 0.10. Seven Σ^+ hyperons that decayed into protons at rest are used to find a Σ^+-hyperon mass of $2329.5\pm1.0\ m_e$. Two examples of K^- captures on free protons in the emulsion give Σ^- hyperon masses of $2347.4\pm3.5\ m_e$ and $2341.8\pm1.5\ m_e$.

INTRODUCTION

INFORMATION concerning the interaction of negative K particles in emulsion nuclei has been obtained by a number of groups.[1,2] However, the relative frequency of captures on protons and neutrons, the production of Σ^+, Σ^-, and Σ^0 hyperons and the ratio of Σ hyperon to Λ^0-hyperon production are still open questions. Recently much information on the interactions of K^- particles on free protons has been obtained by the Berkeley hydrogen bubble chamber group.[3] Data from captures of K^- particles on free protons in emulsion also give additional information. In this paper there is presented a method for analyzing K^- captures on protons bound in nuclei and the method is applied to K^- captures in nuclear emulsion which give stars of two prongs, one of which is a π meson. Two cases of capture on a free proton in the emulsion are discussed.

The one-nucleon capture reactions that satisfy the conservation laws of heavy particles, charge, and strangeness may be written as follows:

$$K^-+p\rightarrow\Sigma^++\pi^- \quad (1a)$$

$$\rightarrow\Sigma^-+\pi^+ \quad (1b)$$

$$\rightarrow\Sigma^0+\pi^0 \quad (1c)$$

$$\rightarrow\Lambda^0+\pi^0, \quad (1d)$$

$$K^-+n\rightarrow\Sigma^-+\pi^0 \quad (1e)$$

$$\rightarrow\Sigma^0+\pi^- \quad (1f)$$

$$\rightarrow\Lambda^0+\pi^-. \quad (1g)$$

All two-nucleon captures and captures with three or more secondaries have been neglected.

INTERACTION MODEL

In this paper, primarily reactions (1a) and (1b) will be considered. The capture of a K^- particle on a proton which is bound in the nucleus differs from the capture on a free proton at rest. The bound proton is moving with a kinetic energy in a nuclear potential well and the reaction products, the Σ hyperon and the π meson, have to escape from the product nucleus which is then left in an excited state.

A simple model is proposed for the capture of a K^- particle on a proton bound in the nucleus. The K^- particle, with zero laboratory kinetic energy in an unbound state, is captured in a nucleus by a proton that is moving with a laboratory kinetic energy T_p, and momentum, P_p. The highest orbit energy of a K^- particle in the light elements of the emulsion, C, N, and O, is less than 1 Mev. For the heavier elements, Ag

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[1] J. Hornbostel and E. O. Salant, Phys. Rev. **93**, 902 (1954); Phys. Rev. **98**, 218 (1955); Phys. Rev. **98**, 1202 (1955); Phys. Rev. **99**, 338 (1955); and Phys. Rev. **102**, 502 (1956). Fry, Schneps, Snow, and Swami, Phys. Rev. **100**, 939, 950 (1955); and Phys. Rev. **100**, 1448 (1955). George, Herz, Noon, and Solntseff, Nuovo cimento **3**, 94 (1956). Herz, May, Noon, O'Brien, and Solntseff, Nuovo cimento **3**, 1491 (1956). Chupp, Goldhaber, Goldhaber and Webb, University of California Radiation Laboratory Report UCRL-3044, 1955 (unpublished); and Suppl. Nuovo cimento **4**, 382 (1956). S. Goldhaber, *Proceedings of the Sixth Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1956). S. C. Freden and H. K. Ticho, Phys. Rev. **99**, 1057 (1955). D. M. Fournet and M. Widgoff, Phys. Rev. **102**, 929 (1956).

[2] Hashkin, Bowen, and Schein, Phys. Rev. **103**, 1512 (1956).

[3] Alvarez, Bradner, Falk-Vairant, Gow, Rosenfeld, Solmitz, and Tripp, University of California Radiation Laboratory Report UCRL-3583 (unpublished).

and Br, the K^- particles are expected to be captured from orbits farther out but with about the same energy. The momentum and the binding energy of the K^- particle have been neglected as being small compared to the same quantities for the proton. If the K^--particle momentum is significant, P_p is then the momentum of the (K^-,p) system. The final state consists of a free Σ hyperon, a free π meson and the resultant excited nucleus. Conservation of energy between the initial and final states is expressed by Eq. (2).

$$M_K+M_p-E_B+M_n=M_\Sigma+M_\pi+T_{0\Sigma}+T_{0\pi}+M_{n'}. \quad (2)$$

M_K, M_p, M_Σ, and M_π are the masses of the K^- particle, proton, Σ hyperon, and π meson, respectively. M_n is the mass of the ground state of the residual nucleus and $M_{n'}$ is the mass of the residual excited nucleus in the final state. $T_{0\Sigma}$ and $T_{0\pi}$ are the kinetic energies of the Σ hyperon and π meson, respectively, outside the nucleus in the laboratory system. E_B is the binding energy of the last proton in the capture nucleus. The kinetic energy of the residual excited nucleus has been neglected. If $(M_{n'}-M_n)$ is defined as the excitation energy E_{ex}, then Eq. (2) can be solved for $E_{\text{ex}}+E_B$ to give

$$E_{\text{ex}}+E_B=Q-(T_{0\Sigma}+T_{0\pi}), \quad (3)$$

where Q is equal to $(M_K+M_p)-(M_\Sigma+M_\pi)$. Equation (3) is independent of momentum-conservation considerations.

In order to calculate the kinetic energies of the Σ hyperon and the π meson separately, one must make additional assumptions. The impulse approximation is adopted. It is assumed that the capture proton momentum is imparted unaltered to the Σ hyperon and π meson and that no momentum is transferred to the nucleus in the process. It is also assumed that the wavelengths of the π meson and Σ hyperon are small enough that they may be treated as classical particles in potential wells. The wavelength, $\lambda\!\!\!^{-}$, of the Σ hyperon at 10 Mev is 1.2×10^{-13} cm compared to a nuclear radius of $1.3\times A^{\frac{1}{3}}\times10^{-13}$ cm, where $A^{\frac{1}{3}}$ ranges from 2.3 for C^{12} to 4.8 for Ag^{109}. The laboratory kinetic energies, $T_{I\Sigma}$ and $T_{I\pi}$, of the Σ hyperon and π meson inside the nucleus are altered from their values outside by the potentials of the nucleus:

$$\begin{aligned} T_{I\pi}&=T_{0\pi}+V_{n\pi}\pm V_c,\\ T_{I\Sigma}&=T_{0\Sigma}+V_{n\Sigma}\mp V_c, \end{aligned} \quad (4)$$

where V_c is the Coulomb potential and $V_{n\Sigma}$ and $V_{n\pi}$ are the nuclear potentials for the Σ hyperon and the π meson, respectively. Attractive potentials occur with a positive sign in Eqs. (4).

Some qualitative conclusions can be obtained from the nonrelativistic calculations for the case that $P_p=0$. For reaction (1a), the kinetic energies for the π^- meson and Σ^+ hyperon outside the nucleus are

$$\begin{aligned} T_{0\pi^-}&=(Q-E_B-E_{\text{ex}})\frac{M_\Sigma}{M_\Sigma+M_\pi}+(V_{n\Sigma}-V_c)\frac{M_\Sigma}{M_\Sigma+M_\pi}-(V_{n\pi}+V_c)\frac{M_\pi}{M_\Sigma+M_\pi},\\ T_{0\Sigma^+}&=(Q-E_B-E_{\text{ex}})\frac{M_\pi}{M_\Sigma+M_\pi}-(V_{n\Sigma}-V_c)\frac{M_\Sigma}{M_\Sigma+M_\pi}+(V_{n\pi}+V_c)\frac{M_\pi}{M_\Sigma+M_\pi}, \end{aligned} \quad (5)$$

where Q is taken as 103 Mev[4] and M_π and M_Σ are the masses of the π^- meson and Σ^+ hyperon, respectively. If the effect of the potentials is neglected, the kinetic energies of the π^- meson and the Σ^+ hyperon are seen to be inversely proportional to their masses; i.e., $T_{0\pi^-}$ is about 8.5 times as large as $T_{0\Sigma^+}$. The Coulomb potential, V_c, reduces the kinetic energy of the negative particle and increases the kinetic energy of the positive particle. The π-meson nuclear potential energy is multiplied by $M_\pi/(M_\pi+M_\Sigma)$ in Eq. (5), while the Σ hyperon potential energy is multiplied by $M_\Sigma/(M_\pi+M_\Sigma)$ so that a π-meson nuclear potential as large as 40 Mev[5] contributes only 4 Mev to $T_{0\pi}$ and $T_{0\Sigma}$, while 0.9 of the Σ-hyperon nuclear potential is contributed to the meson and hyperon kinetic energies. If charge symmetry is assumed so that $V_{n\Sigma^+}=V_{n\Sigma^-}$, $V_{n\pi^+}=V_{n\pi^-}$, and $(E_B+E_{\text{ex}})_+=(E_B+E_{\text{ex}})_-$, the difference in kinetic energies of the emitted Σ^+ and Σ^- hyperons is

$$T_{0\Sigma^+}-T_{0\Sigma^-}=(2V_c+1)\text{ Mev}. \quad (6)$$

The Q value for reaction (1b) is taken as 96 Mev[4] and the difference in Q values contributes 1 Mev to the difference in the kinetic energies of the Σ^+ and Σ^- hyperons.

In the actual case the momentum distribution of the capture protons in the nucleus affects both the width and peak position of the Σ-hyperon distribution. The width and position are also affected by the Σ-hyperon angular distribution in the center-of-mass system. A nuclear potential, independent of energy, shifts the spectrum by a constant energy, while a velocity-dependent nuclear potential could, in addition, change the width of the energy spectrum. If the above effects are identical for the Σ^+ and Σ^- hyperons, as is expected from charge symmetry, the result of Eq. (6) for the value of V_c is still valid.

It is of interest to see if the energy distributions of the reaction products are compatible with the model. For this purpose the following assumptions are made:

[4] See Results, Sec. B, for a discussion of the masses of the Σ^+ and Σ^- hyperons.

[5] Frank, Gammel, and Watson, Phys. Rev. **101**, 891 (1956).

TABLE I. Exposure data for stacks used in this experiment.

Stack	Area (in.²)	No. of emulsions	K-particle momentum (Mev/c)	Angle of K^- to proton beam (deg)	Sepa-rated	No. of stopped K^- found
B	6×6	112	270–380	90	No	99
F	6×6	250	285–315	90	No	121
J	6×12	250	400–420	60	Yes	198
K	6×12	160	250–320	0	Yes	175[a]

[a] Kp endings were not included.

(1) The sum of the Σ-hyperon and π-meson total energies, outside the nucleus, is a constant and is equal to $(M_K+M_p-E_B-E_{ex})$. (2) The proton momentum distribution is Gaussian with a peak at α Mev/c. (3) The angular distribution of the Σ-emission direction relative to the proton direction is isotropic in the center-of-mass system. (4) The nuclear part of the π potential is assumed to be 40 Mev attractive[5] and velocity-independent. The nuclear part of the Σ potential is assumed to be 25 Mev attractive and velocity-independent.[6] The Coulomb potential of 10 Mev is determined from the relative position of the Σ^+ and Σ^- distributions. (5) The Σ^+- and Σ^--energy distributions are assumed to have the same shape inside the nucleus.

The Σ-hyperon energy inside the nucleus is given by

$$E_{I\Sigma}=\frac{(p^2+M_\Sigma^2)^{\frac{1}{2}}+\beta p\cos\theta}{(1-\beta^2)^{\frac{1}{2}}}, \tag{7}$$

where p here is the momentum of the Σ or π in the center-of-mass system, β is the center-of-mass velocity and is given by

$$\beta=\frac{P_p}{M_K+M_p-E_B-E_{ex}+V_{n\Sigma}+V_{n\pi}}, \tag{8}$$

and θ is the angle in the center-of-mass system between the Σ hyperon and the proton. The energy distribution of the Σ hyperon for a given proton momentum is

$$\frac{dN}{dE_{I\Sigma}}=\frac{dN}{d\theta}\frac{d\theta}{dE_{I\Sigma}}. \tag{9}$$

If the angular distribution $dN/d\theta$ is assumed isotropic, then

$$\frac{dN}{dE_{I\Sigma}}=\frac{(1-\beta^2)^{\frac{1}{2}}}{2\beta p}. \tag{10}$$

This is a flat distribution from E_{min} to E_{max}, where

$$E_{I\Sigma\,min}=\frac{(p^2+M_\Sigma^2)^{\frac{1}{2}}-\beta p}{(1-\beta^2)^{\frac{1}{2}}}, \tag{11}$$

and

$$E_{I\Sigma\,max}=\frac{(p^2+M_\Sigma^2)^{\frac{1}{2}}+\beta p}{(1-\beta^2)^{\frac{1}{2}}}. \tag{12}$$

When the proton momentum distribution is folded in, the resulting distribution in Σ energy is

$$\frac{dN}{dE_{I\Sigma}}=\int_{P_{p\,min}}^{P_{p\,max}}\frac{(1-\beta^2)^{\frac{1}{2}}}{2\beta p}P_p^2\exp(-P_p^2/\alpha^2)dP_p. \tag{13}$$

$P_{p\,min}$ and $P_{p\,max}$ are obtained from β_{min} and β_{max} through Eq. (8). β_{min} and β_{max} are obtained from Eqs. (11) and (12) as functions of $E_{I\Sigma}$, when $E_{I\Sigma\,max}$ and $E_{I\Sigma\,min}$ are respectively set equal to $E_{I\Sigma}$.

The resulting distribution, calculated for α equal to 170 Mev/c and E_B+E_{ex} equal to 20 Mev, is shown superimposed on the energy distributions of the reaction products in Figs. 4 and 5. The Σ^+ distribution has been modified at the low-energy end to take account of the Σ^+-hyperon reflections at the Coulomb barriers[7] of the capture nuclei. The area under the curve was normalized to the number of Σ^+ hyperons. The Σ^--hyperon curve was obtained by multiplying the ordinate of the Σ^+-hyperon curve by two in order to agree with the ratio of Σ^- to Σ^+ hyperons from K^- captures on free protons[3] (see Table IV) and then by shifting the resultant curve an amount $2V_c+1=22$ Mev. The quantity $(2V_c+1)$ was obtained from the high-energy ends of Σ^+- and Σ^--hyperon energy distributions as described hereafter in the section on results. The π-meson energy distribution curves were obtained by transforming the Σ-hyperon curves with Eq. (3).

RESULTS

A. Captures on Bound Protons

The K^- particles for this experiment have been obtained from exposures made at the Berkeley Bevatron. The exposure data may be found in Table I. The 60-degree separation system, which was designed for positive particles, was modified for use with negative particles for the J-stack exposure. In this arrangement the light-meson to K^--particle ratio was found to be about 150 compared with the less favorable ratio of about 3000 without separation on stacks B and F. Stack K was exposed in the zero-degree separated beam where the light track to K^- particle ratio was about 1000. However, the light track background was primarily due to μ^- mesons. These μ^- mesons do not interact strongly with nuclei and thus did not give the heavy particle background that usually accompanies a heavy flux of π^- mesons. The last column indicates the number of K^- particles found; only a small part of each of the stacks has been scanned.

From about 620 K^- captures at rest, only those

[6] The choice of the value of the Σ-hyperon nuclear potential from the data of this experiment, alone, is not unique. It has been pointed out by Richard Capps, in an analysis of K^- captures on nuclei (private communication), that an attractive potential from 0 up to about 30 Mev is probably compatible with the data presented here and with the data from all K^- captures on emulsion nuclei.

[7] E. Fermi, *Nuclear Physics* (University of Chicago Press, Chicago, 1950), revised edition, p. 57.

TABLE II. Summary of hyperon events.

Event number	Identification	Σ decay or capture[a]	R_s[b] (mm)	$\theta_{\Sigma\pi}$ c.m.[c]	Partner to hyperon	$T_{0\Sigma}$[d] (Mev)	$T_{0\pi}$[e] (Mev)	$\theta_{\Sigma\pi}$[f] (deg)	Residual momentum (Mev/c)	t_Σ[g] (10^{-11} sec)
382	Σ^+	$P(r)$	1.712	140	π^-	8.5	76	160	57	1.4
800	Σ^+	$P(r)$	1.730	128	π^-	18.3	66	158	88	3.6
802	Σ^+	$P(r)$	1.700	107	π^-	28.0	61	123	217	5.3
810	Σ^+	$P(r)$	1.685	160	π	43.5	43	160	218	10.1
66	Σ^+	$P(f)$	2.307	112	π^-	36	37	117	266	7.8
117	Σ^+	$P(f)$	1.560	74	π	20	70	128	173	3.3
378	Σ^+	$P(f)$	1.822	73–104	π^-	15	40	69	253	1.8–2.5
537	Σ^+	$P(f)$	0.155	27	π^-	30	18	41	330	4.0
631	Σ^+	$P(f)$	0.271	27	π	30	60_{-6}^{+8}	153	156	5.5
662	Σ^+	$P(f)$	0.516	45	π	22	76_{-13}^{+15}	167	78	3.2
805	Σ^+	$P(f)$	1.240	63	π^-	35	46	160	182	7.6
806	Σ^+	$P(f)$	17.20	125	π^-	39	20	78	332	1.1
17	Σ^+	$\pi(r)$		76	π	21.2	51 ± 3	145	141	4.3
58	Σ^+	$\pi(r)$		111	π^-	22.0	24	143	171	4.2
390	Σ^+	$\pi(r)$		38	π	11.8	70_{-11}^{+37}	158	64	3.5
426	Σ^+	$\pi(r)$		149	π^-	15.5	69	119	179	3.0
500	Σ^+	$\pi(r)$		109	π^-	18.0	66	140	133	3.6
536	Σ^+	$\pi(r)$		71	π	13.5	59 ± 11	171	46	2.5
843	Σ^+	$\pi(r)$		32	π	13.1	66_{-4}^{+6}	143	106	2.4
871	Σ^+	$\pi(r)$		28	π	7.5	87_{-16}^{+20}	154	82	1.3
123	Σ^+ [h]	$\pi(f)$		21–24	π^-	27–29	51	117	232	4.6–5.8
81	$\Sigma^\pm$	$\pi(f)$		80–89	π	9–14	63 ± 5	157	65	0.9–1.6
314	Σ^-	3			π	16.7	71_{-12}^{+19}	107	214	3.6
385	Σ^-	2			π^+	24.0	45	141	164	5.0
594	Σ^-	3			π	11.9	70_{-7}^{+11}	116	172	2.2
630	Σ^-	3			π	1.8	57_{-10}^{+13}	134	105	0.3
692	Σ^-	3			π^+	1.6	82	136	136	0.2
809	Σ^-	2			π^+	38.0	48	139	224	8.6
839	Σ^- [h]	$\pi(f)$		27–35	π^+	23–40	33	128	227	2.7–4.7
41	*Hp* [i]	1			π^+	4.4	76 ± 4	101	177	0.6
356	*Hp*	0			π^+	5.2	69	120	138	0.8
606	*Hp*	0			π^+	1.6	50	102	130	0.2
751	*Hp*	0			π^+	11.1	68	52	300	2.0
808	*Hp*	0			π^+	2.9	40	88	138	0.5
812	*Hp*	0			π^+	4.3	52	50	212	0.7
817	*Hp*	0			π^+	8.0	57	142	90	1.4
341	*Hp*	0			π	1.3	74_{-8}^{+12}	132	132	0.2
380	*Hp*	0			π	26.0	51_{-6}^{+8}	155	147	5.5
531	*Hp*	0			π	7.2	75_{-5}^{+10}	156	72	1.2
836	*Hp*	0			π	13.2	65	118	168	2.4
852	*Hp*	0			π	13.8	71_{-9}^{+13}	85	248	2.6
C_1 [j]	Σ^+				π	18	78 ± 14		135	
C_2 [j]	Σ^+				π	16.5	76 ± 11		197	
C_3 [j]	Σ^-				π	17	62 ± 9		162	
C_4 [j]	Σ^-				π	23.5	42 ± 7		153	
1*J*20–24 [k]	Σ^+				π^-	43 ± 5	35.5		227	
*T*16–2 [k]	Σ^+				π	23.2	31.5		174	
*T*8–7 [k]	Σ^-				π	23.9	54 ± 20		120	
1*J*20–16 [k]	Σ^-				π	17.0	84 ± 10		213	

[a] The decay mode notations are: $P(r)$—decay at rest of a Σ^+ hyperon into a proton; $P(f)$—decay in flight into a proton; $\pi(r)$—decay at rest into a charged π meson; $\pi(f)$—decay in flight into a charged π meson. For Σ^- captures, the integer indicates the number of prongs in the capture star. A prong is defined as any track longer than 5 microns.

[b] R_s is the range of the decay secondary.

[c] $\theta_{\Sigma\pi}$ c.m. is the angle between the Σ hyperon and its π-meson decay product in the rest system of the Σ hyperon. The angle is included for use ofthose experimenters investigating decay-angle asymmetries.

[d] $T_{0\Sigma}$ is the Σ-hyperon kinetic energy at the K^--capture point.

[e] $T_{0\pi}$ is the π-meson kinetic energy at the K^--capture point. Where no value for the uncertainty is listed, the error is primarily due to range straggle and is about 2% of the kinetic energy.

[f] $\theta_{\Sigma\pi}$ is the angle between the π meson and the Σ hyperon at the K^--capture point.

[g] t_Σ is the proper flight time of the Σ hyperon from production to decay in flight, or from production to stop if it does not decay in flight. The flight time is included for use of those experimenters investigating Σ-hyperon lifetimes.

[h] The charges of the Σ hyperon in these events were inferred from the charges of their π-meson partners.

[i] The heavy track from event 41 had a sharp bend 26 microns from its end. This point is probably the Σ^--capture point giving a one-prong star.

[j] Data from Haskin, Bowen, and Schein.[2]

[k] Data from S. C. Freden and H. K. Ticho (private communication).

stars which satisfy the following conditions have been selected for analysis. The capture must contain only two prongs, one of which is a π meson, as identified by its ending or by the change in ionization if the prong is not brought to rest in the stack. A track less than 5 microns in length is not considered a prong. The true space angle between the light meson and the heavy track was calculated from measurements of the horizontal angle between the prongs and dip angles on both prongs. The range of each track was measured and the energy of the particle was obtained from range-energy curves[8] which were adjusted to the density of the emulsion. If a track left the stack or interacted in flight before coming to rest, its energy was calculated from its ionization.

In Table II are listed the identified Σ hyperons. Most of the Σ^+ hyperons were recognized because they decayed, at rest or in flight, into a proton or decayed at rest into a π meson. The charges of two Σ hyperons that decayed in flight into π mesons, in events 123 and 839, were inferred from the charge of their π-meson partners in the K-capture reactions. One additional charged Σ hyperon, in event 81, decayed in flight into a charged π meson where the charge of its π-meson partner was not identified. As the Σ^--hyperon lifetime is about twice that of the Σ^+ hyperon[3] and the Σ^+ hyperon decays with about equal probability into either a proton or a π^+ meson, this event has about equal chances of being a Σ^+ or Σ^- hyperon and has therefore been divided into $\frac{1}{2}\Sigma^+$ and $\frac{1}{2}\Sigma^-$ hyperon event. Six Σ^- hyperons were identified by the fact that they were captured at rest to give stars of two or more prongs. The Σ hyperon in event 839 decayed in flight. Since it had a π^+-meson partner it was identified as a Σ^- hyperon. One 1-prong and $8\frac{1}{2}$ zero-prong Σ^--capture stars were inferred from the analysis described later. Two additional events have been analyzed as captures on free protons and will be discussed in the next section.

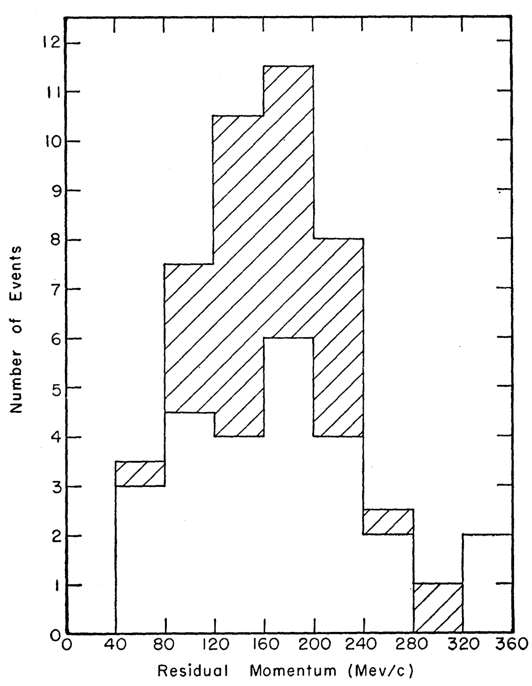

FIG. 1. The number of events *versus* their residual momentum. The residual momentum is the vector sum of the momenta of the Σ hyperon and the π meson. The residual momentum may be interpreted as the momentum of the residual nucleus. The Σ^--hyperon plus π^+-meson events are shown cross-hatched and the Σ^+ hyperon plus π^--meson events are shown blank.

[8] W. H. Barkas and D. M. Young, University of California Radiation Laboratory Report UCRL-2579 Rev. (unpublished); W. H. Barkas, University of California Radiation Laboratory Report UCRL-3384 (unpublished); and W. H. Barkas (private communication).

The residual momentum listed in the next to the last column of Table II is the vector sum of the momentum of the π meson and the Σ hyperon (the distribution of these momenta is shown in Fig. 1). In the absence of nuclear and Coulomb potentials this momentum would be the momentum of the capturing proton. The presence of potentials alters the observed momentum distribution for two reasons. (1) The energies and also the momenta are different outside than inside the nucleus. (2) A potential as large as the kinetic energy might cause a particle to be strongly refracted at the nuclear surface. For these reasons the measured momentum is not the momentum of the capture proton but may be interpreted as the momentum of the residual nucleus.

The two prong events have been summarized in Table III. The events which have, as one member, a prong with an $H\rho$ ending have been included in the third row of Table III. An $H\rho$ ending is an ending of a heavy particle which has a mass that is greater than that of the π meson and has no observable prongs. Included also are the 4 events from the paper of Haskin, Bowen and Schein,[2] hereafter referred to as HBS, and 4 events from Freden and Ticho[9] for which these authors gave measurements of $T_{0\pi}$, $T_{0\Sigma}$, and $\theta_{\Sigma\pi}$.

TABLE III. Summary of two-prong events.

Experiment	Type of event	No. of events	No. with wrong charge of meson
Authors'	Σ^- (identified by ending)	21.5	0
	Σ^- (identified by ending)	7.5	0
	$H\rho$ total	51	23[a]
	$H\rho$ Σ^-	9.5[b]	...
Haskin, Bowen, and Schein[c]	Σ^+	2	0
	Σ^-	2	0
Freden and Ticho[d]	Σ^+	2	0
	Σ^-	2	0
Total	Σ^+	25.5	0
	Σ^-	21	0

[a] Conservation of charge in the capture reaction indicates that these 23 events are not Σ-hyperon events.
[b] See text for identification methods.
[c] See reference 2.
[d] See reference 9.

[9] S. C. Freden and H. K. Ticho (private communication).

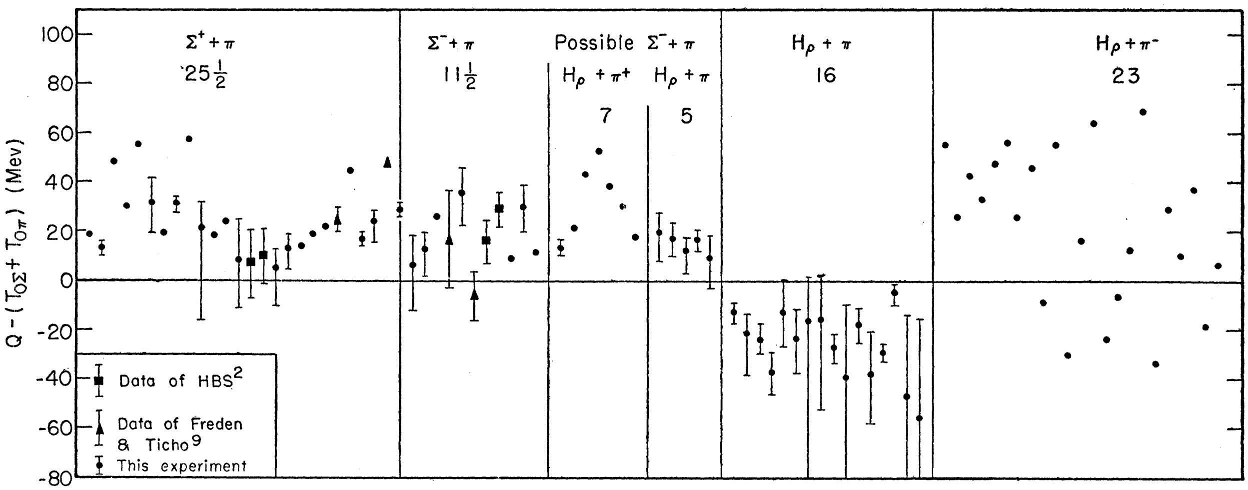

FIG. 2. The value of $Q-(T_{0\Sigma}+T_{0\pi})$ for each of the two-pronged events of this experiment. Q values of 103 and 96 Mev were used for the reactions giving Σ^+ and Σ^- hyperons, respectively. The events are divided into groups according to their identification. An $H\rho$ ending is an ending of a particle which is heavier than a π meson and which has no visible track at its ending. Event 81 in which the Σ hyperon decays in flight into a π meson could be a Σ^+ or Σ^- hyperon with about equal probability. For events plotted as dots without errors, both particles were stopped. In these cases the error is primarily due to range straggle and is about 2% of the π-meson kinetic energy (see Table II).

In the last column of Table III is listed the number of events which have π mesons of the wrong sign, as determined from the meson ending, to conserve charge in a K^- capture on a proton in the nucleus. In 14 out of 29 cases, in which the charge of the Σ hyperon was identified by its ending, the π mesons were followed until they came to rest and their charge was identified. In no case did a Σ hyperon have as a partner a π meson of the wrong sign. If the $H\rho$ events are Σ^- hyperons, they should have π^+ mesons as partners. Twenty-three $H\rho$ events were eliminated from the group of 51 because the π-meson partners ended as π^- mesons. Six events out of the $H\rho$ group had identified π^+ mesons as partners. The light meson from event 41 came to rest with a $\mu - e$ decay and is presumably a μ^+ meson. The μ^+ meson is thought to have resulted from a decay in flight of a π^+ meson which gave no change in grain density or change in direction along the track which could be identified as the decay point. The $H\rho$ track in this event had an apparent large angle scatter at 24 microns from its end and was interpreted as a capture of a Σ^- hyperon to give a one-prong star.

The sum of the kinetic energies of the π meson and the Σ hyperon have been subtracted from the Q value of 103 Mev for reaction (1a) and 96 Mev for reaction (1b), according to Eq. (3), and have been plotted in Fig. 2. The events have been divided into the following categories: (1) Reaction (1a), identified by the Σ^+-hyperon decay. (2) Reaction (1b), identified by the Σ^--hyperon capture with 2 or more charged prongs. (3) $H\rho$ events which have been subdivided into events with π^+-meson partners, π-meson partners and π^--meson partners. The $H\rho$ events with π^+-meson partners are identified as Σ^--hyperon events from reaction (1b). The particles that have $H\rho$ endings and π^--meson partners cannot be Σ^- or Σ^+ hyperons. The events whose value for E_B+E_{ex} is less than zero cannot be Σ hyperons by conservation of energy. In addition to the 11.5 identified Σ^- hyperons (the two events of HBS and the two of Freden and Ticho have been included) and 7 events with π^+-meson partners, there remain only 5 possible candidates for Σ^- hyperons among the $H\rho+\pi$ events.

Each of the 5 candidates has an (E_B+E_{ex}) value in the range of 0–40 Mev. However, some of the events with π^--meson partners also have (E_B+E_{ex}) values from 0–40 Mev and some or all of the five Σ^--hyperon candidates could be events of that type and not Σ^- hyperons. The problem is to determine, if possible, what fraction of the 5 events are Σ^- hyperons. The fraction may be estimated by one of two methods. (1) All $H\rho+\pi^+$ events are assumed to be $\Sigma^-+\pi^+$ reactions. The fraction of π^+ mesons in the $H\rho+\pi$ events is assumed to be the same as in the rest of the $H\rho+\pi^+$ and $H\rho+\pi^-$ events whose $Q-(T_{0\pi}+T_{0\Sigma})$ values are in the same energy range; in this experiment 5/14. By this argument 2 of the five $H\rho+\pi$ events are Σ^- hyperons. (2) The number of π^+ mesons in the $H\rho+\pi$ events may be obtained by dividing the number of $H\rho+\pi^+$ events by the probability of stopping the π^+ to identify its charge. The probability may be approximated by taking the experimentally observed stopping probability for all π mesons from events with $Q-(T_\pi+T_\Sigma)$ in the same energy range. For this experiment the π-stopping-probability is 0.6. Since there are 5 π^+ mesons stopped in the given energy range, there should be 8 total, including the 5 which stopped, so that 3 of the 5 events in question should be Σ^- hyperons.

An average of methods (1) and (2) yields 2 $\frac{1}{2}\Sigma^-$ hyperons from the five $Hp+\pi$ events. In conclusion the total number of Σ^- hyperons is 21. This number includes two Σ^- hyperons each from HBS[2] and from Freden and Ticho.[9]

A large fraction of the $Hp+\pi^-$ events, observed in this experiment, could arise from $\Sigma^++\pi^-$ events where the Σ^+ hyperon was captured internally to give a proton by the reaction

$$\Sigma^++n\rightarrow\Lambda^0+p, \tag{14a}$$

or

$$\rightarrow\Sigma^0+p. \tag{14b}$$

Some of the $Hp+\pi$ events whose visible energy was too great to permit them to be $\Sigma^-+\pi^+$ events (i.e., $Q-[T_\pi+T_\Sigma]<0$) could originate from reaction (14a) because of the additional energy (76 Mev) available. Some of these latter events could also be due to Σ^- hyperons which were captured to give one-pronged stars. However, since the primary capture reactions for Σ^- hyperons yield only neutral particles,

$$\Sigma^-+p\rightarrow\Lambda^0+n, \quad \text{or} \quad \rightarrow\Sigma^0+n, \tag{15}$$

it is unlikely that many of the $Hp+\pi^-$ events are due to Σ^- captures. This is borne out by the low fraction (0.1) of one-pronged stars among the identified Σ^--capture stars (Fig. 6). A large fraction of the Σ^- hyperons are in negative energy states and are captured before they escape the nucleus. The π^+-meson partners to these Σ^- hyperons have energies greater than 76 Mev, Eq. (3), and usually appear in stars with only one prong; therefore, they are not included in this paper. If there are an appreciable number of K^- captures on neutrons through reactions (1f) giving $\Sigma^0+\pi^-$, or (1g) giving $\Lambda^0+\pi^-$, then $Hp+\pi^-$ events could arise when the Σ^0 is captured by a proton to give a Λ^0 hyperon and proton,

$$\Sigma^0+p\rightarrow\Lambda^0+p, \tag{16}$$

or when the Λ^0 from reaction (1g) does not escape from the nucleus but interacts to give one black prong.

The number of Σ hyperon events has been plotted *versus* the quantity $Q-(T_{0\pi}+T_{0\Sigma})=E_B+E_{ex}$ in Fig. 3.

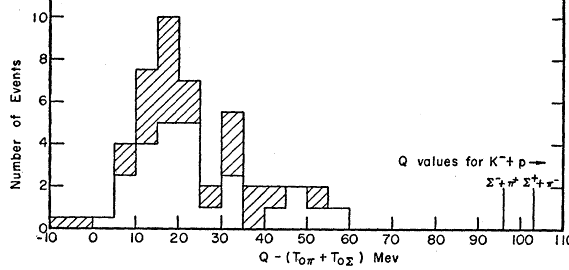

FIG. 3. Distribution in $Q-(T_{0\Sigma}+T_{0\pi})$ values for the events with Σ hyperons. The Σ^- events are cross-hatched. The Σ^+ events are blank.

From this figure, it appears that the best value for E_B+E_{ex} is about 20 Mev with a spread that extends from about 0 to 40 Mev. Since the capture process is a statistical one and since the captures occur on different nuclei of the emulsion, Ag, Br, O, N, and C, the variation in the value of (E_B+E_{ex}) is expected. Seven events have values of (E_B+E_{ex}) larger than 40 Mev. Six of these have π-meson energies of 40 Mev or less. It is likely that these 6 events are cases where the π mesons suffered inelastic collisions before escaping from the nucleus.

If the quantity (E_B+E_{ex}) is the same for both Σ^+- and Σ^--hyperon production, the kinetic energies of the π mesons and Σ hyperons may be used to obtain the difference in the masses of the Σ^- and the Σ^+ hyperons by using Eq. (2). The mass difference is

$$M_{\Sigma^-}-M_{\Sigma^+}=\langle T_{\Sigma^+}+T_{0\pi^-}\rangle-\langle T_{0\Sigma^-}+T_{0\pi^+}\rangle,$$

where $\langle T_{0\Sigma^+}+T_{0\pi^-}\rangle$ and $\langle T_{0\Sigma^-}+T_{0\pi^+}\rangle$ are the average values for the Σ^+- and Σ^--hyperon events, respectively. HBS[2] have pointed out that their data may be interpreted as suggesting that the mass of the Σ^- hyperon is slightly greater than the mass of the Σ^+ hyperon. The data from this experiment (including the events of HBS and Freden and Ticho) gives $\langle T_{0\Sigma^+}+T_{0\pi^-}\rangle=84.5\pm1.7$ Mev, and $\langle T_{0\Sigma^-}+T_{0\pi^+}\rangle=73.8\pm2.6$ Mev, respectively, for the Σ^+ and Σ^--hyperon events. The 8 events for which $Q-(T_{0\pi}+T_{0\Sigma})$ is outside the range 0 to 40 Mev have been excluded, as it is expected that many of these 8 events are cases where the π meson interacted inelastically before leaving the nucleus. The 5 inferred Σ^- events in the $Hp+\pi$ category and event 81 have been omitted because their identity is uncertain. The resulting mass difference is $21\pm6\ m_e$. This value is consistent with the more accurate results stated in the next section.

From the data of Tables II and III the value for the ratio of the number of Σ^- hyperons to the number of Σ^+ hyperons which are produced and escape from the nucleus in the capture of K^- particles on protons in emulsion nuclei can be estimated. On the basis of 21 Σ^- hyperons and 25.5 Σ^+ hyperons, the Σ^-/Σ^+ ratio is 0.83 ± 0.25. This result is different from the value of 2

TABLE IV. Summary of emulsion data for K^- captures on free protons.

Source	No. of Σ^+ events	No. of Σ^- events	Prongs from Σ^- captures
Chupp, Goldhaber, Goldhaber and Webb[a]	3	2	0, 0
Fry, Schneps, Snow, Swami, and Wold[b]	1	1	0
Freden and Ticho[c]	0	1	3
Giles and Heckman[d]	1	4	0, 1, 2, 3
Present authors	0	2	0, 0

[a] See reference 10.
[b] See reference 11.
[c] See reference 9.
[d] See reference 12.

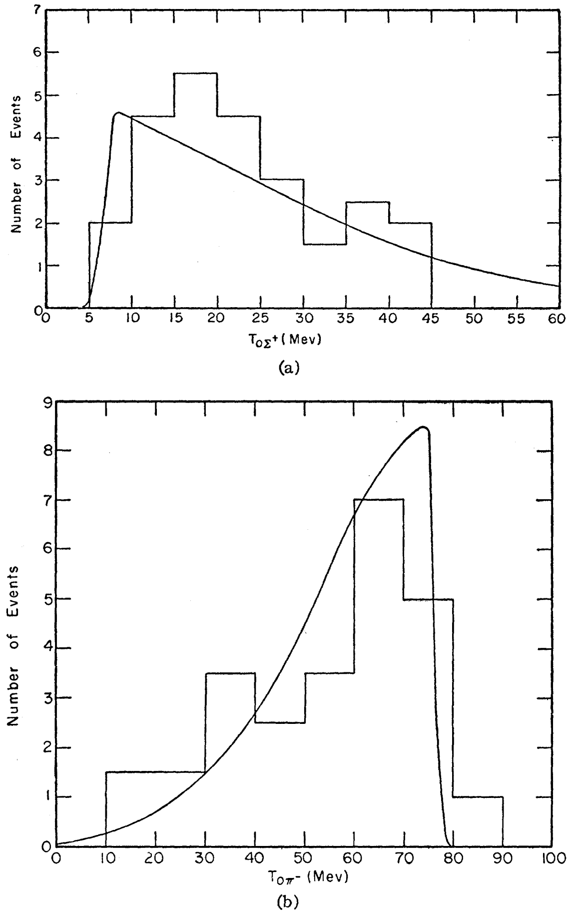

FIG. 4(a). The Σ^+-hyperon energy distribution; (b) the energy distribution if its π^--meson partner. The theoretical Σ^+-hyperon curve was obtained from Eq. (13) in the text and is based on the capture model. The low-energy end of the Σ^+-hyperon curve is modified to take account of the reflection of the Σ^+ hyperon at the Coulomb barrier. The same curve, transformed by Eq. (3), is plotted on the π^--meson distribution.

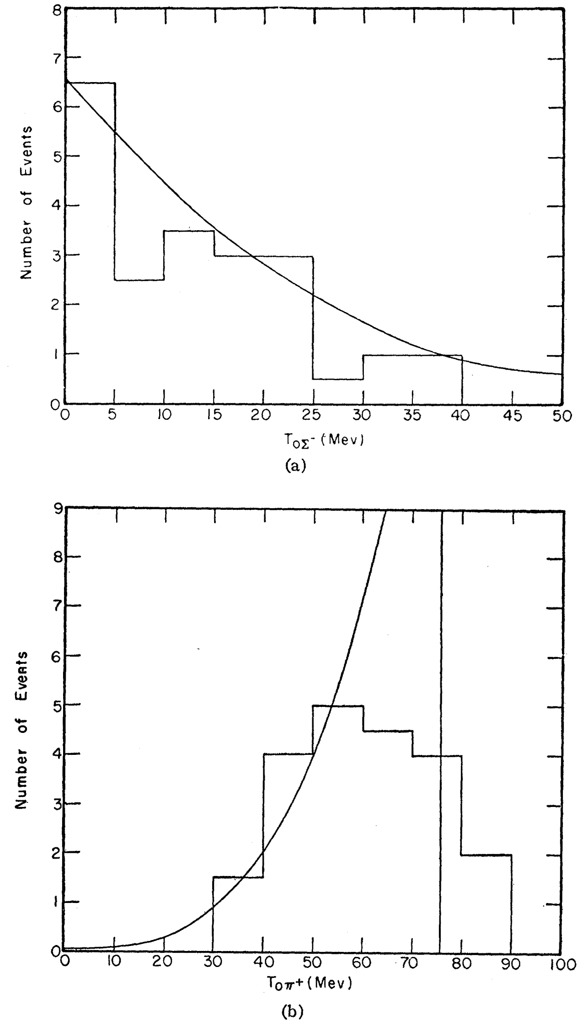

FIG. 5(a). The Σ^--hyperon energy distribution; (b) the energy distribution of its π^+-meson partner. The ordinate of 5(a) has been obtained by multiplying the ordinate of Fig. 4(a) by 2 (in agreement with the ratio of Σ^- to Σ^+ hyperons from K^- captures on free protons), and the curve has been displaced along the energy axis by an amount equal to 22 Mev in agreement with an average Coulomb potential of about 10 Mev. The same curve, transformed by Eq. (3), is plotted on the π^+-meson energy distribution.

which was obtained by the hydrogen bubble chamber group[3] for the capture of K^- particles on free protons. It should be pointed out that the emulsion data from K^--particle captures on free protons give a ratio for Σ^- to Σ^+ hyperons of 10/5 in agreement with the bubble chamber result. The emulsion data are summarized in Table IV.[9–12] The low ratio of Σ^- to Σ^+ hyperons that is observed for captures on bound protons may be explained as follows. Since there are twice as many Σ^- as Σ^+ hyperons produced by captures on free protons, there are twice as many Σ^- as Σ^+ hyperons made inside the nucleus by captures on bound protons. In leaving the nucleus, the Σ hyperons are displaced in energy by the Coulomb potential, the Σ^+ hyperons are increased in energy by V_c and the Σ^- hyperons decreased by V_c as is indicated by Eq. (4). The Σ^- hyperons in negative energy states cannot escape the nucleus and are eventually captured. This severely restricts the number of Σ^- hyperons that are observed. The Σ^+ hyperons with external energies between 0 and V_c are partly reflected by the Coulomb barrier with a high probability of subsequent capture so that the Σ^+-energy distribution is cut off on the low-energy end. The high-energy ends of the Σ^-- and Σ^+-hyperon energy distributions should not be distorted by the Coulomb barrier, but only displaced in energy. Consequently, outside the nucleus, the number of Σ^- hyperons with kinetic energies above 0 Mev is equal to twice the number of Σ^+ hyperons with energies above $(2V_c+1)$ Mev. See Figs. 4(a) and 5(a). From 21 Σ^- hyperons of

[10] Chupp, Goldhaber, Goldhaber, and Webb, University of California Radiation Laboratory Report UCRL-3593, 1956 (unpublished).

[11] Fry, Schneps, Snow, Swami, and Wold, Phys. Rev. **104**, 270 (1956).

[12] P. C. Giles and H. H. Heckman (private communication).

the experimental Σ^--hyperon energy distribution and 10.5 Σ^+ hyperons from the Σ^+ distribution, $(2V_c+1)$ is found to be 22±6 Mev and V_c to be 10±3 Mev. This value is about the same as the Coulomb barrier for silver (10 Mev). It is of interest that the maximum height of the Coulomb potential is not limited to the Coulomb barrier energy for particles that are made near the center of the nucleus; i.e., the potential of a uniformly charged sphere is 1.5 times as great at the center as on the surface. The large value of V_c suggests that most of the captures of this experiment are taking place on the heavy elements of the emulsion, i.e., Ag and Br.

Because the sum of the kinetic energies of the Σ hyperon and the π meson is approximately a constant, [Fig. 3 and Eq. (3)] the shape of the distribution in π-meson kinetic energy is also given by Eq. (13). The lower edge to the Σ-hyperon kinetic-energy distribution becomes an upper edge to the π-meson energy distribution. The experimental data is plotted on Figs. 4(b) and 5(b) for the π^- and π^+ mesons, respectively, and the same curve that was fitted to the Σ hyperons is superimposed on these histograms. Although the uncertainties in the energies of the π mesons are greater than the uncertainties in the energies of the Σ hyperons, as only about 0.6 of the π-meson energies were obtained by range and the rest by ionization measurements, the difference in the π^+- and π^--meson spectra is compatible with the value of V_c that was deduced from the Σ-hyperon distributions.

From the Σ^--hyperon capture stars information is available on the Σ^--hyperon capture mechanism. The analysis of the two-pronged K^--capture stars enables us to identify the Σ^- hyperons that interact with emulsion nuclei to give zero-prong stars so that a complete prong distribution can be obtained. The captures of this experiment plus 10 Σ^--hyperon stars from K^--captures on free protons (Table IV) have been used to obtain the prong distribution shown in Fig. 6. Although the data is limited the distribution can be interpreted as a composite of a distribution that is similar to the π^--meson emulsion capture prong distribution[13] and a superimposed line spectrum of stars with zero prongs. The prong distribution may be explained by the capture of a Σ^- hyperon on a proton of the nucleus according to one of the reactions of Eq. (15). If the Λ^0 or Σ^0 hyperon and neutron escape with little excitation of the capture nucleus, zero-prong stars usually result. On the other hand, if the Λ^0 or Σ^0 hyperons are captured by the nucleus before escaping, energies up to 250 Mev are available to the nucleus for prong emission and, if the neutron is captured, about 40 Mev is available. These cases result in multiple pronged events. There was one case, event 630, in which a hyperfragment was emitted from the Σ^--hyperon capture point and decayed non-mesonically into two heavy prongs. Its identity was not established. Because of the presence of short prongs that could not have penetrated the Coulomb barriers of Ag or Br, it appears that many of the Σ^- hyperons that made stars were captured on the light nuclei of the emulsion.

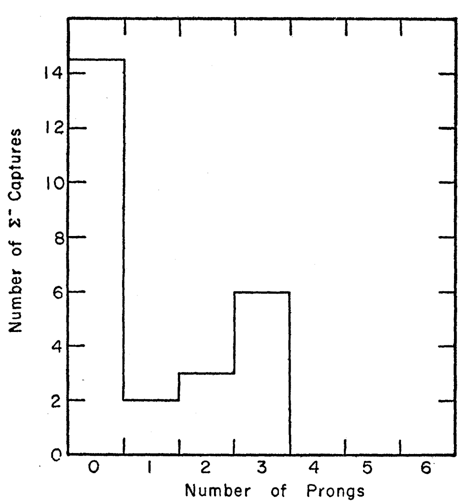

FIG. 6. The prong distribution from Σ^--hyperon interactions in emulsion nuclei. In addition to all of the Σ^- hyperons of this experiment from captures of K^- particles on bound protons, 10 Σ^- hyperons of Table IV have also been included.

TABLE V. Measurements on events 133 and 804.

Event No.	Prong	Range (mm)	Energy (Mev)	Momentum (Mev/c)	Emulsion density
133	π^+	74.5 ±2.4	79.8 ±1.7	169.3±2.2	3.81 ±0.04
	Σ^-	0.773±0.013	13.3 ±0.2	179.1±1.1	
804	Σ^-	0.693±0.010	12.58±0.10	174.0±0.7	3.857±0.004

The Σ^--hyperon prong distribution is also of practical interest as a means of Σ^--hyperon identification in emulsion experiments. The number of interest is the fraction of the total Σ^--hyperon interactions that lead to stars of 0 and 1 prong. Σ^- hyperons with 0 prongs are difficult to identify and stars of 1 prong are sometimes confusable with proton scattering events. This fraction is found to be 0.65±0.10.

B. Captures on Free Protons

Measurements made on events 133 and 804, the collinear events, are shown in Table V. The deviation of the two tracks from collinearity is estimated to be 0.2±1.0 deg and 0.0±0.2 deg, respectively. No recoil, electron or blob was seen at the capture point that would suggest a capture on a nucleus. The quantity $Q-(T_{0\Sigma}+T_{0\pi})$ for these two events is 10 Mev less than for any of the other 22 cases of two-pronged events with identified Σ hyperons where the π meson was stopped and accurate energy measurements were made. Furthermore, in the 38.5 two-pronged events which gave a Σ hyperon and a π meson, more than half had values of

[13] For a discussion of the work on π^- captures in emulsion nuclei, see R. E. Marshak, *Meson Physics* (McGraw-Hill Book Company, Inc., New York, 1952), Chap. 5.

$\theta_{\Sigma\pi}>135$ deg but there was no event with a value of $\theta_{\Sigma\pi}>167$ deg. For these reasons events 133 and 804 appear to be in a class by themselves and are interpreted as examples of captures of K^- particles on free protons.

a. Event 133

From Table V it may be seen that there is not an exact momentum balance between the π meson and the Σ^- hyperon for event 133. The difference of 10 Mev/c is about four times the standard deviation of the measurement and appears to be real. The Σ^--hyperon range is longer and the π^+-meson range shorter than would be expected from a K^- capture at rest but the ranges are correct for a K^- particle of an energy of 0.1 Mev that was captured by a free proton at rest if the Σ^- hyperon was emitted in the K^--particle direction. The angular resolution was such that a transverse momentum unbalance of 3 Mev/c would not have been observed. From the range measurements of the π meson and the Σ hyperon, conservation of energy, and the assumption that the K^--particle mass is the same as the τ^+-meson mass, $966.7\pm0.6\ m_e$,[14] the Σ^--hyperon mass is found to be $2347.4\pm3.5\ m_e$. The uncertainty in the Σ^--hyperon mass is primarily due to the range straggle of the π meson. In the 14 other cases of the capture of a K^- particle on a free proton in nuclear emulsion (Table IV), the π mesons could not be followed to their end to determine the sign of the π meson or to get the most accurate measurement of their momenta by range; therefore, the possibility could not be ruled out that some of those events could be cases of K^--particle capture in flight. The constancy of the Σ-hyperon ranges, on the other hand, leads to the conclusion that most of the events were cases where the K^- particle was captured at rest.

TABLE VI. Data on Σ^+ decays at rest into protons.

Event No.	Proton range (mm)	Emulsion density (g/cm³)	Proton range[a] corrected to 3.815 g/cm³ (mm)	Dip angle θ_v (deg)	Shrinkage factor	θ[b] (deg)
43	1.677	3.757±0.069	1.651±0.040	24	2.26±0.06	106
382	1.712	3.802±0.054	1.706±0.036	42	2.30±0.02	40
552	1.748	3.829±0.004	1.755±0.028	32	2.22±0.02	13
578	1.695	3.829±0.004	1.701±0.027	35	2.33±0.02	68
800	1.730	3.818±0.004	1.731±0.028	38	{2.30±0.02 {2.25±0.02	19
802	1.700	3.818±0.004	1.701±0.030	66	2.30±0.02	81
810	1.685	3.818±0.004	1.686±0.027	15	2.30±0.02	23
		Weighted mean	1.709±0.012			

[a] The density correction was made by multiplying the measured range by the ratio of the measured density to 3.815 g/cm³. This method is not quite correct (see reference 8) but introduces an error less than 0.1% in the weighted mean range. The error in the range is compounded from range straggle (1.4%), uncertainty in the emulsion density as shown in column 3, measurement errors (0.5%), uncertainty in the range-energy relation (0.5%) and uncertainty in the shrinkage factors as shown in column 6. The relative error in the range, dR/R caused by an uncertainty in the shrinkage factor ds/s is approximately $dR/R=(ds/s)\sin^2\theta_v$, where θ_v is the angle between the track and the emulsion surface.

[b] θ is the angle between the emission direction of the Σ^+ at the K-capture star and the emission direction of the proton at the Σ^+-decay point.

TABLE VII. Comparison of Σ^--hyperon mass values.

Source	M_{Σ^-} (m_e)	$M_{\Sigma^-}-M_{\Sigma^+}$ (m_e)
Chupp[a]	2342.1±2.0[f]	13.9±1.8
Budde *et al.*[b]	2342.5±5.2	
Fry *et al.*[c]	2343.3±3.1[f]	15.9±2.9
Freden and Ticho[d]	2340.7±1.3	
Barkas *et al.*[e]	2341.6±2.3[f]	13.6±2.2
Authors' Event 133	2347.4±3.5	
Event 804	2341.8±1.5	
Weighted mean	2341.8±1.0	14.2±1.5

[a] W. Chupp (private communication based upon two events described in reference 10).

[b] Budde, Chretien, Leitner, Samios, Schwartz, and Steinberger, Phys. Rev. **103**, 1827 (1956).

[c] See reference 11.

[d] See reference 9.

[e] See reference 16.

[f] These masses were derived from $(M_{\Sigma^-}-M_{\Sigma^+})$ by using the experimenter's own Σ^+-hyperon mass values[15,16] except for the first experiment listed where the value $2328.2\pm0.7\ m_e$ (see text) was used.

b. Event 804

Event 804 is particularly suited for accurate analysis because of the Σ-hyperon π-meson line made an angle of only 6 deg with the plane of the emulsion. Because of this small angle the uncertainties due to the shrinkage factor and to the measurement of the vertical component of range contributed less than 1 micron error to the total range, and were neglected. The measured range of the Σ hyperon and the laws of conservation of energy and momentum were used to calculate the mass of the Σ^- hyperon. The π meson left the stack after 4 cm of range so that an accurate momentum balance could not be determined. On the assumption that the K^- particle was captured at rest and that the mass of the K^- meson is $966.7\pm0.6\ m_e$,[14] the mass of the Σ^- hyperon in event 804 is found to be $2341.8\pm1.5\ m_e$. The uncertainty in the range of the Σ^- hyperon due to the range straggle is 1.4%, in range due to the range-energy relation is 0.5%,[8] and in the K^--particle mass is 0.6 m_e. These uncertainties lead to the value quoted in the Σ^--hyperon mass. All other errors are considered negligible compared to these.

The data on 7 Σ^+-hyperon decays at rest into protons are given in Table VI. The weighted mean range is used with the range-energy relation of Barkas[8] to give a Σ^+-hyperon mass of $2329.5\pm1.0\ m_e$. This may be compared to the value $2327.4\pm1.0\ m_e$ measured by Fry *et al.*[15] and the value $2328.0\pm0.7\ m_e$ measured by Barkas *et al.*[16] If a systematic error of 0.5 m_e due to the uncertainty in the range-energy relation is taken into account, we obtain a weighted mean Σ^+-hyperon mass of $2328.2\pm0.7\ m_e$.

[14] The Q value for the τ^+ decay is given by R. P. Haddock, Nuovo cimento 4, 240 (1956), as being 75.13±0.20 Mev. Heckman, Smith, and Barkas, Nuovo cimento 4, 51 (1956), give 75.08 ±0.20 Mev for the Q value. These values have been used to obtain a mass of $966.7\pm0.6\ m_e$ for the τ^+ meson when one assumes a mass for the charged π meson of $273.25\pm0.12\ m_e$ as given by Cohen, Crowe, and DuMond, Phys. Rev. **104**, 266 (1956).

[15] Fry, Schneps, Snow, and Swami, Phys. Rev. **103**, 226 (1956).

[16] P. C. Giles and H. H. Heckman [private communication derived from events described by Barkas, Dudziak, Giles, Heckman, Inman, Mason, Nichols, and Smith, University of California Radiation Laboratory Report UCRL-3627 (unpublished)].

In Table VII are tabulated the two Σ^--hyperon mass measurements in this experiment plus those from other experiments. In three of the listed experiments the quantity $(M_{\Sigma^-}-M_{\Sigma^+})$ was determined from the ranges of the Σ^+ and Σ^- hyperons which were both available from K captures on free protons via reactions (1a) and (1b). This quantity is less dependent than the absolute mass value upon systematic errors, i.e., systematic uncertainties in range measurement, emulsion density, and the range-energy relation. In particular, it is independent of the mass of the K^- meson. For these reasons the mass difference is tabulated separately and gives a weighted mean value of 14.2 ± 1.5 m_e. If the mean Σ^+-hyperon mass value of 2328.2 ± 0.7 m_e is combined with this mass difference we obtain a value 2342.4 ±1.7 m_e for the mass of the Σ^- hyperon. This latter value is combined with the other four masses listed in Table VII to give a weighted mean mass for the Σ^- hyperon of 2341.8 ± 1.0 m_e. The uncertainties in the K-meson mass and in the range-energy relation are treated as systematics in obtaining the error of 1.0 m_e.

CONCLUSIONS

From about 620 captures of K^- particles by bound and free protons in nuclear emulsion, 90 events in which a charged π meson and only one additional charged particle were emitted have been selected for study.

1. A model is proposed for the capture of a K^- particle on a moving proton that is bound to the nucleus. The momentum of the proton is imparted unchanged to the Σ hyperon and π meson that are produced. They move like classical particles in the nucleus and escape with energies which are shifted from the values for captures on free protons because of the nuclear and Coulomb potentials. The Σ^+- and Σ^--hyperon and π^-- and π^+-meson energy distributions are explained by the model. The sum of the binding energies of the last proton in the capture nucleus and the excitation energy of the residual nucleus has a distribution which is peaked at about 20 Mev.

2. A Coulomb potential of 10 ± 3 Mev is estimated from the relative positions of the high-energy ends of the Σ^+- and Σ^--hyperon energy distributions and this value suggests that most of the captures were on the heavy elements of the emulsion, Ag and Br.

3. The Coulomb potential, which increases the external energies of the Σ^+ hyperons and reduces the energies of the Σ^- hyperons, is responsible for reducing the ratio of Σ^- to Σ^+ hyperons from a value of 2 for captures on free protons to the observed value of 0.83 ±0.25 for captures on bound protons.

4. Conservation of charge and energy have been applied in order to identify the Σ^- hyperons that end in stars with no prongs. Data from experiments for K^--particle captures on free protons were added to that of this experiment to obtain the Σ^--hyperon capture prong distribution. Although the data are limited, the Σ^--hyperon capture prong distribution can be interpreted as a composite of two distributions; (1) a line spectrum of zero-prong stars that occurs when the Λ^0 or Σ^0 hyperon and neutron escape leaving little excitation energy in the nucleus, and (2) a broad distribution due to the capture of either the neutral hyperon or the neutron, or both, before escaping from the nucleus. It was found that 0.65 ± 0.10 of the Σ^--hyperon capture interactions lead to stars of zero or one prong. In nuclear emulsion experiments this number may be used, along with the observed number of Σ^--hyperon captures that give stars of two or more prongs, to determine the total number of Σ^- hyperons present.

5. Seven Σ^+ hyperons that decayed into protons at rest are used to find a Σ^+-hyperon mass of 2329.5 ± 1.0 m_e. A weighted mean of this and other measurements gives a Σ^+-hyperon mass of 2328.2 ± 0.7 m_e.

6. Two examples of K^- captures on free protons are presented. In event 133, the K^- particle was probably captured in flight with an energy of 0.1 Mev to give a Σ^- mass of 2347.4 ± 3.5 m_e. In event 804 the Σ^--hyperon–π-meson line made an angle of only 6 deg with the plane of the emulsion so that a more accurate Σ^- mass of 2341.8 ± 1.5 m_e could be obtained. A weighted mean of these and other measurements gives a Σ^--hyperon mass of 2341.8 ± 1.0 m_e.

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