Search for Σ^- Hyperfragments*

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A systematic search has been undertaken for possible Σ^- compounds produced by K^- captures in nuclear emulsion. Mass determinations were performed on (a) 15 decays in flight into a charged pion and (b) 84 events resulting in capture configurations; the number of these events produced in single-nucleon K^- captures is estimated to be >32 but <71. All events of type (a) and all but 4 of type (b) are consistent with the interpretation as Σ^-. The 4 events are discussed in detail and it is concluded that, although the $(\Sigma^- n)$ interpretation cannot be ruled out for 3 of them, in no case is the identification unequivocal.

I. INTRODUCTION

THERE is considerable interest in determining experimentally whether or not the Σ^- hyperon forms a bound system with one or more neutrons. The results of searches for such hyperfragments have already been reported by the Berkeley and Milan groups.[1,2] However, in the Berkeley experiment there exists the possibility that a selection rule[3] may operate in inhibiting the process $K^-+H^2 \rightarrow (\Sigma^- n)+\pi^+$ if the K^- capture occurs from an s state,[4] the $K^- - \Sigma$ relative parity is odd, and the $(\Sigma^- n)$ is in a singlet s state. On the other hand, the Milan experiment has been concerned primarily with examining events produced in multinucleon captures of K^- where the momentum transfers in the primary process are large and where it is likely that conditions are unfavorable for making a loosely bound compound.[5] We therefore present here the results of a search for these hyperfragments based on a sample essentially complementary to that of the Milan group, in that a substantial number of our events occur in single-nucleon captures where the momentum transfers are smaller. A preliminary report of this work, based on partial statistics, has been previously discussed.[6]

II. EXPERIMENTAL PROCEDURE

The events selected for measurement were produced by K^- capture in nuclear emulsion. Approximately 200 Λ-hyperfragments, decaying by π^- emission have been observed in this, the EFINS stack, of the EFINS–NU collaboration.[7] About 2×10^4 K^- captures (leading to one or more charged prongs) have been examined in this stack. Details of the exposure, calibration, and scanning are described in reference 7.

In emulsion, possible Σ^- compounds may be found among two types of secondary configurations:

(a) decays in flight into a pion and one or more neutral particles.

(b) captures (e.g., stars with $\geqslant 1$ prong, blob, or Auger electron).

(a) Decays in Flight

Our method of selecting these events was intended to duplicate the conditions of the Milan experiment. Tracks from K^- captures with $\geqslant 2$ grey prongs were traced to their end in the stack. Only those tracks were selected which had (1) dip angle λ with respect to the plane of the emulsion <30° and (2) a path length before decay $\geqslant 1.0$ cm. In all, 15 such events were measured.

Due to the dimensions of our stack, the $\Sigma^\pm$-decay pions could not be traced to their end; hence, the sign of the charge is not known for these events. From the results of the European K^- collaboration[8] one may infer that about half of them should carry a negative charge.

For these events, information bearing on the mass of the particle may be deduced from measurements of ionization vs scattering. The total gap length (of those gaps $>0.2\,\mu$) was measured both for the unknown and for a comparison track of known identity (K^-). From this it is possible to obtain two inferred values of $p\beta$ on the assumption that the particle is a Σ^- or a $(\Sigma^- n)$. From a comparison of these inferred $p\beta$ values with those obtained directly from scattering measurements, one may establish whether the unknown has the mass of a Σ^- or a $(\Sigma^- n)$.

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[1] R. D. Tripp, *1958 Annual International Conference on High-Energy Physics at CERN*, edited by B. Ferretti (CERN Scientific Information Service, Geneva, 1958), p. 184; O. Dahl, N. Horwitz, D. Miller, and J. Murray, Phys. Rev. Letters **4**, 428 (1960).

[2] E. Gandolfi, J. Heughebaert, and E. Quercigh, Nuovo cimento **13**, 864 (1959).

[3] A. Pais and S. Treiman, Phys. Rev. **107**, 1396 (1957).

[4] T. B. Day, G. A. Snow, and J. Sucher, Phys. Rev. Letters **3**, 61 (1959).

[5] In their preliminary report the Milan group did present evidence for a $(\Sigma^- n)$ compound. However, a private communication from G. P. S. Occhialini indicates that this identification is in error and that the event should be removed from further consideration. We are grateful to Professor Occhialini for this information prior to the pending official clarification by Gandolfi *et al.*

[6] O. Skjeggestad, R. Ammar, R. Levi Setti, J. E. Mott, P. E. Schlein, and P. K. Srivastava, Bull. Am. Phys. Soc. **5**, 12 (1960).

[7] R. Ammar, R. Levi Setti, W. E. Slater, S. Limentani, P. E. Schlein, and P. H. Steinberg, Nuovo cimento **15**, 181 (1960).

[8] European K^- Collaboration, Nuovo cimento **13**, 690 (1959).

(b) Captures at Rest

For these events, the mass of the particle which produces the secondary event can be inferred from measurements of ionization vs range on the connecting tracks. The ionization parameter chosen was the integrated gap length of those gaps $>0.2\,\mu$. The tracks selected for measurements were required to have, (1) $\lambda<30°$ and (2) residual range $\geqslant 1.0$ mm. All grey and black prongs from the K^- captures have been traced to their end in the stack yielding a total of 84 such events. In all cases it could be ascertained that the captured particle carried unit charge.

Rather than attempt to assign a mass value to a given event, we checked [as in Sec. II(a)] for consistency with regard to a specific assumption as to its identity. This is accomplished by use of the parameter

$$\eta(x)=\frac{m_x}{m_K}\frac{G_K(Rm_K/m_x)}{G_x(R)}, \qquad (1)$$

where G denotes the total gap length measured over the range denoted by its argument, R the residual range of the unknown while m refers to the mass of the particle. The label x refers to the assumed identity for the unknown and K to a comparison track of known identity (usually a K^- meson or a $\Sigma^+\rightarrow p+\pi^0$ at rest; on the average measurements were made on two such comparison tracks for events with $R<1300\,\mu$ but only on one comparison track for events with $R>1300\,\mu$).

Assuming that, for a particle of unit charge in a given medium, the energy loss per unit length (dE/dR) is a function of velocity only, and that for a given degree of emulsion development the blackening of a track (blob length) is a function of dE/dR only, it follows that, under conditions where discrimination is possible,

$$\begin{aligned}\eta(x)&=1, \quad x=\text{correct identity},\\ &\neq 1, \quad x\neq\text{correct identity},\end{aligned} \qquad (2)$$

TABLE I. Results of measurements on 15 decays in flight $\Sigma^\pm\rightarrow n+\pi^\pm$.

Event	Obtained from multiple scattering	$\langle p\beta\rangle$ (Mev/c) Inferred from ionization, assuming the particle identity to be: Σ	($\Sigma^- n$)
10–501	123±13	129±15	210±25
15–501	80± 8	91± 6	152±12
18–501	95±10	111±10	180±13
20–501	103±11	99± 8	157±20
21–501	82± 8	79± 4	120± 9
22–501	87± 9	103± 8	172±18
26–501	87± 9	93± 4	138±10
29–501	101±10	95± 5	160±10
38–501	124±13	138±12	230±20
40–501	82± 9	78± 4	122± 8
47–501	112±12	102± 8	173±13
48–501	83± 9	98± 7	147±21
49–501	107±11	120±10	194±22
51–501	59± 6	66± 3	95± 8
57–501	102±10	99± 7	165±15

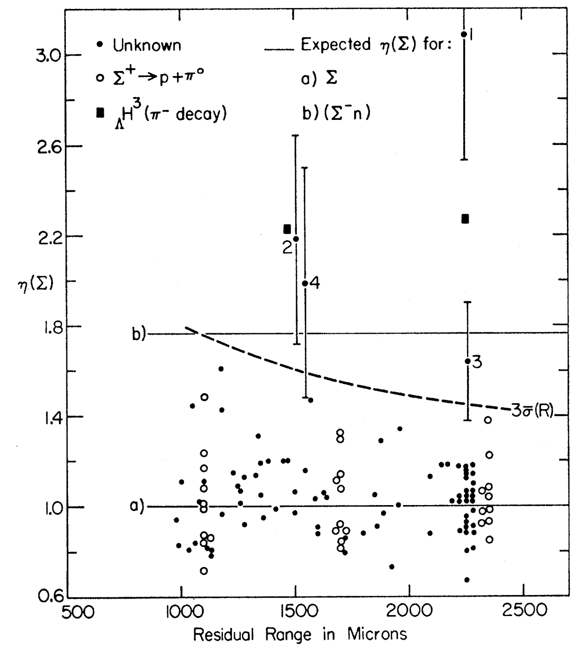

FIG. 1. η as a function of residual range up to which measurements were terminated, on the assumption that the unknown is a Σ. Even when available, no more than 2.3 mm of residual range was used in these measurements. For purposes of calibration several events of known identity have been included and their values of η are also presented on the assumption that they have the mass of the Σ even when this is known not to be the case. The results of measurements on the same calibration tracks have been presented at several residual ranges. $\bar{\sigma}(R)$ is the average standard error of the above events (excluding those numbered 1 through 4 and the two ${}_\Lambda H^3$ calibration tracks) as a function of residual range.

provided the comparison tracks are chosen in the same region of the emulsion and with the same dip angle as the unknown. An empirical check on our method was obtained by applying this procedure to several calibration tracks whose identities are independently known (10 Σ^+ decaying via the proton mode and 2 ${}_\Lambda H^3$ decaying by π^- emission[7]). On the above assumption it also follows that the relative statistical error in $G_x(R)$ and $G_K((m_K/m_x)R)$ is the same if x is the correct identity. Thus a knowledge of the spread as a function of range for, say K^- of a given development, and λ may be used to determine the error in $\eta(x)$. This was verified directly for the known calibration tracks and forms the basis of assigning errors to the "heavy" events described later.

III. RESULTS AND DISCUSSIONS

(a) Decays in Flight

As can be seen from Table I, each of the 15 decays in flight is consistent with the assumption that the particle has the mass of a Σ. None of the events are compatible with the ($\Sigma^- n$) interpretation. From the criteria used in locating these events [Sec. II(a)] it follows that all of them are consistent with having been produced in multinucleon captures of K^-.

TABLE II. Pertinent information on the "heavy" events. See Eqs. (1) and (2) for definition of $\eta(x)$.

Event	Range (R) in microns	Dip angle (λ)	Prongs and range in secondary star	Number of comparison tracks measured	$\eta(\Sigma^-)$	$\eta(\Sigma^- n)$	$\eta({}_\Lambda H^3)$	$\eta({}_\Lambda H^4)$	Possible identification
1	2350	6°	1 (970μ)	4	3.08±0.55	1.83±0.41	1.29±0.33	0.90±0.26	${}_\Lambda H^{3,4}$
2	1510	2°	1 (13 500μ)	4	2.18±0.46	1.27±0.34	0.90±0.30	0.86±0.30	${}_\Lambda H^{3,4}$, ($\Sigma^- n$)
3	5105	24°	2	1	1.60±0.26	0.88±0.19			($\Sigma^- n$), H^2-p elastic scattering
4	1550	26°	4	4	1.99±0.51[a]	0.87±0.27[a]			Σ^-, ($\Sigma^- n$)

[a] Because of large λ, event 4 has a greater percentage error than other events of the same R (see Fig. 1). The error given here was assigned on the basis of the spread of 20 known tracks of comparable dip.

(b) Captures at Rest

The result of the measurement on both calibration and unknown tracks are presented in Fig. 1, on the assumption that the particle has the mass of a Σ. [In each case, other assumptions were made concerning the mass of the unknown in order to ensure that both conditions expressed by Eq. (2) do hold. These results are not included in Fig. 1.] As can be seen, all but about 6 of the events belong to a population indistinguishable from that of the Σ^+ calibration tracks, and can be interpreted as having baryonic mass. Two of the 6 events represent the ${}_\Lambda H^3$ calibration tracks; data pertinent to the remaining four "heavy" events are summarized in Table II.

Those numbered 1 and 2 consist of a secondary configuration involving a single prong and are each kinematically compatible with the nonmesonic decay of ${}_\Lambda H^{3,4}$ involving more than one neutron. The mass determination on event 1 makes an identification as ($\Sigma^- n$) rather unlikely and favors the above interpretation; however, the ($\Sigma^- n$) interpretation cannot be ruled out for event 2. Event 3 appears to have approximately twice baryonic mass and has moreover two charged prongs. Interpretation as a possible ($\Sigma^- n$) is however not unambiguous. The event is in fact kinematically compatible with the nuclear scattering of a slow deuteron (residual range $\sim 30\,\mu$) on a free proton. The final event 4 has four prongs in the secondary interaction and, from the standpoint of the mass measurement, can be interpreted either as a Σ^- or a ($\Sigma^- n$). Although the mass measurement favors the latter, it should be noted that $\eta(\Sigma^-)$ for this event deviates from unity by only 2 standard deviations.

Figure 2 shows the energy distribution of the 80 identified Σ^- events. Of these 71 have energies less than 42 Mev (the upper energy limit attributed to Σ arising from single-nucleon K^- captures[8]). A lower limit on the number of Σ^- produced in single-nucleon processes may be inferred from the fact that 32 of these events were produced in conjunction with charged pions.

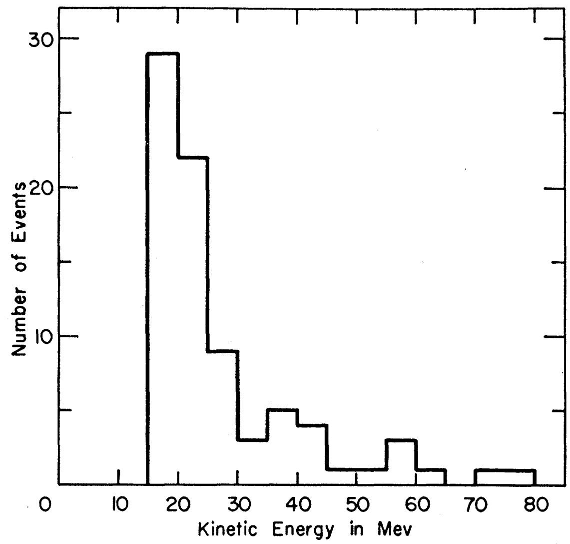

FIG. 2. Energy spectrum of 80 identified Σ^- events of range $>1000\,\mu$ coming to rest in the emulsion.

In conclusion, we note that although there are several events which could be interpreted as ($\Sigma^- n$), in no case is the interpretation unequivocal. If it exists, the frequency of ($\Sigma^- n$) in our sample is $\lesssim 1/30$, the value being relatively insensitive as to whether it is based on the total population or, for example, on a subset consisting of events with $R > 2000\,\mu$ where the ability to discriminate is greatest. Clearly in the matter concerning existence of this compound, far more concrete evidence than that presently existing would be necessary before more stringent conclusions can be drawn.

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