in the experiments to guard against such a possibility [M. B. Stearns (private communication)]. It should also be noted that the Rochester group independently found a similar decrease in π-L x-ray yield, but with a somewhat weaker fall-off at the lower energies [M. Camac, M. L. Halbert, and J. B. Platt, Phys. Rev. 99, 905 (1955)]. One can only conclude that similar experimental conditions must have prevailed.

UPPER LIMIT FOR PRODUCTION OF Σ^-n HYPERFRAGMENTS BY K^- CAPTURE IN DEUTERIUM*

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Recently, Gondolfi et al. reported evidence for the existence of a bound state of the Σ^-n system.[1] Pais and Treiman had already suggested that such a system might be produced when K^- mesons were captured in deuterium.[2] They assumed that the Σ^-n would form a deuteron-like structure bound in either the ^1S or ^3S state and used an impulse-type model to estimate the relative rates for the processes

$$K^- + d \to \Sigma^- n + \pi^+, \qquad (1)$$

$$K^- + d \to \Sigma^- + n + \pi^+, \qquad (2)$$

for both odd and even K-Σ parities. Day and Snow have pointed out that the strong S-wave K^--nucleon interaction will dominate the capture process from either S or P atomic orbitals and have extended the calculations of Pais and Treiman to the latter case.[3] Typical values calculated for the fraction of all Σ^- productions leading to the formation of the bound state are summarized in Table I.

In order to determine the relative rates for reactions (1) and (2), we are examining 2100 $\Sigma^-(n)$ productions obtained during two exposures of the Alvarez 15-in. deuterium chamber to the separated 450-Mev/c K^- beam. Of the $\Sigma^-(n)$ productions, $85 \pm 5\%$ result from K^- absorptions at rest. Thus far we have analyzed in detail 227 events in which the $\Sigma^-(n)$ came to rest and was captured via the reactions[4]

$$\Sigma^-(n) + d \to \Lambda \text{ (or } \Sigma^0) + n + n (+n).$$

For the three cases giving best fits when these events are interpreted as examples of reaction (1), the probabilities for exceeding the observed values of χ^2 were 30%, 10%, and 1%. From this result it is concluded that the fraction of Σ^- productions leading to formation of the bound state is $< 1\%$.

Day, Snow, and Sucher have argued that it is extremely likely that K^- mesons, when stopped in liquid H_2 or D_2, are captured from high-lying S orbitals.[5] If their prediction is correct and if the existence of the Σ^-n is confirmed, the present

Table I. Probability for formation of a Σ^-n with binding energy E_b when a K^- meson is captured in deuterium via the S-wave K-nucleon interaction.

K-Σ parity	Σ^-n bound state	S-orbit capture[a] $E_b = 0.1$ Mev	S-orbit capture[a] $E_b = 0.5$ Mev	P-orbit capture[b] $E_b = 0.1$ Mev	P-orbit capture[b] $E_b = 0.5$ Mev
−	^3S	0.20	0.37	0.03	0.06
−	^1S	forbidden		0	0
+	^3S	0.13	0.25	0.02	0.04
+	^1S	0.07	0.13	0.01	0.02

[a]See reference 2.
[b]See reference 3.

result can be consistent with the calculations of Pais and Treiman only if (a) the binding energy of the $\Sigma^- n$ is exceedingly small ($\lesssim 5$ kev) or (b) the K^--Σ parity is odd so that reaction (1) is forbidden by conservation of angular momentum and parity.

In the absence of any special mechanism, the usual de-excitation processes for the K^--d atom (collisional Auger effect and radiation) will lead to population of the $2P$ atomic orbital from which a large fraction of K^-'s will undergo direct nuclear capture. Since the hyperfragment rates are suppressed by a factor ~10 (see Table I), no strong conclusion could then be drawn from the present experiment.

The following considerations lead us to believe that the $\Sigma^-(n)$ capture events are more favorable than decay events for correct identification of hyperfragments:

(a) Ross has examined the interactions of Σ^- hyperons produced by absorption of stopped K^- mesons in hydrogen.[6] He finds that more than 95% of the Σ^- captures occur at rest. Therefore, it may be assumed that the present analysis is effectively limited to events in which the $\Sigma^-(n)$ does not interact (or decay) before traveling its full range. If reaction (1) is produced by a stopped K^-, the $\Sigma^- n$ will be collinear with the π^+ and have a range of 2.43 ± 0.05 mm. Since the diameter of such a heavily ionizing stub is ~0.3 mm, the usefulness of the collinearity requirement would decrease rapidly if the shorter path lengths of the decay events were included in the analysis.

(b) The distribution in the Σ^--π^+ included angle for reaction (2) peaks at 180°, and many events in which the Σ^- decays within 2.5 mm of the production vertex would be indistinguishable from those of (1). Therefore, the present requirement of unique range provides a strong additional criterion for correct identification.

(c) No corrections are necessary for (i) events in which the $\Sigma^-(n)$ range is poorly determined because of emission of a decay pion at a small angle or (ii) collinear Σ^-'s produced by a K^- absorption in the hydrogen contamination of the bubble chamber.

The film coordinates of all tracks associated with the Σ^--capture events were punched onto IBM cards with the LRL measuring projector and the tracks were spatially reconstructed by means of suitable IBM programs. The distribution in range and included angle for the reconstructed events (with included angle greater than 140 deg and Σ^- range between 1 and 6 mm) is shown in Fig. 1. There is no evidence for increased concentration of events in the region expected for hyperfragments. As a check on the machine measurements, all events were re-examined on the scanning projector and obviously noncollinear events rejected. For the remainder, the $\Sigma^-(n)$ was assumed to be collinear with the π^+ so that the measured values of the π^+ dip and azimuthal angles (determined to ± 0.5 deg) could be used to calculate the lengths expected on the film for a range of 2.43 mm. Comparison of calculated lengths with direct measurements on the film gave results consistent with the χ^2 estimates deduced from the machine measurements.

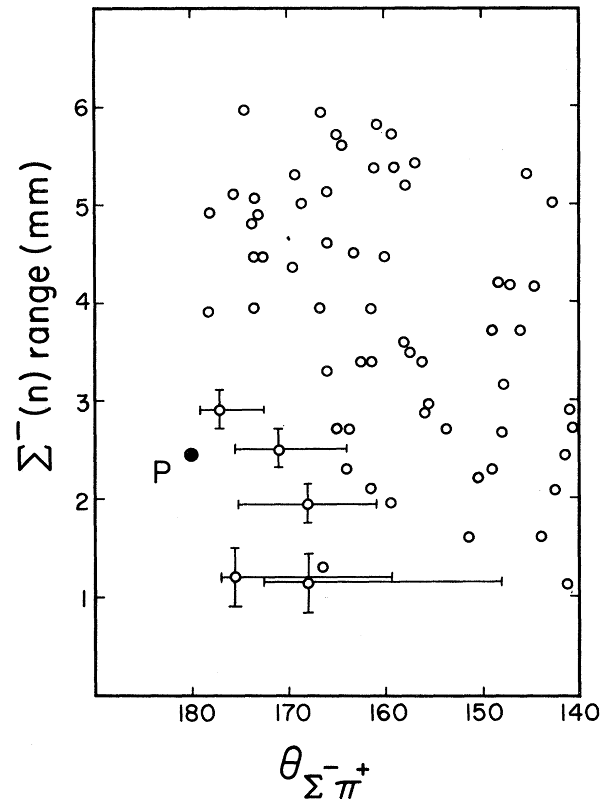

FIG. 1. Measured range vs $\Sigma^-(n)$ - π^+ included angle for reactions (1) and (2). The angle and range required for a $\Sigma^- n$ hyperfragment are designated by P. Typical measurement errors are indicated for the six closest events.

The significance of the present measurement depends upon the probability P_c that a $\Sigma^- n$ will come to rest and be captured. This quantity may be written

$$P_c = \exp[-\Gamma_b(T_1 + T_2 + T_c^{\,D})], \qquad (3)$$

where Γ_b is the decay rate for the bound Σ^-, T_1 is the proper time from production to the time the $\Sigma^- n$ has slowed down to a velocity $v/c = 0.05$ (the approximate lower limit for the validity of the usual range-momentum relation), T_2 is the time from $v/c = 0.05$ to initial capture by a D_2 molecule, and T_c^D is the time from molecular capture to nuclear absorption.

Snow has shown that if charge independence is valid, the $\Sigma^- n$ will probably be bound by less than 0.5 Mev.[7] Dalitz and Liu have argued that for such loosely bound systems, the major modifications in decay rates should arise from the change in phase space available and from the operation of the Pauli principle in the final state.[8] Using Eq. (3.3) given in their paper, we have estimated the magnitude of these effects. Since the S- and P-channel decay amplitudes for the free Σ^- are not known, results for Γ_b are given in Table II for the extreme cases.

Integration of the range-momentum relation yields $T_1 = 0.99 \times 10^{-10}$ sec. Wightman has estimated T_2 for particles of various masses;[9] a slight extrapolation of his results gives $T_2 = 0.19 \times 10^{-10}$ sec. Because of the complexity of the deexcitation process, no reliable estimate is available for T_c; however, some orientation may be gained by consideration of a related process. An equation analogous to Eq. (3) may be used to calculate the capture rate for Σ^- hyperons produced by K^- absorption in hydrogen. The observed capture rate is obtained with $T_c^H = (0.10 \pm 0.25) \times 10^{-10}$ sec.[10] To relate this result to the present situation, we make the rough assumption that the mass dependence is not worse than that characteristic of energy loss to electrons by collision,[11] i.e.,

$$T_c^D \simeq (\mu_D/\mu_H) T_c^H \simeq (0.2 \pm 0.5) \times 10^{-10} \text{ sec},$$

where μ_D (μ_H) is the reduced mass of the $\Sigma^- n$-d (Σ^--p) systems.

Under the above assumption, Eq. (3) gives $P_c = 0.32_{-0.11}^{+0.17}$ for the most unfavorable case (K^--Σ parity even, $\Sigma^- n$ bound in the ^1S state). Using this value, we estimate that if the fraction of Σ^- productions leading to the bound state were 1%, 6_{-2}^{+3} $\Sigma^- n$ capture events should have been observed. Since the entire distribution of events is completely consistent with all Σ^-'s being produced via reaction (2), and since, at most, one event can reasonably be interpreted as a hyperfragment production, it is probable that the branching ratio for reaction (1) is substantially less than 1%.

Table II. Decay rate of $\Sigma^- n$ relative to the free Σ^-. The $\Sigma^- n$ was assumed to be bound by 0.5 Mev.

Amplitude for Σ^- decay into S and P channels	Bound state of $\Sigma^- n$ ^1S	^3S
$S \neq 0$; $P = 0$	1.28	0.94
$S = 0$; $P \neq 0$	0.94	1.04

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[10]For the free Σ^- decay rate we used $\Gamma_b = (0.642 \pm 0.039) \times 10^{10}$/sec, the weighted average of the values measured in associated production experiments. These values were reported by Luis W. Alvarez at the Ninth Annual International Conference on High-Energy Physics, Kiev, 1959 (unpublished). The preliminary value, 0.099 ± 0.007, for the Σ^- capture rate was kindly supplied by Dr. Rosenfeld, Dr. Solmitz, and Dr. Tripp of our group.

[11]This is the mass dependence determined by Wightman for T_2 (reference 9). E. Fermi and E. Teller, Phys. Rev. 72, 406 (1947) obtain a similar mass-dependence for particles losing energy by electronic collisions after capture into high-lying atomic orbitals in solids.