Formation of $A = 12$ Σ^- Hypernucleus from K^- Absorption at Rest; Observation of a Σ^- Spin-Orbit Doublet of Narrow Widths

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High-resolution spectroscopy of π^+ from K^- absorption at rest has been used for the first time to identify Σ^- hypernuclear states. The observed spectrum from a $(\mathrm{CH})_n$ target has revealed a $p_{3/2}$-$p_{1/2}$ doublet of $^{12}_{\Sigma^-}\mathrm{Be}$ with narrow widths. The spin-orbit splitting of Σ^- is deduced to be 5 MeV, 0.8 times that for nucleons.

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In this Letter we report on the first experimental attempt to form Σ hypernuclei from K^- absorption at rest. The basic principle, motivation, and aims underlying this experiment are described in a separate paper.[1] The stopped K^- method is characterized by (i) efficient production of hyperons after nearly 100% absorption of K^- by nucleons in the surface region, (ii) large formation probability of Σ hypernuclei, and (iii) population of nonsubstitutional states, such as ground and low-lying states and both members of a spin-orbit doublet, while in the recoilless method only the substitutional states are enhanced. A theoretical treatment of the formation probabilities for Λ hypernuclei was given by Hüfner, Lee, and Weidenmuller.[2] An extensive calculation of the formation probabilities of various hypernuclear states was completed recently by Yazaki and Matsuyama,[3] and some of the characteristic features have been discussed in Ref. 1.

The experiment was performed with the existing heavy-neutrino-search experimental setup.[4] Since a plastic scintillator was used as an active target, the target nuclei available were only $^{12}\mathrm{C}$ and protons. A similar experiment was done at CERN by Faessler *et al.*[5] They used a magnetic spectrometer with a momentum range of 200–280 MeV/c for π^-, and succeeded in observing both $(p_{3/2})_n^{-1}(p_{3/2})_\Lambda$ and $(p_{3/2})_n^{-1}(s_{1/2})_\Lambda$ states. Since we measured π^+ and π^- in a wider momentum range of 120–280 MeV/c, we have obtained information on Σ hypernuclei. We are thus in a position to study a most important current problem, namely, how large is the spin-orbit interaction of Σ in contrast to the small spin-orbit splitting of Λ,[6] and why do the Σ hypernuclear states exist with narrow widths?[7]

The experimental setup and procedure were nearly the same as those used for the $K_{\mu 2}$ experiment.[4] The 550-MeV/c K^-'s from the KEK K3 beam line were stopped in multilayered plastic scintillators. The K^- stopping rate was about 5000 per spill (1 spill period $= 2.4$ sec). The K^- stopping layer was identified from the energies deposited in these scintillator layers. The charged particles were momentum analyzed by a magnetic spectrometer, which possessed a broad-range focal plane (100–260 MeV/c) and a large solid angle ($\simeq 100$ msr). The target was almost completely covered by 200 pieces of $6.5 \times 6.5 \times 30$ cm^3 NaI(Tl) crystals. For the present purpose these counters served as a π^0 spectrometer.

The measured momentum spectra of π^+ after the correction for the momentum dependence of the spectrometer acceptance are shown in Fig. 1. These data were taken for 80 h, corresponding to K^- stopping events of 1.1×10^8. This is substantially shorter than the typical beam time for an in-flight reaction experiment. The branching ratios of π^+ were estimated by comparison of these spectra with the 205-MeV/c π^+ peak in the decay of K^+. The pion momentum is uniquely related to the hypernuclear mass, $M_{\mathrm{hy}} - M_A$,

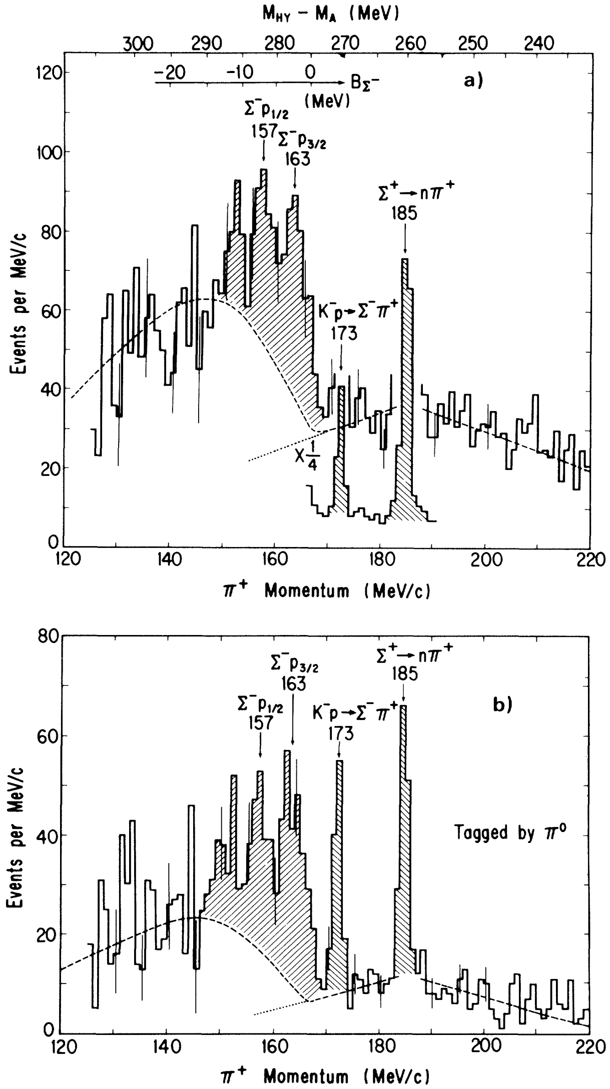

FIG. 1. Observed π^+ spectra from K^- stopped in a plastic scintillator $(CH)_n$ after acceptance correction for each momentum. Typical statistical errors are indicated. (a) All π^+. (b) π^+ tagged by π^0-like events. The dashed curves show quasifree background together with in-flight decay of Σ^+.

which is scaled in the upper part of the figure.

In the π^+ spectrum of Fig. 1(a) we first notice the largest peak at $p_\pi = 185$ MeV/c (1.2% per stopped K^-). This is the monochromatic peak from the decay of stopped Σ^+ to $n + \pi^+$. This peak can be mostly ascribed to a Σ^+ which escaped the carbon nucleus. This is consistent with the known escape probability of 40%.[8] This peak can be used for the calibration of the instrumental resolution. The full width at half maximum momentum resolution as seen from this peak is 1.6 MeV/c, which corresponds to a full width at half maximum resolution $\Delta E = 1.3$ MeV in the hypernuclear energy level. The next distinct peak is seen at $p_\pi = 173$ MeV/c (0.6% per stopped K^-). This is due to the elementary process $K^- p \rightarrow \Sigma^- \pi^+$ on hydrogen atoms.

Now we consider the broader peak at 164.0 ± 0.3 MeV/c. This peak corresponds to $M_{\mathrm{hy}} - M_A = 277.2 \pm 0.3$ MeV and agrees well with the substitutional level of $(p_{3/2})_p^{-1}(p_{3/2})_{\Sigma^-}$, which has been observed in a recent CERN experiment by Bertini *et al.*[9] in the (K^-, π^+) reaction on ^{12}C.[9] The binding energy for Σ^- is -2.1 ± 0.3 MeV. Its intensity is around 0.8% of the stopped K^- total. The calculation of Yamazaki *et al.*[1,3] predicts the total $0p$ population to be 5% of the total $\Sigma^- \pi^+$ production and thus 1% of all stopped K^-. This is expected to be split into the two spin-orbit doublet states with intensities 0.7% for $(p_{3/2})_p^{-1}(p_{3/2})_{\Sigma^-}$ and 0.3% for $(p_{3/2})_p^{-1}(p_{1/2})_{\Sigma^-}$ per stopped K^-. Therefore, the observed intensity is in good agreement with the prediction. The calculated shape of a the quasifree continuum is shown by a dashed curve. The absolute scale of this curve is adjusted so as to explain the continuum part below 150 MeV/c. The hatched areas correspond to discrete hypernuclear peaks above the quasifree continuum.

An extremely interesting question arises as to where the $\Sigma^- p_{1/2}$ level is located. In Fig. 1(a) there is an additional peak at 158.0 ± 0.6 MeV/c, which corresponds to $M_{\mathrm{hy}} - M_A = 281.8 \pm 0.5$ MeV, 5 MeV above the $\Sigma^- p_{3/2}$ level. This peak stands out very clearly above the quasifree continuum. Its intensity is estimated to be about 40% as much as that of the 277-MeV peak.

Figure 1(b) shows a π^+ spectrum tagged by a π^0-like signal in the photon counters. Among the various sources of π^0 emission the only possible process in coincidence with the present π^+-triggered events is the free decay of Λ into $n\pi^0$ (36%). When a Σ decays in the nucleus via $\Sigma N \rightarrow \Lambda N$ conversion, a Λ is produced and then a π^0 is emitted. Thus, the π^+ spectrum tagged by π^0 is expected to enhance the Σ^- states that do not escape the nucleus. Actually, the spectrum of Fig. 1(b) reveals the hypernuclear peaks at 158 and 164 MeV/c more distinctly, while the continuous background is substantially suppressed because it arises from the quasifree production of Σ^- and the in-flight decay of Σ^+.

In the present case of K^- absorption at rest each particle-hole configuration (j_p^{-1}, j_Σ) appears as a multiplet of states $(I = |j_p - j_\Sigma|, \ldots, j_p + j_\Sigma)$, which are split in energy and are also mixed with other configurations by the residual ΣN interaction. On the other hand, the recoilless method populates dominantly the $I = 0$ component of the substitutional configuration. The structure of p-shell hypernuclei with configuration interactions has been studied theoretically by Auerbach *et al.*[10] and by Majling *et al.*[11] In these realistic calculations the experimental data on particle pickup reactions have been taken into account. In general, the hypernuclear states are expressed as linear combinations of various configurations $(I_c \otimes j_\Sigma)I$, where I_c is one of the core states. In the case of $^{12}\mathrm{C} \rightarrow {}^{11}\mathrm{B}+p$, most of the pickup strength goes to the ground state $(\frac{3}{2}^-)_1$, while the 2.1-MeV $\frac{1}{2}^-$ state and the 5.0-MeV $(\frac{3}{2}^-)_2$ state take 20% and 10% of the total strength, respectively. Then, for $I=2^+$ we expect two major peaks separated by the spin-orbit splitting energy of Σ^-. The lower peak has a main configuration of $I_c=(\frac{3}{2}^-)_1, j_\Sigma=p_{3/2}$, while the upper peak involves two mixed configurations, $I_c=(\frac{3}{2}^-)_1, j_\Sigma=p_{1/2}$ and $I_c=(\frac{3}{2}^-)_2, j_\Sigma=p_{3/2}$.

The theoretical result of Majling *et al.*[11] indicates that the energy of the upper peak with respect to the lower remains nearly equal to the spin-orbit splitting energy ϵ_Σ, though the wave functions of the upper states include substantial mixing of the core excited state. The configuration-mixing theory can also account for another small peak, 4 MeV above the second peak; its main configuration is $I_c=(\frac{3}{2}^-)_2, j_\Sigma=p_{1/2}$. In this way we understand the whole structure revealed in the present experimental study. In spite of the importance of configuration mixing, however, we can continue to use the "single-particle" and "weak-coupling" terminology to a large extent. We have deduced the single-particle energies for Σ^-, as shown in Fig. 2.

Let us discuss some important features obtained in the present experiment.

(i) *ΣN residual interaction.*—The K^- absorption at rest populates both $I=0^+$ and 2^+ members of the $(p_{1/2},p_{3/2})$ configuration equally well, while the recoilless method enhances only the $I=0^+$ member. The energy of the present peak (277.2 MeV) appears to be only slightly lower than the energy reported by Bertini *et al.*[9] (278 MeV). This means that the ΣN residual interaction is very small. This fact supports the assignment of the 282-MeV level to the spin-orbit partner; an extreme opposite case of a small spin-orbit splitting and a large residual interaction cannot be reconciled at all.

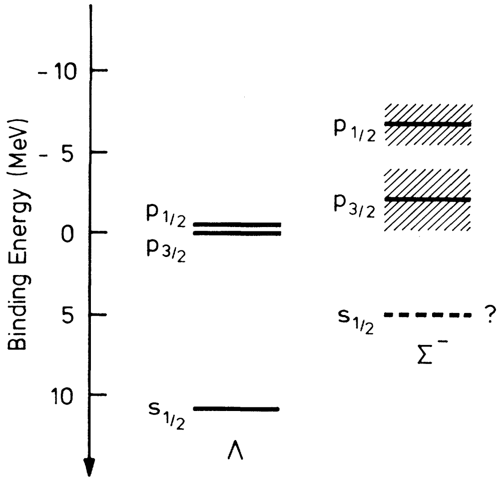

FIG. 2. Level structure of the $A=12$ hypernuclei revealed from the present study (for Σ^-) as well as from the earlier work (Ref. 3) (for Λ). The widths are shown by the hatching.

(ii) *The $p_{3/2}$-$p_{1/2}$ spin-orbit splitting of Σ^-.*—The present experiment yields unambiguously $\epsilon_\Sigma=5.0 \pm 0.5$ MeV. The corresponding nucleon value in $^{16}\mathrm{O}$ is $\epsilon_N = 6.4$ MeV. Then, we obtain a ratio $R = \epsilon_\Sigma/\epsilon_N = 0.8 \pm 0.1$. Since both the $p_{3/2}$ and $p_{1/2}$ orbitals of Σ^- lie above the threshold, it is not straightforward to deduce the spin-orbit term in the one-body potential. This remains an open theoretical problem. While the smallness of the spin-orbit splitting of Λ[6] is understood in most theories, the spin-orbit splitting of Σ plays a crucial role in the discriminating of different theories related to the origin of the spin-orbit interaction.[12-16] The present result can be compared with various theoretical predictions. Roughly speaking, the present result ($R=0.8$) is in favor of the quark-cluster model of Morimatsu *et al.*[13] ($R=0.7$), but is far from the predictions of the additive-quark model of Pirner[12] ($R=1.3$), of the one-boson-exchange model of Dover and Gal[14] ($R=0.3$–0.4), and of the meson-mean-field theory of Bouyssy[15] ($R=0.5$) and of Brockmann and Weise[16] ($R=0.5$).

(iii) *Widths of the $p_{3/2}$ and $p_{1/2}$ levels.*—The observed width of the $p_{3/2}$ level is around 4 MeV, which is in good agreement with the Bertini *et al.* result,[9] while the $p_{1/2}$ level seems to be narrower. In view of the doublet structure of the $p_{3/2}$ peak ($I=0^+$ and 2^+) the width of the individual $p_{3/2}$ level may also be narrower. The width for an unbound Σ hypernuclear state arises not only from the $\Sigma N \rightarrow \Lambda N$ conversion process but also from the escaping and spreading widths. The former process ends up in the emission of Λ and subsequently of π^0, while the latter does not. Therefore, a spectrum tagged by π^0 will reflect the conversion-to-escape ratio. In the spectrum of Fig. 1(b) the 158- and 164-MeV/c peaks appear to be enhanced more or less equally. This may imply that both states decay predominantly via the conversion process. It is surprising that the $p_{1/2}$ level, which lies 7 MeV above the threshold, has still a narrow width.

(iv) *$0s_{1/2}$ orbital.*—The narrow conversion width is currently explained in different ways.[17-20] Here, the most crucial test to discriminate among them is to look for the $0s_{1/2}$ state. If the narrow width of the substitutional states is due to a particular type of spin-isospin selection or to a small overlap with nucleons,[18] the deep-lying $0s_{1/2}$ state should be broader. On the other hand, if it is due to some Pauli exclusion effect in nuclei[19] or the suppression of nuclear spin-isospin excitations,[20] a narrow width is expected also for the $0s_{1/2}$ state. For this purpose the stopped K^- method is ideal, because the ground state is expected to be populated about $\frac{1}{3}$ as much as that of the $p_{3/2}$ state. Unfortunately, in the present parasite experiment this interesting region was disturbed by the 173-MeV/c hydrogen peak. In the present data there is no structure around the single sharp peak at 173 MeV/c. This means that the Σ^- 0s level is either too narrow ($\Gamma \leq 2$ MeV) sitting on the 173-MeV/c peak ($B_{\Sigma^-} = +4.9 \pm 0.3$ MeV) or too broad ($\Gamma \geq 8$ MeV) to be observed as a visible bump. This is all that we can say from the present data, but a planned experiment with a pure-carbon target will provide a clear-cut test.

In conclusion, we have demonstrated for the first time that stopped-K^-, π^+ spectroscopy is a powerful method for the production of Σ^- hypernuclei and found that the spin-orbit interaction of Σ^- is slightly smaller than that for nucleons. An extended experimental program is under way at KEK.

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