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Formation of $^4_\Lambda$H hypernuclei from K^- absorption at rest on light nuclei

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Formation of $^4_\Lambda$H hypernuclei from K^- absorption at rest on light nuclear targets was studied by measuring monochromatic π^-'s from the two-body decay, $^4_\Lambda\text{H} \rightarrow {}^4\text{He} + \pi^-$. The formation probabilities of $^4_\Lambda$H from ^{4}He, ^{7}Li, ^{9}Be, ^{12}C, and ^{16}O targets were extracted to be $(0.74 \pm 0.10) \times 10^{-2}$, $(3.0 \pm 0.4) \times 10^{-2}$, $(1.57 \pm 0.18) \times 10^{-2}$, $(1.00 \pm 0.14) \times 10^{-2}$, and $(0.47 \pm 0.08) \times 10^{-2}$ per stopped K^-, respectively. Possible mechanisms for the production of $^4_\Lambda$H are discussed.

Various Λ hypernuclei are produced as hyperfragments from K^- absorption at rest, as was known since the 1960s from emulsion experiments.[1] In those experiments, Λ hypernuclei were identified through the weak decay, and the binding energies of Λ were determined. However, the formation mechanism of hyperfragments was rarely studied, partly because the unique identification of the target nucleus responsible for each fragment was impossible in the emulsion experiments.

Since the 1970s Λ and Σ hypernuclei have been studied by use of direct reactions, such as (K^-,π) (Ref. 2) and (π,K^+) (Ref. 3) reactions. Recently, we performed a series of experiments to measure (K^-,π^-) spectra from K^- absorption at rest on several light nuclear targets. The measured pion momentum range is wide enough (110–300 MeV/c) to cover the regions both for direct Σ-hypernuclear formation (160–190 MeV/c) and for direct Λ-hypernuclear formation (250–280 MeV/c). Moreover, π^- from mesonic decays of Λ hypernuclei, of which the momentum is around 100 MeV/c, can be partly measured in our experiments. In fact, the obtained π^- spectra exhibited a monochromatic peak at 133 MeV/c, which is a unique signature for the two-body mesonic decay of $^4_\Lambda$H: $^4_\Lambda\text{H} \rightarrow {}^4\text{He} + \pi^-$. The measured peak intensity yields the formation probability of $^4_\Lambda$H per stopped K^- for each of the target nuclei. In this Rapid Communication, we present formation probabilities of $^4_\Lambda$H from ^{4}He, ^{7}Li, ^{9}Be, ^{12}C, ^{16}O, and ^{40}Ca targets and discuss the mechanism of $^4_\Lambda$H formation. An excerpt of the preliminary results was already reported in Ref. 4.

The experiment was performed at the National Laboratory for High Energy Physics (KEK) 12-GeV Proton Synchrotron. The experimental setup is similar to the previous one.[5] A detailed description of the setup is found in Refs. 4 and 6. Negative kaons (650 MeV/c) from the $K3$ beam line were degraded and stopped in the target, and the momenta of emitted pions were measured with a magnetic spectrometer. The characteristic features of this spectrometer are (i) a large acceptance ($\sim$100 msr), (ii) a high momentum resolution of 1.4-MeV/c full width at half maximum (FWHM) (effect of energy loss in the target is not included), and (iii) a wide momentum range from 110 to 300 MeV/c. After the correction of the π^- momentum for energy loss in the target, the momentum resolution was 1.9–3.3 MeV/c FWHM (depending on the target material) at 205 MeV/c. A plastic scintillator $[(\text{CH})_n]$ was used for the ^{12}C target, and water was used for the ^{16}O target.

Figure 1 shows the measured (stopped K^-,π^-) spectrum on the ^{12}C target. The gross structure of the spectrum is well accounted for by productions and decays of hyperons.[4,6] Two peaks observed at 261 and 273 MeV/c are assigned to the $(p\frac{3}{2})_n^{-1}(p)_\Lambda$ and $(p\frac{3}{2})_n^{-1}(s)_\Lambda$ states of $^{12}_\Lambda$C, respectively, which are formed directly in the (K^-,π^-) reaction.

We observed another peak at 132.6 ± 0.3 MeV/c with strength larger than the two $^{12}_\Lambda$C peaks mentioned above. Since the π^- from the free Λ decay at rest has a momentum of 100 MeV/c, it is likely that the peak stems from a two-body π^--mesonic decay of a Λ hypernucleus. We calculated π^- momenta of the two-body π^--mesonic decays of various Λ hypernuclei (hyperfragments) which may be produced from stopped K^- on ^{12}C, using the binding energies of the hypernuclei as measured in emulsion experiments.[7] The position of the observed peak agrees well with the value expected from the two-body π^--mesonic decay of $^4_\Lambda$H, 132.9 MeV/c. This momentum is the highest among the momenta of two-body π^--

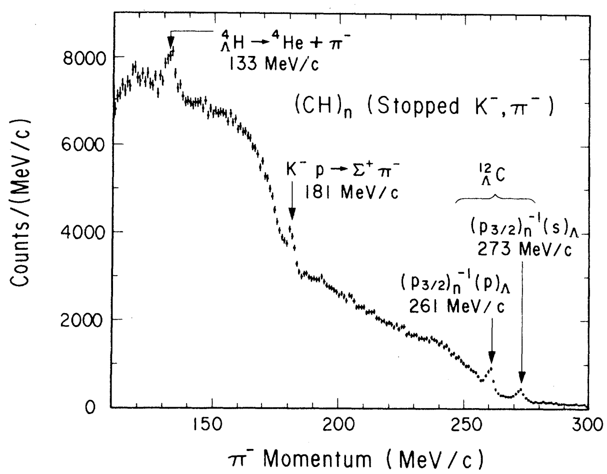

FIG. 1. (Stopped K^-,π^-) spectrum on the ^{12}C target. Momentum dependence of the acceptance is corrected.

mesonic decays of hyperfragments identified in the emulsion experiments, because of the high Q value reflecting the large binding energy of ^4He. No other hypernucleus is known that produces such a π^- decay peak near this momentum. Therefore, the observed peak is assigned to the π^- from the two-body mesonic decay of $^4_\Lambda H$,

$$^4_\Lambda H \rightarrow {}^4He + \pi^- .$$

Figure 2 shows the relevant momentum region of all measured (stopped K^-,π^-) spectra on ^4He, ^7Li, ^9Be, ^{12}C, ^{16}O, and ^{40}Ca targets. The peak at 133 MeV/c from the two-body π^--mesonic decay of $^4_\Lambda H$ is observed in the spectra on the ^4He, ^7Li, ^9Be, ^{12}C, and ^{16}O targets. The peak positions in these spectra agree well with the value of 132.9 MeV/c. No peak is seen in the case of the ^{40}Ca target. In the case of the ^4He target, $^4_\Lambda H$ is produced through the direct reaction $^4He(K^-,\pi^0)^4_\Lambda H$, while in the other targets $^4_\Lambda H$ is produced indirectly, to be called a hyperfragment.

Our observation of the $^4_\Lambda H$ hyperfragment itself is not surprising. In fact, $^4_\Lambda H$ is one of the most copiously produced hyperfragments from K^- absorption at rest in emulsion.[8] Even γ rays from the 1.1-MeV excited state of $^4_\Lambda H$ were observed in K^- absorption on ^7Li nuclei, and the formation probability of this excited state was derived.[9,10] However, the formation probability of $^4_\Lambda H$(g.s.) for each target nucleus was not available from these experiments. Our experiments can provide the formation probability of $^4_\Lambda H$ for individual target nucleus, including the ^4He target where $^4_\Lambda H$ is directly produced.

The formation probability of $^4_\Lambda H$ is the peak intensity per stopped K^- divided by the branching ratio of $^4_\Lambda H \rightarrow {}^4He+\pi^-$ decay. In order to obtain the peak intensity per stopped K^-, we estimated the total number of stopped K^- and the detection and analysis efficiencies for each target. The number of stopped K^- was directly measurable only in the active ^{12}C target, where we could use information from multilayered target counters. We also measured the number of stopped K^+ from the $K^+ \rightarrow \pi^+\pi^0$ peak and obtained a ratio between the number of stopped K^+ per K^+ beam and that of stopped K^- per K^- beam. We applied this ratio to the other targets after minor correction for target dependence of K^- reaction loss, and the number of stopped K^- was estimated from the number of stopped K^+ in calibration runs on those targets.

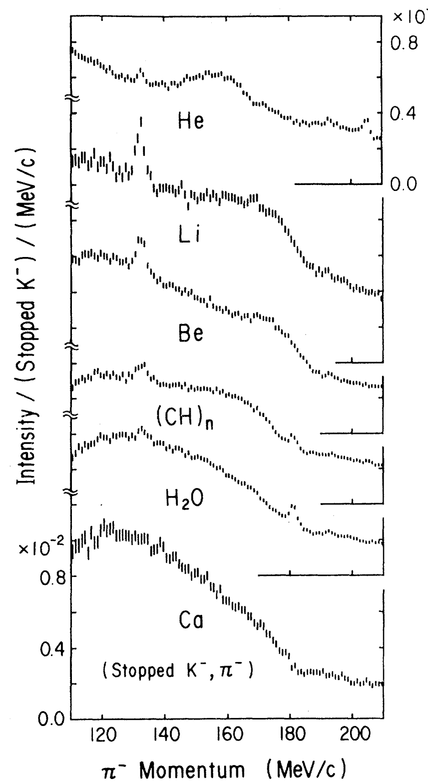

FIG. 2. Low momentum regions of (stopped K^-,π^-) spectra on ^4He, ^7Li, ^9Be, ^{12}C, ^{16}O, and ^{40}Ca targets. The vertical scale of all the spectra is intensity per stopped K^-. Momentum dependence of the acceptance is corrected.

The branching ratio $BR(^4He+\pi^-)$ was derived as

$$BR(^4He+\pi^-) = \frac{\Gamma(^4He+\pi^-)}{\Gamma(NM)+\Gamma(\pi^-)+\Gamma(\pi^0)} \approx 0.49 ,$$

using the following relations for the $^4He+\pi^-$ decay rate $[\Gamma(^4He+\pi^-)]$ and the nonmesonic, π^--mesonic, and π^0-mesonic decay rates of $^4_\Lambda H$ [$\Gamma(NM)$, $\Gamma(\pi^-)$, and $\Gamma(\pi^0)$, respectively]: $\Gamma(NM)/\Gamma(\pi^-)=0.26\pm0.13$ (Block *et al.*[11]), $\Gamma(\pi^0)/\Gamma(\pi^-)\approx 0.16$ (calculated by Dalitz and Liu[12]), and $\Gamma(^4He+\pi^-)/\Gamma(\pi^-)=0.69\pm0.02$ (Bertrand *et al.*[13]).

It is known that a non-negligible part of $^4_\Lambda H$ produced from stopped K^- in emulsion decays in flight, which results in a tail component added to the π^- peak of the two-body mesonic decay. The momentum distribution of $^4_\Lambda H$ from light target nuclei (C, N, and O) was measured in an emulsion experiment.[14] Assuming that this measured momentum distribution can be applied to all of the target nuclei, we made a Monte Carlo simulation to calculate the π^- peak shape with the tail component, which was then employed in the peak fitting of the data. For the

^{4}He target, a discrete momentum of 256 MeV/c for the direct reaction was used.

Table I lists the formation probabilities of $^{4}_{\Lambda}$H, giving values both with and without the in-flight decay correction mentioned above. The errors include an ambiguity in the total number of stopped K^-. Only an upper limit for the $^{4}_{\Lambda}$H formation probability is given for the ^{40}Ca target. It should be mentioned that hyperons emitted out of the nucleus can react with another nucleus in the target. The probability of such secondary hyperon absorption was estimated to be less than 5% per stopped K^-, stemming mainly from Σ^- absorption at rest and Λ reaction in flight. So, the contribution of the secondary hyperon absorption to the $^{4}_{\Lambda}$H formation probabilities might be small. Our formation probabilities per stopped K^-, $(10.0\pm1.4)\times10^{-3}$ for ^{12}C and $(4.7\pm0.8)\times10^{-3}$ for ^{16}O, are consistent with $^{4}_{\Lambda}$H formation probability on light emulsion nuclei (C, N, and O), 7.3×10^{-3}.[15] Our $^{4}_{\Lambda}$H formation probability includes the probability of the 1.1-MeV excited state of $^{4}_{\Lambda}$H. In fact, our probability on ^{7}Li, $(3.0\pm0.4)\times10^{-2}$, is larger than the reported probability of the excited state on ^{7}Li, $(0.37\pm0.04)\times10^{-2}$ (Ref. 9) and $(0.7\pm0.2)\times10^{-2}$.[10]

The formation probability of the $^{4}_{\Lambda}$H hyperfragment (for the $A>4$ target) reveals a clear dependence on the target mass number, as shown in Fig. 3. It is also remarkable that the formation probability of $^{4}_{\Lambda}$H per stopped K^- on ^{12}C is much larger than those of discrete states of $^{12}_{\Lambda}$C formed via the direct (K^-,π^-) reaction. From the ^{12}C spectrum (Fig. 1), the formation probabilities of $^{12}_{\Lambda}$C for the $(p\frac{3}{2})_n^{-1}(p)_\Lambda$ and $(p\frac{3}{2})_n^{-1}(s)_\Lambda$ states were derived to be $(2.3\pm0.3)\times10^{-3}$ and $(0.98\pm0.12)\times10^{-3}$ per stopped K^- (errors not including ambiguity from the background shape), respectively, while the formation probability of $^{4}_{\Lambda}$H is $(10.0\pm1.4)\times10^{-3}$, being more than four times as large as the direct formation probabilities of these $^{12}_{\Lambda}$C states.

In the following, we will discuss the formation mechanism of $^{4}_{\Lambda}$H from K^- absorption at rest. As shown in Fig. 2, the formation probabilities of the $^{4}_{\Lambda}$H hyperfragment on the $A=7$–16 nuclei are of the same order of the direct formation probability of $^{4}_{\Lambda}$H on the ^{4}He target. Thus, it may be reasonable to consider a model for the $^{4}_{\Lambda}$H hyperfragment formation via a direct (K^-,π^0) reaction on an α-cluster in a nucleus, K^-+"^{4}He"$\rightarrow {}^{4}_{\Lambda}\mathrm{H}+\pi^0$. This reaction is expected for some of the light nuclei such as ^{9}Be,

TABLE I. $^{4}_{\Lambda}$H formation probability per stopped K^- on various target nuclei. It shows numbers with and without the correction for the in-flight decay of $^{4}_{\Lambda}$H. The branching ratio of $^{4}_{\Lambda}\mathrm{H}\rightarrow{}^4\mathrm{He}+\pi^-$ decay is assumed to be 0.49.

	$^{4}_{\Lambda}$H probability per stopped K^-	
Target	(Without correction)	(With correction)
^{4}He	$(2.9\pm0.4)\times10^{-3}$	$(7.4\pm1.0)\times10^{-3}$
^{7}Li	$(24\pm3)\times10^{-3}$	$(30\pm4)\times10^{-3}$
^{9}Be	$(14.4\pm1.6)\times10^{-3}$	$(15.7\pm1.8)\times10^{-3}$
^{12}C	$(9.0\pm1.2)\times10^{-3}$	$(10.0\pm1.4)\times10^{-3}$
^{16}O	$(4.2\pm0.7)\times10^{-3}$	$(4.7\pm0.8)\times10^{-3}$
^{40}Ca	$<2.4\times10^{-3}$	$<2.7\times10^{-3}$

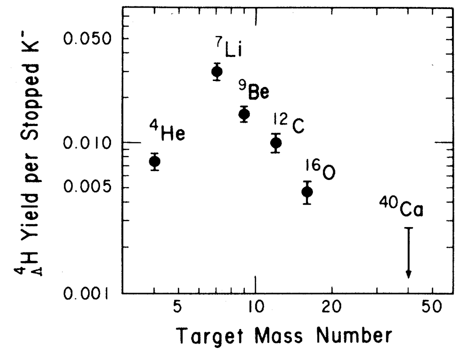

FIG. 3. Target mass number dependence of the $^{4}_{\Lambda}$H formation probabilities per stopped K^-.

which are well described by the α-cluster model. For other nuclei, this reaction may also be enhanced if an α-cluster exists in the surface region, since the K^- is absorbed on the surface of the nucleus.

If $^{4}_{\Lambda}$H is formed by the α-cluster absorption, the $^{4}_{\Lambda}$H events should be accompanied by π^0. We tagged the spectra by π^0 and by $\pi^\pm$, using information from the "peripheral counters," a set of NaI(Tl) and plastic scintillation counters surrounding the target. From the peak intensities in the π^0-tagged and $\pi^\pm$-tagged spectra combined with the π^0 and $\pi^\pm$ detection efficiencies in the peripheral counters, we found that for the Li target $38\pm8\%$ of the $^{4}_{\Lambda}$H events were accompanied by π^0 and $49\pm8\%$ by $\pi^\pm$, and for the Be target $36\pm7\%$ and $34\pm11\%$ were accompanied by π^0 and $\pi^\pm$, respectively. Since a fairly large amount of $^{4}_{\Lambda}$H events were accompanied by charged pions, we can conclude that the $^{4}_{\Lambda}$H formation cannot be explained by the direct reaction on an α cluster alone.

The observation of both π^0 accompanying events and $\pi^\pm$ accompanying events suggests that various hyperon production processes ($\Lambda\pi^0$, $\Lambda\pi^-$, $\Sigma^+\pi^-$, $\Sigma^0\pi^0$, $\Sigma^0\pi^-$, $\Sigma^-\pi^+$, and $\Sigma^-\pi^0$) may be responsible for the formation of $^{4}_{\Lambda}$H. The $\Sigma\pi$ as well as the $\Lambda\pi$ processes possibly contribute to form $^{4}_{\Lambda}$H, because about one-half of all Σ's produced from stopped K^- are converted into Λ's within the same nucleus.[16] In the case of a nucleon ($E_N\sim30$ MeV) injection into a nucleus, a compound nucleus is formed with an appreciable probability, which then decays into fragments. In a similar way we can imagine a picture of a "hyperon compound nucleus."[17] The Λ generated by the $\Lambda\pi$ production or by the $\Sigma N\rightarrow\Lambda N$ conversion ($E_\Lambda\sim30$ MeV) is trapped in the nucleus and forms a Λ compound nucleus, which may decay into a hyperfragment such as $^{4}_{\Lambda}$H. Recently, a theoretical estimation was made based on this model for the ^{12}C and ^{16}O targets,[18] which showed that the observed formation probability of $^{4}_{\Lambda}$H can possibly be explained by this description.

In order to further investigate the formation mechanism of hyperfragments, it would be important (i) to measure the momenta of pions in the hyperon formation stage in coincidence with pions from the hypernuclear decay, and (ii) to measure formation probabilities of various hyperfragments as well as $^{4}_{\Lambda}$H. In our spectra, we observed no two-body decay peaks other than $^{4}_{\Lambda}$H, presumably because the experimental setup has too small of a sensitivity in a momentum region below ~ 120 MeV/c to allow efficient detection of pions from other hyperfragments, due to lower spectrometer efficiency and worse momentum resolution. With a spectrometer system fitted for the momentum region around 100 MeV/c, π^- decay peaks from various hyperfragments would be observed.

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