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Formation Probabilities of ${}^{4}_{\Lambda}$H Hyperfragment from Stopped K⁻ on Light Target Nuclei

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The formation probabilities of ${}^{4}_{\Lambda}$H from stopped K^- on ^{7}Li, ^{9}Be, ^{12}C, and ^{16}O targets were measured to be $(3.3\pm0.4)\times10^{-2}$, $(1.57\pm0.18)\times10^{-2}$, $(1.00\pm0.14)\times10^{-2}$, and $(0.47\pm0.08)\times10^{-2}$ per stopped K^-, respectively. The observed ${}^{4}_{\Lambda}$H formation cannot be accounted for only by the direct reaction on α cluster, ^{4}He(K^-,π^0)${}^{4}_{\Lambda}$H. The model of "hyperon compound nucleus" seems to explain the observed formation probabilities.

§1. Introduction

Hypernuclei have been studied by use of direct reactions since the 1970's, mainly by the in-flight (K^-,π) reaction, [1)] and by the (stopped K^-,π) [2)] and (π,K^+) reactions. [3)] Before the hypernuclear spectroscopy by these direct reactions was established, various light Λ hypernuclei had been observed as hyperfragments from stopped K^- in emulsion in the 1960's. [4)] In those emulsion experiments, Λ hypernuclei formed indirectly from stopped K^- were identified through the weak decay, and the binding energies of Λ were determined.

The most remarkable feature of this old style of hypernuclear formation is that the formation rate of hypernuclei per stopped K^- is very large. Emulsion and heavy liquid bubble chamber experiments reported that the trapping probability of hyperon (the probability for a strangeness to remain in a nucleus till the weak decay) is about 10% and 50% for light and heavy target nuclei, respectively, [5)] which corresponds to the formation probability of any Λ hypernuclei (hyperfragments) per stopped K^-. Thus stopped K^- gives an efficient source of Λ hypernuclei, if the hypernuclear species are well identified.

This abundance should be related to the mechanism of hyperfragment formation from stopped K^-. A stopped K^- forms a kaonic atom, falls down to lower orbits, and is absorbed in the surface region of the nucleus. Therefore, the hyperfragment formation may be sensitive to the surface structure of the nucleus. It is another interest in the study of the hyperfragment formation mechanism.

The formation mechanism seems to be so complicated that yields of hyperfragments were not calculated theoretically so far, in contrast with the hypernuclear formations by the direct reactions which have been theoretically studied. Experimentally, the mechanism of hyperfragment formation was rarely studied either, partly because the unique identification of the target nucleus responsible for each fragment was impossible in the emulsion experiments.

Using a magnetic spectrometer we have detected π^- from the weak decay of hyperfragments produced from K^- absorption at rest on several target nuclei, and measured the formation probabilities of the hyperfragments from each target nucleus for the first time. In this report we present the formation probability of ${}^{4}_{\Lambda}$H from each of ^{7}Li, ^{9}Be, ^{12}C, ^{16}O and ^{40}Ca targets and discuss the formation mechanism.

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§2. Experimental Method

Recently, we performed a series of experiments to measure π^- momentum spectra from stopped K^- on several light nuclei. The original purpose of these experiments is to study Σ and Λ hypernuclei produced by the direct (stopped K^-,π^-) reactions. Thanks to the wide momentum range of the spectrometer (110 MeV/c $\sim$ 300 MeV/c), we can also observe π^- from mesonic decays of Λ hypernuclei (hyperfragments), and study hyperfragment formation in K^- absorption at rest.

The experiment was performed at the KEK 12 GeV Proton Synchrotron. A detailed description of the setup is found in Ref. 6, 7.

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 and a set of four tracking chambers. The characteristic features of this spectrometer system are: (1) a large acceptance ($\sim$100 msr), (2) a high momentum resolution ($\Delta p = 1.4$ MeV/c FWHM, effect of the energy loss in the target is not included), and (3) a wide momentum range from 110 MeV/c to 300 MeV/c. This momentum range, which is designed to cover the regions both for the direct Σ hypernuclear formation (160$\sim$190 MeV/c) and for the direct Λ hypernuclear formation (250$\sim$280 MeV/c), partly includes the region for mesonic decays of Λ hypernuclei (around 100 MeV/c). Correcting the π^- momentum for energy loss in the target, we achieved momentum resolution of 2.3$\sim$3.3 MeV/c FWHM (depending on the target material) at 205 MeV/c.

The target was surrounded by NaI counters with plastic scintillation counters in front of them. These peripheral counters were used to detect π^o, $\pi^{\pm}$, protons, and γ rays which may be emitted in the formation and the decay of hypernuclei. Plastic scintillator ($(CH)_n$) was used for the ^{12}C target, and water for the ^{16}O target.

§3. Experimental Results

Fig. 1 shows the measured (stopped K^-,π^-) spectrum on ^{12}C target. The gross structure of the spectrum is well accounted for by productions and decays of hyperons. [6),7)] Two peaks observed at 261 MeV/c and 273 MeV/c are assigned to the $(p3/2)_n^{-1}(p)_\Lambda$ and $(p3/2)_n^{-1}(s1/2)_\Lambda$ states of $^{12}_{\Lambda}C$, respectively, which are formed directly in the (stopped K^-,π^-) reaction.

We observed another peak at 132.6$\pm$0.2 MeV/c with strength larger than the two $^{12}_{\Lambda}C$ peaks. Since the π^- from the free Λ decay 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 produced from stopped K^-. Table I shows calculated π^- momenta in the two-body π^--mesonic decays of various Λ hypernuclei (hyperfragments) which have been identified in emulsion experiments with stopped K^-. 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. Therefore, the observed peak is assigned to the π^- from:

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

This momentum is the highest of the two-body decay momenta as shown in Table I, because of the high Q-value reflecting the large binding energy of ^4He.

Fig. 2 shows low momentum regions of measured (stopped K^-,π^-) spectra on ^7Li, ^9Be, ^{12}C, ^{16}O, and ^{40}Ca targets. The 133 MeV/c peak from $^4_{\Lambda}H \rightarrow {}^4He + \pi^-$ is observed in the ^7Li, ^9Be, ^{12}C and ^{16}O spectra. The peak positions in these spectra agree well with the value of 132.9 MeV/c. No peak is seen for the ^{40}Ca target.

The formation probability of $^4_{\Lambda}H$ was obtained from the peak intensity divided by the branching ratio of $^4_{\Lambda}H \rightarrow {}^4He + \pi^-$ decay. The branching ratio $BR(^4He\ \pi^-)$ was derived as :

$$BR(^4He\ \pi^-) = \frac{\Gamma(^4He\ \pi^-)}{\Gamma(n.m.) + \Gamma(\pi^-) + \Gamma(\pi^o)} \approx 0.49,$$

using the following relations for the non-mesonic, π^--mesonic, and π^o-mesonic decay rates of $^4_{\Lambda}H$ (denoted as $\Gamma(n.m.)$, $\Gamma(\pi^-)$, and $\Gamma(\pi^o)$, respectively) :

$\Gamma(n.m.)/\Gamma(\pi^-) = 0.26 \pm 0.13$ (Block et al.[10)]),
$\Gamma(\pi^o)/\Gamma(\pi^-) \approx 0.16$ (calculated by Dalitz [11)]), and
$\Gamma(^4He\ \pi^-)/\Gamma(\pi^-) = 0.69 \pm 0.02$ (Bertrand et al.[12)]).

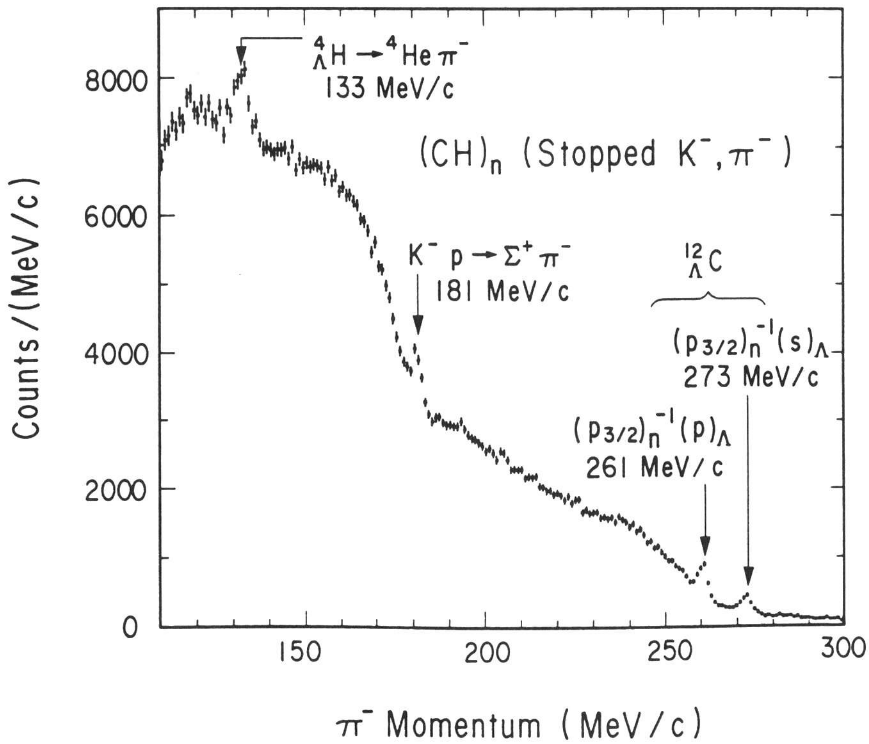

Figure 1: (Stopped K^-,π^-) spectrum on ${}^{12}C$ target. Momentum dependence of the acceptance is corrected for.

Table I: π^- decays of light Λ hypernuclei observed in emulsion experiments. Numbers of events for the two-body π^- decay and for other π^- decays are taken from Ref. 8. Momenta and Q-values of the two body decays are calculated from the Λ binding energies in Ref. 9.

Hypernuclei	Number of π^- decay events			Q value	p_π (two body)
	(two body decay)		(others)	(MeV)	(MeV/c)
${}^3_\Lambda$H	π^- ^{3}He	112	22	43.1	114.2
${}^4_\Lambda$H	π^- ^{4}He	760	93	55.5	132.9
${}^4_\Lambda$He	-	-	179	-	-
${}^5_\Lambda$He	-	-	1025	-	-
${}^6_\Lambda$He	π^- ^{6}Li	0	11	38.1	108.2
${}^7_\Lambda$Li	π^- ^{7}Be	3	64	37.8	108.0
${}^7_\Lambda$Be	-	-	67	30.3	95.6
${}^8_\Lambda$Li	π^- ^{7}Li	0	229	48.2	124.1
${}^8_\Lambda$Be	π^- ^{8}B	17	12	31.1	97.0
${}^9_\Lambda$Li	π^- ^{9}Be	5	9	46.1	121.1
${}^9_\Lambda$Be	π^- ^{9}B(g.s)	159	16	30.9	96.8
${}^{11}_\Lambda$B	π^- ^{11}C	4	7	36.2	105.9
${}^{12}_\Lambda$B	π^- ^{12}C	0	24	42.3	115.7
${}^{13}_\Lambda$C	π^- ^{13}N	1	0	28.5	92.9

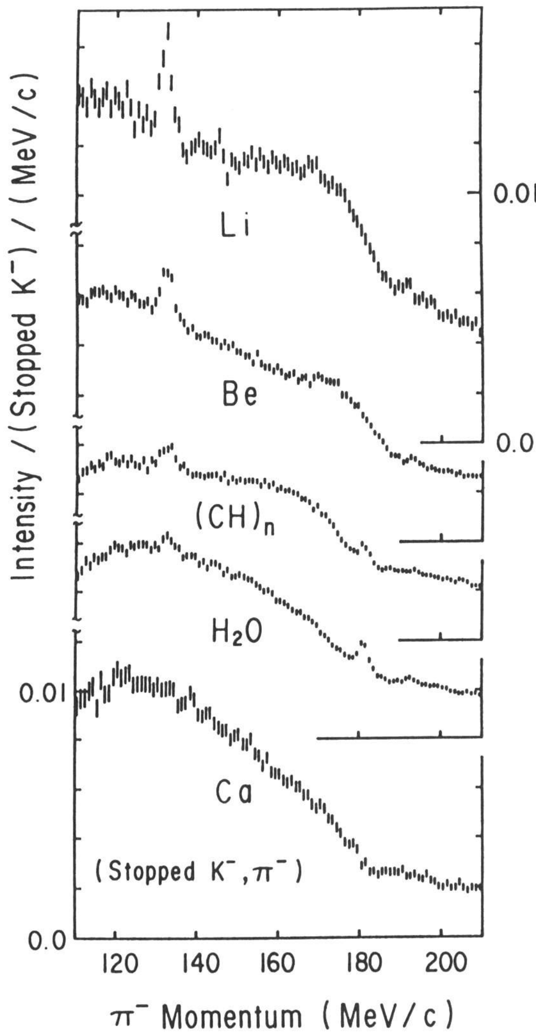

Figure 2: Low momentum regions of (stopped K$^-$,π^-) spectra on ^{7}Li, ^{9}Be, ^{12}C, ^{16}O and ^{40}Ca targets. The vertical scale of all the spectra is intensity per stopped K$^-$. Momentum dependence of the acceptance is corrected for.

It is known that a non-negligible part of ${}^{4}_{\Lambda}$H produced from stopped K$^-$ in emulsion decays in flight, [13] 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 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.

Table II lists the formation probabilities of ${}^{4}_{\Lambda}$H derived by this method, giving both values 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.

The derived formation probabilities of ${}^{4}_{\Lambda}$H reveal a clear dependence on the target mass number as shown in Fig. 3. Empirically, it is roughly proportional to A^{-2} for $A = 7\sim16$ with A being the mass number. It is also remarkable that the formation probability of ${}^{4}_{\Lambda}$H per stopped K$^-$ is much larger than those of discrete states of ${}^{12}_{\Lambda}$C formed via the direct (stopped K$^-$,π^-) reaction. From the ^{12}C spectrum (Fig. 1), the formation probabilities of ${}^{12}_{\Lambda}$C for the $(p3/2)_{\rm n}^{-1}(p)_\Lambda$ and $(p3/2)_{\rm n}^{-1}(s1/2)_\Lambda$

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

Target	$^4_\Lambda$H Probability per Stopped K^- (without correction)	(with correction)
^{7}Li	$26 \pm 3 \times 10^{-3}$	$33 \pm 4 \times 10^{-3}$
^{9}Be	$14.4 \pm 1.6 \times 10^{-3}$	$15.7 \pm 1.8 \times 10^{-3}$
^{12}C	$9.0 \pm 1.2 \times 10^{-3}$	$10.0 \pm 1.4 \times 10^{-3}$
^{16}O	$4.2 \pm 0.7 \times 10^{-3}$	$4.7 \pm 0.8 \times 10^{-3}$
^{40}Ca	$< 2.4 \times 10^{-3}$	$< 2.7 \times 10^{-3}$

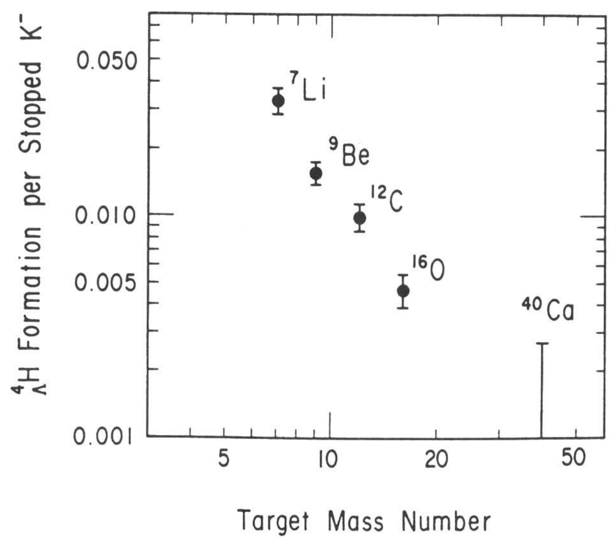

Figure 3: Target mass number dependence of the $^4_\Lambda$H formation probabilities per stopped K^-.

states were extracted to be $(2.3 \pm 0.3) \times 10^{-3}$ and $(0.98 \pm 0.12) \times 10^{-3}$ per stopped K^-, respectively. The formation probability of $^4_\Lambda$H ($(10.0 \pm 1.4) \times 10^{-3}$) is more than 4 times as large as the direct formation probabilities of these hypernuclear states.

It is interesting to ask what is the mechanism of such abundant formation of $^4_\Lambda$H. The observed clear A-dependence may be indicative of the formation mechanism. In the following sections we will discuss the formation mechanism of $^4_\Lambda$H from K^- absorption at rest.

§4. Model of Direct Reaction on α Cluster

Remembering that stopped K^- is absorbed in the surface region of the nucleus, we can consider a model of the direct formation of $^4_\Lambda$H from K^- absorbed on an α cluster which may exist in the nuclear surface,

$$K^- + \text{“}^4\text{He”} \rightarrow {}^4_\Lambda H + \pi^0.$$

This reaction is expected to be enhanced in some light nuclei such as ^{9}Be which are well described by the alpha-cluster model.

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. 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±8% of the $^4_\Lambda$H events were accompanied by π^0 and 49±8% by $\pi^\pm$, and for the Be target 36±7% and 34±11% were accompanied by π^0 and $\pi^\pm$, respectively. Since a fairly large amount of $^4_\Lambda$H events were accompanied by charged

TableIII: The calculated $^4_\Lambda$H formation probabilities (in units of 10^{-3} per stopped K$^-$), $P(^4_\Lambda\mathrm{H})$, on ^{12}C and ^{16}O targets (taken from Ref 19). Four values base on the different treatment of $F_C(E_\Lambda)$ are displayed, that is, estimation from the experimental hyperon trapping probability ($P_{\rm trap}$), those from the imaginary part of the Λ potential calculated by the G-matrix, and by the t-matrix, and that estimated by Yazaki from the ΛN cross section with the Pauli suppression effect.

Target	Experimental	Compound Nucleus	Calculated from $P_{\rm trap}$	G-matrix	t-matrix	$\sigma^{\rm eff}_{\Lambda N}$
^{12}C	10.0±1.4	$^{12}_\Lambda$C*	1.9±0.9	0.9	1.7	2.3
		$^{12}_\Lambda$B*	5±2	2.4	4.3	6.4
^{16}O	4.7±0.8	$^{16}_\Lambda$O*	0.9±0.4	0.5	0.9	1.2
		$^{16}_\Lambda$N*	2.3±1.0	1.2	2.2	3.1

pions, we can conclude that the $^4_\Lambda$H formation cannot be explained only by the direct reaction on α cluster alone, though we cannot exclude a certain contribution of the α-cluster reaction.

The formation probability of $^4_\Lambda$He from the direct ^{4}He (stopped K$^-$, π^-)$^4_\Lambda$He reaction is predicted to be about $1 \sim 2 \times 10^{-3}$ per stopped K$^-$ in a DWIA calculation by Matsuyama and Yazaki.[15] The observed $^4_\Lambda$H formation probabilities on the Li and Be targets are larger than this value by about an order of magnitude. Considering that K$^-$ absorption on an α cluster is a part of the K$^-$ absorption on a nucleus, the $^4_\Lambda$H formation probability is, in this model, expected to be smaller than the probability of ^{4}He (stopped K$^-$, π°)$^4_\Lambda$H, which should be a half of the probability of ^{4}He (stopped K$^-$, π^-)$^4_\Lambda$He. It also implies that the observed $^4_\Lambda$H formation cannot be explained only by the direct reaction on α cluster.

§5. Model of "Hyperon Compound Nucleus"

The observation of both π°-accompanying events and $\pi^\pm$-accompanying events implies that various hyperon production processes ($\Lambda\pi^\circ$, $\Lambda\pi^-$, $\Sigma^+\pi^-$, $\Sigma^\circ\pi^\circ$, $\Sigma^\circ\pi^-$, $\Sigma^-\pi^+$, and $\Sigma^-\pi^\circ$) may be responsible for the formation of $^4_\Lambda$H. The $\Sigma\pi$ processes 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),17] In the case of a nucleon ($E_N \sim 30$ 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 in which the Λ generated by the $\Lambda\pi$ process or by the ΣN $\rightarrow$ ΛN conversion ($E_\Lambda \sim 30$ MeV) is trapped in the nucleus to form a "Λ compound nucleus", which may decay into a hyperfragment such as $^4_\Lambda$H, as suggested by Yamazaki.[18]

Recently a theoretical estimation was made based on this model for the ^{12}C and ^{16}O targets.[19] In this estimation, the formation probability of $^4_\Lambda$H per stopped K$^-$, $P(^4_\Lambda\mathrm{H})$, is given by

$$P(^4_\Lambda\mathrm{H}) = \int P_\Lambda(E_\Lambda)F_C(E_\Lambda)D_C(^4_\Lambda\mathrm{H}; E_x)dE_\Lambda.$$

The energy distribution of Λ generated from stopped K$^-$, $P_\Lambda(E_\Lambda)$, was calculated by PWBA. The formation probability of Λ compound nucleus, $F_C(E_\Lambda)$, was estimated from the imaginary part of Λ optical potential calculated from the ΛN effective interaction by G-matrix method. The probability for the Λ compound nucleus to decay into $^4_\Lambda$H, $D_C(^4_\Lambda\mathrm{H}; E_x)$, was calculated by using a statistical model. In Ref. 19, two compound nuclei formed by (K$^-$,π^-) and (K$^-$,π°) reactions are considered ($^{12}_\Lambda$C* and $^{12}_\Lambda$B* for ^{12}C target and $^{16}_\Lambda$O* and $^{16}_\Lambda$N* for ^{16}O target).

The calculated $P(^4_\Lambda\mathrm{H})$ for the C and O targets was shown in TableIIItogether with the experimental data. To be compared with the experiment is a weighted average of the two compound nuclei. The ratio of $P(^4_\Lambda\mathrm{H})$ between the C target and the O target is 0.5 in the calculation, which agrees with the experimental value, 0.47±0.10. Though the absolute values of the calculated $P(^4_\Lambda\mathrm{H})$ are by a factor of 2∼4 smaller than the experimental values, they may be regarded to be close to the experimental values in view of simplifications in the model.

In conclusion, the observed formation probability of ${}^4_\Lambda$H may be explained by this model, that is, the ${}^4_\Lambda$H formation through the Λ compound nucleus.

§6. Conclusion

We measured the formation probabilities of ${}^4_\Lambda$H from K^- absorption at rest on each of ^{7}Li, ^{9}Be, ^{12}C, and ^{16}O nuclei. The observed abundant formation and the target mass number dependence can roughly be explained by the model of Λ compound nucleus. The model of the direct reaction on α cluster cannot account for the whole of the observed ${}^4_\Lambda$H formation.

In order to investigate further the formation mechanism of hyperfragments, it is important to measure formation probabilities of various hyperfragments as well as ${}^4_\Lambda$H. Relative yields of various hyperfragments, if measured, can be compared with the predictions by the Λ compound nucleus model. Then the contribution of the α-cluster absorption in the ${}^4_\Lambda$H formation may be extracted, which will give information on the α clustering on the nuclear surface.

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