Double-Λ hypernuclear formation via a neutron-rich Ξ state

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Conversion processes for ${}^{7}_{\Xi}$H are discussed as a typical example of the double-Λ hypernuclear formation via a neutron-rich Ξ state. ${}^{5}_{\Lambda\Lambda}$H is formed with a surprisingly large branching ratio of about 90% from ${}^{7}_{\Xi}$H that is produced by the (K^-,K^+) reaction on the ^{7}Li target. The ${}^{7}_{\Xi}$H state has a narrow width, 0.75 MeV, and its population can be confirmed by tagging K^+ momentum. [S0556-2813(96)50507-8]

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Recent hypernuclear studies have aroused much interest in double strangeness ($S=-2$) systems. Several double-Λ hypernuclei events and Ξ atoms (or nuclei) were reported in an experiment at KEK using emulsion-counter hybrid techniques [1]. Such double strangeness systems provide unique information concerning the $\Lambda\Lambda$ and ΞN interaction, which is closely related to the existence of H-dibaryon [2] and is awaited to deduce properties of strange hadronic matter [3]. However, information from $S=-2$ systems is still very limited. One reason is the difficulty in identification of $S=-2$ hypernuclear species in emulsion events, and the other is a lack of events themselves.

If an intense K^- beam is available, the (K^-,K^+) reaction can sufficiently populate certain Ξ-nuclear states, which become doorway states to double-Λ hypernuclei. In this paper a typical example of this line of producing double-Λ hypernuclei is explored. The first step is to produce a narrow-width bound Ξ state using the ${}^{7}\text{Li}(K^-,K^+){}^{7}_{\Xi}\text{H}$ reaction. Then, the Ξ^- particle interacts with a proton in the ^{6}He core, and they convert into two Λ particles. Our primary concern is how large the branching to the double-Λ nuclear formation is for the neutron-rich Ξ-nucleus ${}^{7}_{\Xi}$H.

The conversion processes of ${}^{7}_{\Xi}$H are limited to the following:

$$ {}^{7}_{\Xi}\text{H} \to {}^{5}_{\Lambda\Lambda}\text{H}+n+n \quad \sim 11 \ \text{MeV}, \tag{1}$$

$$ \to {}^{4}_{\Lambda}\text{H}+\Lambda+n+n \quad \sim 7 \ \text{MeV}, \tag{2}$$

$$ \to {}^{4}_{\Lambda}\text{H}^{*}+\Lambda+n+n \quad \sim 6 \ \text{MeV}, \tag{3}$$

$$ \to {}^{3}\text{H}+\Lambda+\Lambda+n+n \quad \sim 5 \ \text{MeV}. \tag{4}$$

To fix the Q values, we need knowledge of the binding energies (BE) of ${}^{7}_{\Xi}$H and ${}^{5}_{\Lambda\Lambda}$ H. In the above equations, we have tentatively assigned BE(Ξ^- in ${}^{7}_{\Xi}$H)$\sim$2 MeV and BE ($\Lambda\Lambda$ in ${}^{5}_{\Lambda\Lambda}$H)$\sim$6 MeV, which are estimated from a calculation of double-strange five-body systems by Myint *et al.* [4]. The point is that the Q values become small for these processes because the 28.33 MeV energy released due to $\Xi N\to\Lambda\Lambda$ conversion is almost exhausted in breaking the α cluster in ${}^{7}_{\Xi}$H. The three-body decay process in Eq. (1) would be favored by such small Q values, because the available phase space is less reduced than that for the four-body and the five-body decays.

We apply distorted-wave Born approximation (DWBA) with a finite range $\Xi^- p$-$\Lambda\Lambda$ interaction to calculate the conversion widths. For the $\Xi^- N$ channel, the $\Lambda\Lambda$ channel, and the $\Xi^- p$-$\Lambda\Lambda$ coupling interactions we use the Shinmura potential [5] determined so as to reproduce S matrices of the Nijmegen model D potential [6] at low energies. The potential parameters are summarized in Table I.

For the $\Xi^- N$ channel interaction, we multiply the repulsive part by a reduction factor f_c due to short-range correlations to obtain an effective interaction. We use the YNG effective interaction for ΛN [7], the parameters of which are readjusted to reproduce the binding energies of ${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$H*, and the NHN effective interaction for NN [8].

Initial-state and final-state wave functions for the conversion processes are constructed as follows. For the initial state ${}^{7}_{\Xi}$H, the five-body part without two neutrons ("${}^{5}_{\Xi}$H") is firstly solved as a 3N-N-Ξ^- three-body system within the framework of the resonating group method. The total Hamiltonian is given by

$$\mathcal{H}_{{}^{5}_{\Xi}\text{H}}=\sum_{i=1}^{A} t_i - T_{\text{c.m.}} + \sum_{i<j\in N} v_{ij}^{NN} + \sum_{\substack{i\in N\\ j\in\Xi}} v_{ij}^{N\Xi} + \sum_{i<j} v_{ij}^{\text{Coulomb}}, \tag{5}$$

where t_i and $T_{\text{c.m.}}$ are kinetic energy operators of the ith nucleon or the Ξ^- particle and the center-of-mass motion of the five-body system, respectively. The Coulomb interaction for $\Xi^- p$ and pp is taken into account, since it plays an important role in binding ${}^{5}_{\Xi}$H [4]. We employ a variational method using a Gaussian basis with three rearrangement channels in the Jacobi coordinate system (CRCG method) [9]. Secondly, wave functions for the remaining neutrons are independently determined by solving the following equation of ${}^{5}_{\Xi}$H-n:

$$(T_{{}^{5}_{\Xi}\text{H}n} + V_{{}^{4}\text{He}\,n} + V_{\Xi^- n} - E)|\psi_n\rangle = 0, \tag{6}$$

where the potential is a sum of contributions from ^{4}He and Ξ^-. We use the Kanada potential [10] for ^{4}He n, the parameter values of which are multiplied by 1.15 for the $p_{3/2}$ potential so as to reproduce one half of the two-neutron separation energy in ^{6}He. For Ξ^- n, we regard the Ξ wave function as a simple (0s) harmonic oscillator one, the size parameter of which corresponds to the rms radius of the Ξ^- determined from the calculation of ${}^{5}_{\Xi}$H. Then the $\Xi^- n$

interaction, which is averaged among odd-state parts for a p-wave neutron, is folded with the $(0s)_\Xi$ density.

For the final states, $^{5}_{\Lambda\Lambda}$H is solved as a ^{3}H-Λ-Λ system using the CRCG method, and $^{4}_{\Lambda}$H ($^{4}_{\Lambda}$H*) is solved as a ^{3}H-Λ system with spin zero (unity). The oscillator size parameter of ^{3}H is taken to be 1.5 fm. The emitted Λ wave functions in Eqs. (2) and (3) are determined by solving a scattering equation for the $^{4}_{\Lambda}$H ($^{4}_{\Lambda}$H*)-Λ system, where we assume that the $^{4}_{\Lambda}$H ($^{4}_{\Lambda}$H*) wave function is same as for the bound state. For Eq. (4), which has only a small contribution, we neglect distortions of the Λ particles. Wave functions for the two scattered neutrons $[\tilde{j}_1(k_n r)]$ are obtained by solving Schrödinger equations with a potential corresponding to the sum of the ^{3}H-n and Λ-n parts. We use a phenomenological potential by Teshigawara for ^{3}H n [11], which reproduces well the phase-shift behavior of low energy scattering, and a folding potential for the Λ-n part obtained by the same procedure as the Ξ-n part in the initial state. Though we use simple neutron wave functions neglecting the two-neutron correlation, this does not sensitively affect the branching ratio for the conversion process, since the two-neutron emission is a common factor in all decay processes. For the convenience of calculating conversion widths, the two neutron coordinates are taken from the center-of-mass of $^{5}_{\Xi}$H. We show the formula for the conversion width of Eq. (1) as an example,

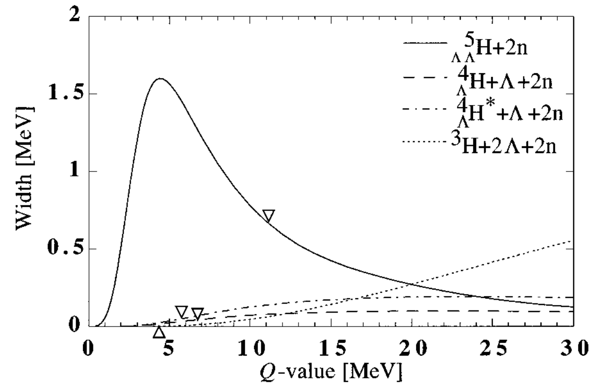

FIG. 1. Q-value dependence of conversion widths from the $^{7}_{\Xi}$H state. The solid, dashed, dash dotted, and dotted lines are for the processes (1), (2), (3), and (4), respectively. The marks denote respective Q values of the processes.

$$\Gamma_{^{5}_{\Lambda\Lambda}\mathrm{H}nn}=\frac{8\mu_n}{\pi\hbar^2}\int_0^{k_n^{\max}} dk_n k_n' k_n^2 |F(k_n)F(k_n')\langle\psi(^{5}_{\Lambda\Lambda}\mathrm{H})|V_{\Lambda\Lambda\text{-}\Xi^- p}|\psi(\text{``}^{5}_{\Xi}\mathrm{H}\text{''})\rangle|^2, \tag{7}$$

$$\text{where}\quad k_n'=\sqrt{\frac{2\mu_n Q}{\hbar^2}-k_n^2},\qquad k_n^{\max}=\sqrt{\frac{2\mu_n Q}{\hbar^2}}, \tag{8}$$

$$F(k_n)\equiv\int_0^\infty r^2\tilde{j}_1(k_n r)\psi_n(r)dr, \tag{9}$$

where μ_n and Q denote the reduced mass of the $^{5}_{\Xi}$H-n system and the reaction Q value, respectively. Widths for the other processes can be calculated in a similar manner.

Table II lists the decay width and the branching ratio (in parentheses) of each process together with their dependence on the $\Xi^- N$ correlation factor f_c. When we take f_c as 0.8, the resulting binding energy and the rms radius of the Ξ in $^{5}_{\Xi}$H are almost the same as the values given by Myint *et al.* [4]. The total conversion width of $^{7}_{\Xi}$H is 0.75 MeV in this case. If f_c has a smaller value, process (1) has a larger

TABLE I. The Shinmura potential for $S=-2$ two-body systems in units of MeV and fm. In the calculation, we use the coupling potential of $V_{\Xi^- p\text{-}\Lambda\Lambda}=57.87e^{-(r/0.8550)^2}$ for the $^1S_0$ state, and a triplet-odd state potential averaged with weights $(2J+1)$ among $^3P_0$, $^3P_1$, and $^3P_2$. The repulsive part of the potential is given as $V_c=5000\,e^{-(r/0.355)^2}$.

	$V_{\Lambda\Lambda}$	$V_{\Xi^- p}$	$V_{\Xi^- n}$
$^1S_0$	$V_c-332.97e^{-(r/0.8550)^2}$	$V_c-310.93e^{-(r/0.8550)^2}$	$V_c-188.57e^{-(r/0.9279)^2}$
$^3S_1$	—	$V_c-179.17e^{-(r/0.8550)^2}$	$V_c-141.52e^{-(r/0.9279)^2}$
$^1P_1$	—	$V_c-435.05e^{-(r/0.8)^2}$	$V_c-587.53e^{-(r/0.7369)^2}$
$^3P_0$	$V_c-36.432e^{-(r/0.8)^2}$	$V_c-118.17e^{-(r/0.8)^2}$	$V_c-32.873e^{-(r/1.0658)^2}$
$^3P_1$	$V_c-187.33e^{-(r/0.8)^2}$	$V_c-264.08e^{-(r/0.8)^2}$	$V_c-58.265e^{-(r/1.2054)^2}$
$^3P_2$	$V_c-274.44e^{-(r/0.8)^2}$	$V_c-332.20e^{-(r/0.8)^2}$	$V_c-130.82e^{-(r/1.0305)^2}$

TABLE II. Conversion width Γ [MeV], branching ratio and corresponding Q value [MeV] of each process from the ${}^{7}_{\Xi}\mathrm{H}$ state. The obtained binding energy [MeV] and rms radius [fm] of the Ξ^- particle in "${}^{5}_{\Xi}\mathrm{H}$" are also listed in each case of ΞN correlation factor f_c.

f_c	1.0	0.9	0.8	0.7
Ξ BE (rms)	0.5 (6.1)	0.9 (5.1)	1.5 (4.2)	2.5 (3.4)
Process	Γ (B.R.) Q	Γ (B.R.) Q	Γ (B.R.) Q	Γ (B.R.) Q
(1)	0.241 (84%) 12.0	0.398 (86%) 11.6	0.671 (89%) 11.0	1.200 (95%) 9.7
(2)	0.019 (7%) 7.5	0.029 (6%) 7.1	0.039 (5%) 6.5	0.036 (3%) 5.2
(3)	0.024 (8%) 6.4	0.035 (8%) 6.1	0.042 (6%) 5.4	0.029 (2%) 4.2
(4)	0.002 (0.7%) 5.4	0.002 (0.5%) 5.1	0.002 (0.2%) 4.4	0.0004 (0.02%) 3.2
Γ_{total}	0.286	0.464	0.754	1.264

width as shown in Table II, since the overlap between the initial "${}^{5}_{\Xi}\mathrm{H}$" state and the final ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ state becomes larger due to the larger binding energy of Ξ.

The double-Λ nuclear formation of Eq. (1) has a significantly large branching ratio, about 90%. This results from the small Q values in the conversion processes, which suppress substantially the available phase space for the four-body and the five-body decays. Figure 1 shows the Q-value dependence of the partial widths.

While the five-body process of Eq. (4) monotonically decreases as Q goes to zero, the three-body process of Eq. (1) has a maximum at a small Q value around 4 MeV.

Zhu *et al.* investigated double-Λ nuclear formation with neutron emission in the case of the atomic Ξ^- capture in ${}^{6}\mathrm{Li}$, and they obtained a branching ratio for the process of about 3% [12]. Compared to this, our value of about 90% is extremely large, which will enable us to make a clear identification of the double-Λ hypernucleus. An essential difference between the conversion processes in $[{}^{6}\mathrm{Li}\cdot\Xi^-]_{\mathrm{atom}}$ and that in ${}^{7}_{\Xi}\mathrm{H}$ comes from the reaction Q values. In the process $[{}^{6}\mathrm{Li}\cdot\Xi^-]_{\mathrm{atom}}\rightarrow{}^{6}_{\Lambda\Lambda}\mathrm{He}+n$, the Ξ^- particle and the proton in the deuteron cluster convert into two Λ particles. Then the Q value is a large 36 MeV, where the Λ particles can get enough energies to escape the nucleus.

In summary, we have discussed the $\Lambda\Lambda$ conversion processes for ${}^{7}_{\Xi}\mathrm{H}$ as a typical example of the double-Λ nuclear formation through a doorway Ξ state. Due to the breakup of the α cluster in ${}^{7}_{\Xi}\mathrm{H}$, the processes have small reaction Q values that suppress many-body decays. The double-Λ nuclear formation ${}^{7}_{\Xi}\mathrm{H}\rightarrow{}^{5}_{\Lambda\Lambda}\mathrm{H}+n+n$ involves a three-body decay, while the others are four-body and five-body decay processes. Thus, ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ is almost exclusively formed with a large branching ratio of about 90%, once ${}^{7}_{\Xi}\mathrm{H}$ is populated by the (K^-,K^+) reaction on the ${}^{7}\mathrm{Li}$ target. Though we need to estimate the production cross section for ${}^{7}_{\Xi}\mathrm{H}$, the double-Λ nuclear formation through such doorway Ξ states should become feasible in the near future by using intense K^- beams. The point is that to produce effectively double-Λ hypernuclei requires that the core nucleus digests the 28.33 MeV energy released by the elementary process, not convert it to Λ particle kinetic energy. We again emphasize the usefulness of the α-cluster breakup process, where almost all of the energy is absorbed.

The ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ produced is an appropriate object for investigation of $S=-2$ systems, since there exists less ambiguity in any effort to extract information about the $\Lambda\Lambda$ interaction due to its simple structure, and it is easy to identify the nucleus by the use of monoenergetic decay pions. The detection of sequential decay pions is clear evidence of ${}^{5}_{\Lambda\Lambda}\mathrm{H}$ production, ${}^{5}_{\Lambda\Lambda}\mathrm{H}\rightarrow{}^{5}_{\Lambda}\mathrm{He}+\pi^-$ $(p_\pi\approx 130\ \mathrm{MeV}/c)$ and ${}^{5}_{\Lambda}\mathrm{He}\rightarrow{}^{4}\mathrm{He}+p+\pi^-$ $(p_\pi\sim 100\ \mathrm{MeV}/c)$. The branching ratio of the former pionic decay is expected to be about 25% [13] and the latter one is experimentally known to be about 40% [14]. Therefore, this sequential pion detection is feasible.

The ${}^{7}_{\Xi}\mathrm{H}$ state has a narrow conversion width of 0.75 MeV. This suggests the possibility of its identification by means of tagging the K^+ momentum. Thus, the procedure presented here is an example in which we are able to investigate the entire life of an $S=-2$ system—Ξ-hypernuclear formation, double-Λ hypernuclear conversion, and sequential pionic weak decays. Though we have not discussed other cases, a similar situation occurs in the case of the (K^-,K^+) reaction on a ${}^{6}\mathrm{Li}$ target. Such experiments are awaited as a first step to explore the interaction and properties of $S=-2$ systems.

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