Formation of $\Lambda\Lambda$ Hypernuclei by Ξ^- Capture in Light Nuclei

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We discuss the production of doubly strange $\Lambda\Lambda$ hypernuclei in Ξ^- atomic capture. The two-body $\Xi^- + {}^6\mathrm{Li} \to {}^{\;6}_{\Lambda\Lambda}\mathrm{He} + n$ reaction is a relatively favorable case, with a yield of order 3%. For heavier *p*-shell targets, such as ^{14}N, the $(1s_\Lambda)^2$ ground-state yields in the $\Xi^- + {}^AZ \to {}^{\;A}_{\Lambda\Lambda}(Z-1) + n$ reaction are suppressed, and states of $(1s_\Lambda 1p_\Lambda)$ structure, coupled to an excited nuclear core, are preferentially populated.

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The stability and spectroscopy of multistrange hadronic systems is of considerable interest from the point of view of both nuclear and particle physics. At the microscopic level of quantum chromodynamics (QCD), there is the exciting possibility that many-body systems containing a number of strange quarks may be stable with respect to strong decay. Among these possibilities, we mention the six-quark *H* dibaryon of Jaffe [1], a (*ssuudd*) composite with spin parity 0^+ and isospin zero, multiply strange SU(3) solitons [2] (for example, a bound state of two Σ^- hyperons), and "strangelets," of much larger baryon number and strangeness [3]. The search for such exotic strange composites is the object of several proposed experiments [4]. These speculative possibilities have led to a rekindling of interest in the properties of doubly strange hypernuclei, which consist of two Λ hyperons bound to a nuclear core.

The study of $\Lambda\Lambda$ hypernuclei is of considerable interest for several reasons. First, the level schemes and binding energies of such systems provide insight into the nature of the $\Lambda\Lambda$ interaction, which in turn sheds light on the SU(3) flavor structure of the strong forces of QCD. Second, the observation of $\Lambda\Lambda$ hypernuclei, which decay by weak interactions, may be used to rule out the existence of the *H* dibaryon in a certain mass range: If the *H* lies more than a few MeV below the $\Lambda\Lambda$ threshold, one would expect to observe strong decay (e.g., ${}^{\;6}_{\Lambda\Lambda}\mathrm{He} \to H + {}^4\mathrm{He}$) rather than weak decay. In experiments involving the exposure of nuclear emulsions to strange meson (K^-) beams, evidence for the existence of ${}^{\;6}_{\Lambda\Lambda}\mathrm{He}$ and ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$ has been reported [5,6]. The identification of these species rests on the observation of the strangeness-changing weak decays of the two hyperons. We study here another method for producing $\Lambda\Lambda$ hypernuclei, namely, via Ξ^- hyperon capture at rest by a nuclear core (*Z* protons, *A* baryons), followed by the emission of a monoenergetic neutron: $\Xi^- + {}^AZ \to {}^{\;A}_{\Lambda\Lambda}(Z-1) + n$. The production signature is provided by the two-body kinematics, and does not rely on the observation of weak decay.

We simulate $\Lambda\Lambda$ production in Ξ^- capture at rest by a two-body $\Xi^- p \to \Lambda\Lambda$ conversion amplitude, given by a spin-dependent local form factor $v_S(\mathbf{r}_1 - \mathbf{r}_2)$ which in potential models is short ranged, corresponding to exchanging K and K^* mesons. An immediate corollary is the following selection rule for the production of the $^1S_0$ $(1s_\Lambda)^2$ ground-state (g.s.) configuration: *The Ξ^- must be captured from atomic orbits $(nl)_\Xi$ such that $l_\Xi = l_p$*, where l_p corresponds to the orbital angular momentum of a target proton. This places severe restrictions on the possibility of direct $\Lambda\Lambda$ particle-stable production in Ξ^- capture, since the data [7] on other atomic capture processes $(K^-, \bar{p}, \Sigma^-)$ suggest that $l_\Xi \gtrsim l_p$. For example, one expects Ξ^- capture on ^{4}He to occur dominantly from *p* orbits ($l_\Xi = 1$), thus forbidding the formation of ${}^{\;4}_{\Lambda\Lambda}\mathrm{H}$, in contrast to a claim [8] made recently. Results of Ξ^- atomic cascade calculations [9,10] in ^{6}Li and ^{14}N are assembled in Table I, from which we conclude that the direct production of the $(1s_\Lambda)^2$ configuration is excluded for 70%–80% of the captures in ^{6}Li, whereas for ^{14}N and larger *A*, it is almost completely blocked out. Hence, only a narrow "window" exists for targets around ^{6}Li

TABLE I. Calculated Ξ^- capture probabilities (in %) from *s*, *p*, *d*, and *f* atomic orbits,[a] for various choices of Ξ^--nucleus real and imaginary potential-well depths[b] V_0 and W_0.

Target	V_0 (MeV)	W_0 (MeV)	*s*	*p*	*d*	*f*
^{6}Li	23.7	6.4	0.04	18.6	80.6	···
	23.7	3.2	0.04	30.3	68.9	···
	0	3.2	0.07	35.7	63.4	···
^{14}N	28.6	7.7	0.00	0.2	54.1	45.6
	28.6	3.9	0.03	0.4	69.9	29.6
	0	3.9	0.03	1.3	75.7	22.9

[a]Provided by Batty [9]; for a description of the cascade calculations, see Ref. [7]. Less than 0.1% capture from *f* orbits, and 0.8% decay while cascading in ^{6}Li. About 0.1% capture from *g* orbits, and 0.1% decay while cascading in ^{14}N.

[b]First row for ^{6}Li and ^{14}N taken from Ref. [10]; second and third rows show sensitivity to changes of V_0 and W_0.

where g.s. production is feasible (with a yield about 3×10^{-2} as calculated for ${}_{\Lambda\Lambda}^{6}$He). On the other hand, around ^{14}N one expects the $1p_\Lambda 1s_\Lambda$ configuration to be particle stable, with a production rate for ${}_{\Lambda\Lambda}^{14}$C smaller than for ${}_{\Lambda\Lambda}^{6}$He.

We now outline the calculation of the yield for the capture reaction

$$\Xi^- + {}^6\mathrm{Li} \to {}_{\Lambda\Lambda}^{6}\mathrm{He} + n\,. \tag{1}$$

Observation of this reaction would identify the 0^+ g.s. uniquely, since no other states are expected in ${}_{\Lambda\Lambda}^{6}$He below the $\Lambda + {}_{\Lambda}^{5}$He threshold at 7.8 MeV. The main competing reactions are

$$\Xi^- + {}^6\mathrm{Li} \to \begin{cases} {}_{\Lambda}^{5}\mathrm{He} + \Lambda + n, & (2) \\ {}^4\mathrm{He} + \Lambda + \Lambda + n. & (3) \end{cases}$$

Reactions which result in breaking up the ^{4}He core of the ^{6}Li target, as well as (Ξ^-, Ξ^0) charge-exchange reactions, are suppressed because of the very limited phase space and will be ignored. We consider the dominant $^3S_1$ g.s. configuration of ^{6}Li, treat the outgoing neutron in the plane-wave approximation (PWA), and ignore spin for the moment. The amplitude for Ξ^- capture from an lm atomic orbit to $\Lambda\Lambda$ states α and β, with a spectator ^{4}He core, is given by

$$F_m^{(l)}(\alpha,\beta;\mathbf{q}) = \sum_{m'=-1}^{+1} (-1)^{1-m'} \frac{1}{\sqrt{3}} g_{-m'}(\mathbf{q}) f_{mm'}^{(l)}(\alpha,\beta)\,, \tag{4}$$

where

$$g_m(\mathbf{q}) = \int \exp(-i\mathbf{q}\cdot\mathbf{r})\phi_m(\mathbf{r})d^3r \tag{5}$$

is the p-wave form factor corresponding to the emission of a final neutron with momentum $\mathbf{q}$. The basic $\Xi^- p \to \Lambda\Lambda$ amplitudes $f_{mm'}^{(l)}$ are defined by

$$f_{mm'}^{(l)}(\alpha,\beta) = (1+\delta_{\alpha\beta})^{-1/2} \times \int [\psi_\alpha(\mathbf{r}_1)\psi_\beta(\mathbf{r}_2) + \psi_\beta(\mathbf{r}_1)\psi_\alpha(\mathbf{r}_2)]^* \times v(|\mathbf{r}_1-\mathbf{r}_2|)\Phi_{lm}(r_1)\varphi_{m'}(\mathbf{r}_2)d^3r_1 d^3r_2\,, \tag{6}$$

where Φ is the Ξ^- atomic wave function and $\varphi_{m'}$ is a bound-nucleon $1p$ wave function for ^{6}Li with projection m'. We singled out the spatially symmetric combination of ψ_α, ψ_β in anticipation of the limit $v(\mathbf{r}_1-\mathbf{r}_2) \to \delta^{(3)}(\mathbf{r}_1-\mathbf{r}_2)$, which we employ in practice. This forces spin $S=0$ on the final $\Lambda\Lambda$ system, so the spin recoupling is the same for the reactions (1)-(3), thus justifying our disregard of Pauli spin. For finite-range potentials, we have estimated the $S=1$ contribution to be less than a few percent.

In the calculation, we use $1p$ harmonic-oscillator nucleon wave functions $\varphi_m \sim \mathbf{r}_m \exp(-r^2/2b^2)$ with $b=1.62$ fm, and Ξ^- atomic wave functions which vary as $\Phi_{lm} \sim r^l Y_{lm}(\hat{\mathbf{r}})$ inside the nuclear radius. For a $1s$ bound Λ we take $\psi_{1s} \sim \exp(-r^2/2b^2)$ with the same b as above. For an unbound Λ, we improve the PWA by modifying the complete orthonormal set of plane waves $\{\mathbf{k}\}$ to a nonorthogonal incomplete set $\{\mathbf{k}'\}$ given in coordinate space by

$$\exp(i\mathbf{k}\cdot\mathbf{r}) - (2\pi)^{3/2}\tilde{\psi}_{1s}^*(k)\psi_{1s}(r)\,, \tag{7}$$

where $\tilde{\psi}$ is the normalized Fourier transform of ψ. This set becomes complete once the bound state ψ is added:

$$\int \frac{d^3k}{(2\pi)^3}\langle\mathbf{r}|\mathbf{k}'\rangle\langle\mathbf{k}'|\mathbf{r}'\rangle + \psi_{1s}(\mathbf{r})\psi_{1s}^*(\mathbf{r}') = \delta^{(3)}(\mathbf{r}-\mathbf{r}')\,. \tag{8}$$

Furthermore, the continuum states of $\{\mathbf{k}'\}$ are all orthogonal to the bound state ψ_{1s}. By using these continuum Λ wave functions, even though no account is taken here of the Λ-nuclear final-state interactions, one approximately avoids overcounting. That is, the rate calculated for the $\Lambda\Lambda$ continuum (3) no longer includes (as in the PWA) that for the Λ continuum reaction (2), and the rate calculated for the latter does not include that for the bound-state reaction (1). We note that by avoiding this kind of bound-state subtraction for neutrons [cf. Eq. (5)], we effectively count, in the rate for the reaction (2), the strength of the final two-body branch ${}_{\Lambda}^{6}$He$+\Lambda$ (here the neutron is bound by only 0.2 MeV). The uncertainty due to the above approximations is estimated to be less than about 40%, based on experience gained by detailed tests of these approximations in a similar calculation [11] of the yield of bound-state Σ hyperons in K^--meson capture at rest.

The partial rates for capture from Ξ^- atomic orbit nl into the final channels (1)-(3) are obtained by squaring the absolute value of the amplitudes $F_m^{(l)}$ of Eq. (4), averaging over the atomic m distribution, and integrating over the final phase space. In arbitrary units we have

$$\Gamma_1 = \frac{m_n q_n}{2\pi^2}\frac{1}{3}\sum_m |F_m^{(1)}((1s)^2;\mathbf{q}_n)|^2\,, \tag{9}$$

where $E_n = q_n^2/2m_n = 30.7$ MeV is the kinetic energy of the outgoing neutron. We recall that capture from d orbits is forbidden. Furthermore,

$$\Gamma_i^{(l)} = \int g_i^{(l)}(E)\theta(E_{\max}^{(i)} - E)dE\,, \tag{10}$$

where the shape functions $g_i^{(l)}(E)$ are given by

$$g_2^{(l)}(E_q) = \frac{m_n q}{2\pi^2}\int \frac{1}{2l+1}\sum_m |F_m^{(l)}(1s,\mathbf{k};\mathbf{q})|^2 \delta(E_k + E_q - E_{\max}^{(2)})\frac{d^3k}{(2\pi)^3}\,, \tag{11}$$

$$g_3^{(l)}(E_q) = \frac{m_n q}{2\pi^2}\int \frac{1}{2l+1}\sum_m |F_m^{(l)}(\mathbf{k}_1,\mathbf{k}_2;\mathbf{q})|^2 \delta(E_{k_1} + E_{k_2} + E_q - E_{\max}^{(3)})\frac{1}{2}\frac{d^3k_1}{(2\pi)^3}\frac{d^3k_2}{(2\pi)^3}\,. \tag{12}$$

Here, $E_k = k^2/2m_\Lambda$, $E_q = q^2/2m_n$, and the end-point energies are given by $E^{(2)}_{\max} = 24.0$ MeV and $E^{(3)}_{\max} = 21.3$ MeV. The factor $\frac{1}{2}$ in front of the integration in (12) follows from the indistinguishability of the final Λ hyperons. The differential yields dY_i/dE for the reactions (2) and (3) are plotted in Fig. 1, together with their sum dY/dE. These are given by

$$\frac{dY_i}{dE} = p_1 \frac{g_i^{(1)}(E)}{\Gamma_1 + \Gamma_2^{(1)} + \Gamma_3^{(1)}} + p_2 \frac{g_i^{(2)}(E)}{\Gamma_2^{(2)} + \Gamma_3^{(2)}}, \quad i = 2,3 , \quad (13)$$

where p_1 and p_2 are the Ξ^- capture probabilities for atomic orbits with $l = 1$ and $l = 2$, respectively, as given in Table I. The general shape of these curves is roughly similar to the neutron kinetic-energy distribution [cf. Eqs. (4) and (5)], which for harmonic-oscillator wave functions is given by

$$q \sum_m |g_m(\mathbf{q})|^2 \sim (bq)^3 \exp(-b^2 q^2) . \quad (14)$$

Also shown in the figure is the expected yield of the two-body reaction (1) for a typical neutron energy resolution of 1 MeV, assuming $p_1 = 0.2$. The calculated yields are

$$Y_1 = \frac{p_1 \Gamma_1}{\Gamma_1 + \Gamma_2^{(1)} + \Gamma_3^{(1)}} = 0.17 p_1 ,$$
$$Y_2 = 0.37, \quad Y_3 = 0.59 , \quad (15)$$

where p_1 is expected to lie in the range 0.2–0.3. Although Y_1 is not large, the neutrons from reaction (1) are well separated from the continuous neutron background due to reactions (2) and (3), and hence represent a clear signal for $\Lambda\Lambda$ hypernuclear formation.

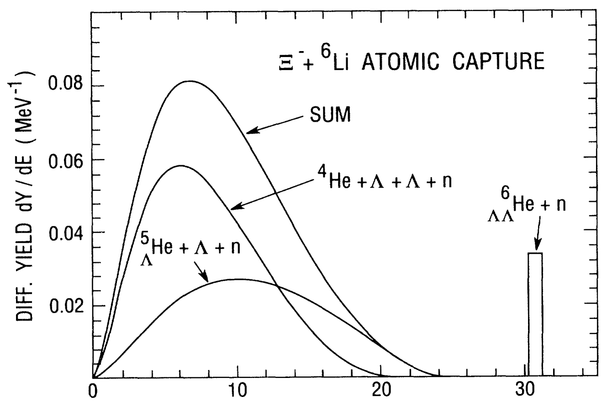

FIG. 1. Calculated differential yield dY/dE as a function of the outgoing neutron kinetic energy, for $\Xi^- + {}^6\mathrm{Li}$ capture at rest. The contributions of the reaction branches of Eqs. (2) and (3), as well as their sum, are indicated, assuming 20% p capture and 80% d capture. Assuming 1 MeV energy resolution for the neutron, the contribution of the $n + {}^{6}_{\Lambda\Lambda}\mathrm{He}$ channel is shown as a rectangle centered at 30.7 MeV; the integrated yield for this branch is about 3.4% per stopped Ξ^-.

The anticipated level diagram of ${}^{14}_{\Lambda\Lambda}\mathrm{C}$ is plotted in Fig. 2. As was mentioned in the introduction, the direct production of the $(1s_\Lambda)^2$ g.s. configuration in the two-body capture at rest,

$$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{14}_{\Lambda\Lambda}\mathrm{C} + n , \quad (16)$$

is strongly suppressed. In ${}^{14}_{\Lambda\Lambda}\mathrm{C}$, we expect some states of the $1p_\Lambda 1s_\Lambda$ configuration to be particle stable, the ${}^1P_1$ state at about 10 MeV excitation likely being the lowest lying of these. Its production, accompanied by monoenergetic neutrons of energy $E_n \simeq 31.4$ MeV (5.7 MeV higher than the end-point energy for ${}^{13}_{\Lambda}\mathrm{C} + \Lambda + n$), is allowed in Ξ^- capture from d orbits (cf. Table I). The signature of the ${}^1P_1$ state would be a fast $E1$ γ ray, $1^- \rightarrow 0^+$, to the ${}^{14}_{\Lambda\Lambda}\mathrm{C}$ g.s. We have roughly estimated the production yield of the ${}^1P$ states as 10^{-3} for the lowest one, and 4×10^{-3} in total for those based on the 2^+ ${}^{12}\mathrm{C}$ core, although it is uncertain whether all of these states are particle stable. The yields are smaller than for cap-

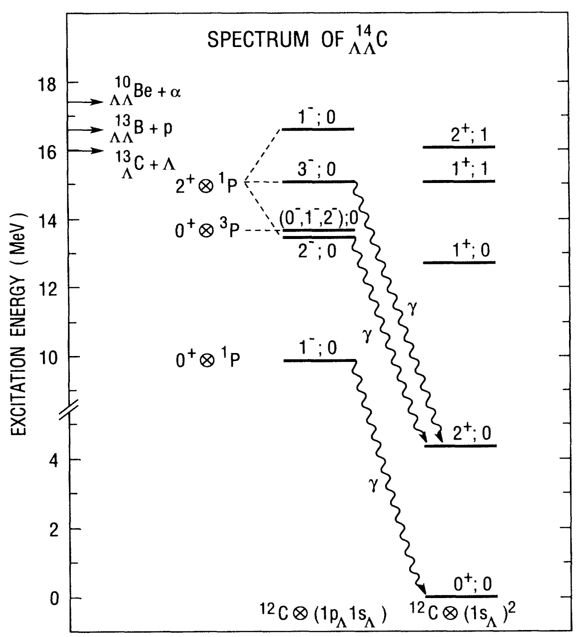

FIG. 2. The anticipated particle-stable spectrum of ${}^{14}_{\Lambda\Lambda}\mathrm{C}$. The arrows mark the lowest thresholds computed by using reported [6] binding energies B_Λ and $B_{\Lambda\Lambda}$, assuming that the value $\Delta B_{\Lambda\Lambda} = M({}^{A-2}Z) + 2m_\Lambda - M({}^{A}_{\Lambda\Lambda}Z) - 2B_\Lambda({}^{A-1}_{\Lambda}Z) = 4.3$ MeV holds for $A \geq 10$. The levels are assigned spin-parity and isospin values J^π and T. The right-hand column represents the ${}^{12}\mathrm{C} \otimes (1s_\Lambda)^2$ weak-coupling states, while the left-hand column corresponds to the ${}^{12}\mathrm{C} \otimes (1p_\Lambda 1s_\Lambda)$ configuration. The latter states are assumed to follow the ${}^{13}_{\Lambda}\mathrm{C}^* \otimes 1s_\Lambda$ weak-coupling scheme, where the ${}^{13}_{\Lambda}\mathrm{C}^*$ energies are taken from Table V of Ref. [12]. The ${}^1P$ levels will decay by $E1$ γ rays as shown. Production yield for the ${}^3P$ states is expected to be below 10^{-3}, and their location is somewhat uncertain (we assumed $\Delta B_{\Lambda\Lambda} = 0.5$ MeV for these states).

ture on ^{6}Li because the *pn* spectroscopic strength in the ^{14}N g.s. is dominated by higher ^{12}C core states. The ^3P states are not produced in the zero-range limit for the two-body capture. Their observation with a yield of order 10^{-3} would indicate the presence of a substantial tensor force component.

It is interesting to note that a substantial $1p_\Lambda 1s_\Lambda$ production yield, estimated roughly as 2×10^{-2}, is concentrated in the particle-unstable portion of the $^{14}_{\Lambda\Lambda}$C spectrum, at about 25-27 MeV excitation. These isospin $T=1$ hypernuclear states (not shown in Fig. 2), based on the 1^+; 1 (15.1 MeV) and 2^+; 1 (16.1 MeV) excitations of the ^{12}C core, will decay by emitting a proton plus $^{13}_{\Lambda\Lambda}$B. This scenario is compatible with the recent observation by Aoki *et al.* [13] of a double hypernucleus event in an emulsion experiment, and yields a $\Lambda\Lambda$ interaction energy consistent with Refs. [5,6].

For heavier target nuclei we expect particle-unstable $\Lambda\Lambda$ configurations to be directly formed in Ξ^- capture at rest. These will decay by emitting nuclear fragments, an Auger-like cascade process by which the hyperons may deexcite to particle-stable configurations in the daughter hypernuclei.

In summary, we have emphasized the merits and limitations of Ξ^- atomic capture in nuclei as a means of producing doubly strange $\Lambda\Lambda$ hypernuclei. An experiment [14] to observe $^6_{\Lambda\Lambda}$He and perhaps also $^{14}_{\Lambda\Lambda}$C appears to be feasible, using the 2-GeV/c K^- beam line available at the Brookhaven AGS. Further emulsion experiments would also be very valuable as a means of clarifying our understanding of the $\Lambda\Lambda$ interaction in a many-body system.

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