Interpretation of a double hypernucleus event

C. B. Dover and D. J. Millener
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973

A. Gal
Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel

D. H. Davis
Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom

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Arguments are put forward to suggest that a double hypernucleus event, recently reported by Aoki *et al.* as either ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$ or ${}^{13}_{\Lambda\Lambda}\mathrm{B}$, should be interpreted as ${}^{13}_{\Lambda\Lambda}\mathrm{B}$. It is proposed that the formation of ${}^{13}_{\Lambda\Lambda}\mathrm{B}$ occurs sequentially via an intermediate excited state of ${}^{14}_{\Lambda\Lambda}\mathrm{C}$, which decays by proton emission: $\Xi^- + {}^{14}\mathrm{N} \to n + {}^{14}_{\Lambda\Lambda}\mathrm{C}^*$, ${}^{14}_{\Lambda\Lambda}\mathrm{C}^* \to p + {}^{13}_{\Lambda\Lambda}\mathrm{B}$. Moreover, it is shown that particular excited states are favored in the Ξ^- hyperon capture process. The binding energy of the two Λ hyperons in ${}^{13}_{\Lambda\Lambda}\mathrm{B}$ is $B_{\Lambda\Lambda} = 27.5 \pm 0.7$ MeV, corresponding to an attractive s_Λ^2 matrix element $\Delta B_{\Lambda\Lambda} = 4.8 \pm 0.7$ MeV, in good agreement with values of $\Delta B_{\Lambda\Lambda}$ obtained from previous events.

I. INTRODUCTION

The world supply of data on doubly strange ($S=-2$) $\Lambda\Lambda$ hypernuclei is very small indeed. There is evidence from older emulsion experiments for the formation of ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ and ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$ (one event each), due to Prowse [1] and Danysz *et al.* [2], in Ξ^- capture at rest. The ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$ event has recently been reanalyzed in detail by Dalitz *et al.* [3], and the original interpretation remains sound. Recently, new experiments [4,5] have been carried out at the KEK proton synchrotron in Japan with a 1.66 GeV/c beam of K^- mesons ($S=-1$). A K^+ meson ($S=+1$) is detected in the final state, and used to tag the production of the Ξ^- hyperon ($S=-2$), which is then slowed down in emulsion and captured at rest. The elementary processes are

$$K^- + p \to K^+ + \Xi^- , \tag{1a}$$

$$\Xi^- + p \to \Lambda + \Lambda . \tag{1b}$$

The proton in process (1b) is embedded in an emulsion nucleus (${}^{12}\mathrm{C}$, ${}^{14}\mathrm{N}$, ${}^{16}\mathrm{O}$, and heavier). The event seen by Aoki *et al.* [5] is depicted in Fig. 1, and interpreted by these authors in terms of the formation and decay of ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$ or ${}^{13}_{\Lambda\Lambda}\mathrm{B}$. For the former, the reaction chain is hypothesized to be as follows (A,B,C refer to the vertices in Fig. 1):

$$\begin{aligned} &A:\ \Xi^- + {}^{12}\mathrm{C} \to {}^{3}\mathrm{H} + {}^{10}_{\Lambda\Lambda}\mathrm{Be} , \\ &B:\ {}^{10}_{\Lambda\Lambda}\mathrm{Be} \to \pi^- + {}^{10}_{\Lambda}\mathrm{B} , \\ &C:\ {}^{10}_{\Lambda}\mathrm{B} \to {}^{3}\mathrm{He} + {}^{4}\mathrm{He} + p + 2n \ \text{etc.} \end{aligned} \tag{2}$$

The binding energy $B_{\Lambda\Lambda} = M({}^{A-2}\mathrm{Z}) + 2M_\Lambda - M({}^{A}_{\Lambda\Lambda}\mathrm{Z})$ is found to be [5] 8.5 ± 0.7 MeV for the ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$ case corresponding to a contribution $\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_\Lambda = -4.9 \pm 0.7$ MeV from the $\Lambda\Lambda$ interaction in the s_Λ^2 configuration ($B_\Lambda = 6.71 \pm 0.04$ MeV is the Λ binding energy [6] in ${}^{9}_{\Lambda}\mathrm{Be}$). The minus sign implies a *repulsive* $\Lambda\Lambda$ interaction. This completely contradicts the values $B_{\Lambda\Lambda} = 17.7 \pm 0.4$ MeV and $\Delta B_{\Lambda\Lambda} = 4.3 \pm 0.4$ MeV obtained by Dalitz *et al.* [3] for ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$; in this case, the $\Lambda\Lambda$ interaction is *attractive.* Rather than summarily rejecting the ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$ event of Danysz *et al.* [2], as in Ref. [5], we strongly advocate the alternative interpretation of the event as ${}^{13}_{\Lambda\Lambda}\mathrm{B}$, and further propose that its formation is via an intermediate excited state of ${}^{14}_{\Lambda\Lambda}\mathrm{C}$. In this interpretation, the reaction sequence is

$$\begin{aligned} &A:\ \Xi^- + {}^{14}\mathrm{N} \to n + {}^{14}_{\Lambda\Lambda}\mathrm{C}^* \to n + p + {}^{13}_{\Lambda\Lambda}\mathrm{B} , \\ &B:\ {}^{13}_{\Lambda\Lambda}\mathrm{B} \to \pi^- + {}^{13}_{\Lambda}\mathrm{C} , \\ &C:\ {}^{13}_{\Lambda}\mathrm{C} \to {}^{3}\mathrm{He} + {}^{4}\mathrm{He} + {}^{4}\mathrm{He} + 2n \ \text{ or} \\ &\qquad {}^{6}\mathrm{Li} + {}^{4}\mathrm{He} + p + 2n \ \text{ etc.} \end{aligned} \tag{3}$$

Note that vertex A in this interpretation corresponds to a

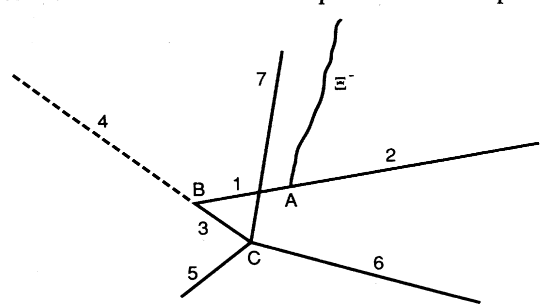

FIG. 1. A schematic drawing of the $\Lambda\Lambda$ hypernuclear event of Aoki *et al.* [5], shown from the horizontal direction. The vertices A, B, and C correspond to production via Ξ^- capture, pionic weak decay of the $\Lambda\Lambda$ hypernucleus, and nonmesonic weak decay of a Λ hypernucleus, respectively.

sequence of two-body decays, proceeding through a relatively long-lived excited state

$$ {}^{14}_{\Lambda\Lambda}\mathrm{C}^* \approx s_\Lambda p_\Lambda \otimes {}^{12}\mathrm{C}^*(T=1) \tag{4}$$

consisting of Λ's in s- and p-wave shell-model orbitals, coupled to $T=1$ states of the ^{12}C core (1^+ at 15.1 MeV, 2^+ at 16.1 MeV). The interpretation outlined in Eq. (3) gives $B_{\Lambda\Lambda}=27.5\pm0.7$ MeV for ${}^{13}_{\Lambda\Lambda}$B, corresponding to an attractive ΛΛ interaction with $\Delta B_{\Lambda\Lambda}=4.8\pm0.7$ MeV in agreement with the values extracted from previous events [1–3].

We now present the arguments supporting our interpretation. There are several aspects to the problem, which we discuss in turn. These include (1) kinematics of the observed charged particle tracks and consistency with energy-momentum conservation; (2) reaction mechanism for ΛΛ hypernuclear production from Ξ^- atoms; (3) strong decay modes of excited ΛΛ hypernuclear states; (4) nonmesonic weak decay modes; (5) arguments that the ${}^1S_0$ ΛΛ interaction is likely to be attractive.

II. KINEMATICS

Aoki *et al.* [5] have shown that any interpretation of the event depicted in Fig. 1 other than as the formation and sequential weak decay of a double hypernucleus may be discounted. An interpretation of the event in terms of the formation of a specific double hypernucleus ${}_{\Lambda\Lambda}^{A}Z$ must consistently satisfy energy and momentum conservation at the production vertex A and the mesonic decay vertex B. The emission of three charged particles at the nonmesonic decay vertex C provides little constraint other than the obvious one on the charge of the single hypernucleus ${}_{\Lambda}^{A}(Z+1)$. Aoki *et al.* give the ranges and emission angles of all charged particles involved in the event. The π^- emitted at B has an energy of 37.4 ± 0.7 MeV while the energies and momenta of the other charged particles follow once an identity for the particle making the track is assumed.

At the mesonic decay vertex B, tracks 3 and 4 are collinear. For the two-body decay ${}_{\Lambda\Lambda}^{A}Z\rightarrow\pi^-+{}_{\Lambda}^{A}(Z+1)$ to the ground state of the single hypernucleus, the mass of the double hypernucleus is

$$M({}_{\Lambda\Lambda}^{A}Z)=M({}_{\Lambda}^{A}(Z+1))+E_\pi+p_\pi^2/2M({}_{\Lambda}^{A}(Z+1)) \ . \tag{5}$$

The value of $B_{\Lambda\Lambda}$ which results is an upper limit since the single hypernucleus could have been produced in an excited state which generally results in an unobserved γ ray.

The $B_{\Lambda\Lambda}$ obtained from the mesonic decay can now be used to calculate the Q value for an hypothesized production reaction involving the capture of a Ξ^- on ^{12}C, ^{14}N, or ^{16}O. For a valid fit, the kinetic energies of the produced particles should sum to the Q value, with the proviso that the Q value is lowered if the double hypernucleus is produced in a particle-stable excited state. Candidates for the charged particle produced along with the double hypernucleus at vertex A are ^{1}H, ^{2}H, ^{3}H, ^{3}He, and ^{4}He in which case the kinetic energies associated with track 2 are 5.3, 6.9, 8.1, 18.8, and 21.0 MeV, respectively. For Ξ^- capture at rest to form a double hypernucleus and one charged particle (tracks 1 and 2 are collinear within errors), the requirement that the recoil energy of the double hypernucleus be consistent with the observed length of track 1 is very restrictive. Generally, ^{1}H and ^{2}H do not give enough recoil energy while ^{3}He and ^{4}He give too much, leaving the reaction $\Xi^-+{}^{12}\mathrm{C}\rightarrow{}^3\mathrm{H}+{}^{10}_{\Lambda\Lambda}\mathrm{Be}$ of Eq. (2) as the only possibility [5].

Other possible production reactions involve the formation of the double hypernucleus, one charged particle and a neutron. The neutron must be emitted in a direction which is close to collinear with tracks 1 and 2. The momentum of the neutron must balance the momentum of the two charged particles. For this calculation we use kinetic energies of 1.8, 2.6, and 3.4 MeV for Li-, Be-, and B-like hyperfragments, respectively. Here the error is relatively large given the short length, 3.9 ± 0.4 μm, of track 1. Then we have to ask whether the sum of the kinetic energies matches the Q value for the reaction.

From the kinematics of the mesonic decay given in Eq. (3), we obtain, using $B_\Lambda({}^{13}_{\Lambda}\mathrm{C})=11.69\pm0.12$ MeV [6], $B_{\Lambda\Lambda}({}^{13}_{\Lambda\Lambda}B)=27.5\pm0.7$ MeV (and $\Delta B_{\Lambda\Lambda}=4.8\pm0.7$ MeV) which then implies a Q value of 27.4 ± 0.7 MeV for the production reaction $\Xi^-+{}^{14}\mathrm{N}\rightarrow n+p+{}^{13}_{\Lambda\Lambda}\mathrm{B}$. From the momentum balance at vertex A with $T_p=5.28$ MeV and $T_B=3.4$ MeV, we obtain $T_n=19.7$ MeV and an energy release of $E_{\mathrm{sum}}=28.4$ MeV with a typical error of 1–2 MeV, which is close enough to the Q value to make ${}^{13}_{\Lambda\Lambda}$B a kinematically acceptable candidate for the double hypernucleus. T_n increases by 0.9 MeV for a 0.1 MeV increase in the kinetic energy of the double hypernucleus. Thus, $T_B=3.3$ MeV gives $T_n=18.8$ MeV and $E_{\mathrm{sum}}=27.4$ MeV for an exact match with the Q value.

The importance of the decay sequence implied in Eq. (3) for the production of the double hypernucleus at vertex A is that the kinetic energy of the neutron is fixed if the Ξ^- capture in ^{14}N proceeds to a definite state in ${}^{14}_{\Lambda\Lambda}$C. This state is at an excitation energy of about 24 MeV in ${}^{14}_{\Lambda\Lambda}$C, commensurate with the energy expected for the configuration shown in Eq. (4) and discussed in more detail in Sec. III. The recoiling ${}^{14}_{\Lambda\Lambda}\mathrm{C}^*$ then undergoes proton decay, analogous to the observed [7] proton decay of excited states in ${}^{12}_{\Lambda}$C, back-to-back in its own center-of-mass system. In the absence of correlations, any direction with respect to the recoil momentum is equally likely.

A final observation is that nonmesonic decays at vertex C which involve a single neutron and three charged particles cannot satisfy energy and momentum conservation; the energy of a neutron which balances the momentum of the charged particles is too small to account for a typical energy release of ~160 MeV.

III. REACTION MECHANISM

We envisage the production of the ΛΛ hypernucleus through a two-body $\Xi^-p\rightarrow\Lambda\Lambda$ process, with a short-ranged form factor dominated by K and K^* exchange. Let us assume that the Ξ^- is captured from an atomic orbit with orbital angular momentum l_Ξ, while the proton occupies an orbit l_p. For a zero-range $\Xi^-p\rightarrow\Lambda\Lambda$ transition potential, the ground state (g.s.) configuration s_Λ^2 of a

$\Lambda\Lambda$ hypernucleus can only be produced from a $\Xi^- + A$ initial state if $l_\Xi = l_p$. This selection rule [8] implies that *excited states* will be preferentially populated when a Ξ^- is captured in an emulsion nucleus. As an example, cascade calculations [8] reveal that the $l_\Xi = 2,3$ states of the $\Xi^- + {}^{14}\mathrm{N}$ atom account for almost all of the population; $l_\Xi = 1$, which could lead to the g.s. of ${}^{14}_{\Lambda\Lambda}\mathrm{C}$ via reaction $(3A)$, accounts for less than 1% for a range of Ξ^--nucleus potentials. Thus most of the $\Lambda\Lambda$ hypernuclear production rate goes into excited configurations $s_\Lambda p_\Lambda$ coupled to a ${}^{12}\mathrm{C}$ core state. Similarly, in $\Xi^- + {}^{12}\mathrm{C}$, only a small fraction corresponds to the population of $l_\Xi = 1$ states, and hence reaction $(2A)$ to the ${}^{10}_{\Lambda\Lambda}\mathrm{Be}$ g.s. is much less likely than $(3A)$, due to the action of the $l_\Xi = l_p$ selection rule.

It is also possible to give some justification for the configuration shown in Eq. (4) on the basis of nuclear structure considerations. The removal of the proton in ${}^{14}\mathrm{N}$ which interacts with the Ξ^- preferentially [9] leaves the ${}^{13}\mathrm{C}$ core in $\frac{5}{2}^-$ and $\frac{3}{2}^-$ states at 7.55 and 10.75 MeV. These states in turn have large neutron parentages to highly excited states, particularly the 15.1 and 16.1 MeV $T=1$ states, of ${}^{12}\mathrm{C}$. Another way to look at the problem is to assume that the Ξ^- interacts with a correlated *np* pair, the spectator neutron being ejected in the formation of ${}^{14}_{\Lambda\Lambda}\mathrm{C}$. The spectroscopic amplitudes for the removal of an *np* pair from ${}^{14}\mathrm{N}$ are particularly large for the two $T=1$ states of ${}^{12}\mathrm{C}$ in question [10]. This configuration, specified in Eq. (4), can be populated with an observable rate in $\Xi^- + {}^{14}\mathrm{N}$ capture from the $l_\Xi = 2$ state, which has a sizable probability [8] (50–75%), since we can satisfy the orbital selection rule $l_\Xi + l_p = l_{\Lambda_1} + l_{\Lambda_2}$, with $l_p = 1$. A rough estimate for the yield of this configuration is 1–2%. A similar rate is expected for the production of $n + p + {}^{13}_{\Lambda\Lambda}\mathrm{B}$ proceeding through $p + {}^{14}_{\Lambda\Lambda}\mathrm{B}^*$, where the ${}^{14}_{\Lambda\Lambda}\mathrm{B}^*$ intermediate configuration is the isospin analog of the ${}^{14}_{\Lambda\Lambda}\mathrm{C}^*$ configuration of Eq. (4), and decays by emitting a neutron. However, the production proton should carry about 20 MeV kinetic energy, by far exceeding the 5.3 MeV derived from the length of track 2 in Fig. 1.

IV. STRONG DECAY MODES

Our scenario $(3A)$ involves the production of a high-lying state in ${}^{14}_{\Lambda\Lambda}\mathrm{C}$, at about 24 MeV of excitation energy, as shown in Fig. 2. The thresholds open for particle decay from a state at ~ 24 MeV in ${}^{14}_{\Lambda\Lambda}\mathrm{C}$ are 16.5, 16.6, 17.3, and 20.6 MeV for Λ, p, α, and n decay ($\Delta B_{\Lambda\Lambda}$ is assumed to be the same for all nuclei and to have the value 4.8 MeV deduced from the mesonic decay of ${}^{13}_{\Lambda\Lambda}\mathrm{B}$). The key point is that the ${}^{14}_{\Lambda\Lambda}\mathrm{C}^*$ state of Eq. (4) has isospin $T=1$. Then decays into the energetically allowed strong decay channels $\Lambda + {}^{13}_{\Lambda}\mathrm{C}$ and $\alpha + {}^{10}_{\Lambda\Lambda}\mathrm{Be}$ are suppressed by isospin conservation, since the final states have $T=0$, and thus proton emission ($p + {}^{13}_{\Lambda\Lambda}\mathrm{B}$) or neutron emission ($n + {}^{13}_{\Lambda\Lambda}\mathrm{C}$) become the only options for strong decay. Since the emission of a charged particle is observed, the process $(3A)$ on the ${}^{14}\mathrm{N}$ component of the emulsion is favored because selection rules on orbital angular momentum in the primary production process and isospin conservation in the decay of ${}^{14}_{\Lambda\Lambda}\mathrm{C}^*$ are both satisfied.

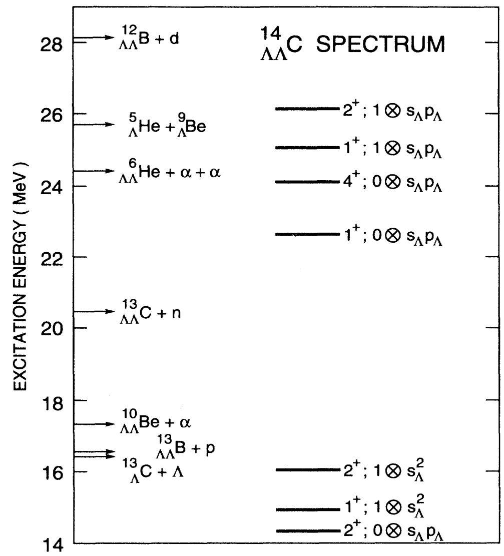

FIG. 2. Excitation spectrum and particle thresholds of ${}^{14}_{\Lambda\Lambda}\mathrm{C}$. The excitation energies of the configurations shown are simply the energies of the ${}^{12}\mathrm{C}$ core state, plus 10 MeV if one of the Λ's is in a *p* orbit. Configuration mixing is ignored and the $s_\Lambda p_\Lambda$ configuration is assumed to be a spin singlet with the same two-body energy as s_Λ^2; a spin-triplet pair must be spatially antisymmetric with a less attractive matrix element. The excitation energies of the core states are 0, 4.4, 12.7, 14.1, 15.1, and 16.1 MeV for $J^\pi;T$ equal to $0^+;0$, $2^+;0$, $1^+;0$, $4^+;0$, $1^+;1$ and $2^+;1$, respectively. The corresponding pickup spectroscopic factors for the removal of an *np* pair from the ${}^{14}\mathrm{N}$ ground state are 0.39, 1.29, 1.01, 2.44, 1.07, and 2.03 (normalized to 25 *np* pairs). Our hypothesis is that reaction $(3A)$ corresponds to the population of a state at about 24 MeV, based on some mixture of $s_\Lambda p_\Lambda$ coupled to the $1^+;1$ and $2^+;1$ states of the ${}^{12}\mathrm{C}$ core.

Similar production processes on ${}^{12}\mathrm{C}$ and ${}^{16}\mathrm{O}$, for example, $\Xi^- + {}^{12}\mathrm{C} \to n + {}^{12}_{\Lambda\Lambda}\mathrm{B}^*$ and $\Xi^- + {}^{16}\mathrm{O} \to n + {}^{16}_{\Lambda\Lambda}\mathrm{N}^*$, are expected to be followed by dominantly *p*-wave Λ emission. Here, the core nuclei ${}^{10}\mathrm{B}$ and ${}^{14}\mathrm{N}$ possess low-lying $T=1$ states for which the strong decay modes ${}^{12}_{\Lambda\Lambda}\mathrm{B}^* \to \Lambda + {}^{11}_{\Lambda}\mathrm{B}$ and ${}^{16}_{\Lambda\Lambda}\mathrm{N}^* \to \Lambda + {}^{15}_{\Lambda}\mathrm{N}$, respectively, are allowed. In contrast, the threshold for the decay ${}^{14}_{\Lambda\Lambda}\mathrm{C}^* \to \Lambda + {}^{13}_{\Lambda}\mathrm{C}(T=1)$ is very high, at about 31.5 MeV. This observation explains why ${}^{14}\mathrm{N}$, in spite of its rather small abundance in emulsion, provides a favorable target nucleus in the search for $\Lambda\Lambda$ hypernuclei.

V. HYPERNUCLEAR WEAK DECAY

In Fig. 1, the vertex *B* corresponds to the emission of a rather energetic pion. Thus the resulting single Λ hypernucleus is likely to be produced in its ground state, although the production of a low-lying excited state, followed by γ emission to the ground state, is not excluded. The most important fact regarding the nonmesonic weak decay is that three charged particles are produced. Although there is not enough information to make definitive statements about the weak decay process at vertex C in Fig. 1 and the nature of the process is not relevant to our interpretation of the double hypernucleus event, we find it interesting to speculate on the mechanism of the nonmesonic weak decay. We noted at the end of Sec. II that energy and momentum conservation cannot be satisfied at vertex C in processes which involve the emission of a single neutron. Our hypothesis is that, starting from ${}^{13}_{\Lambda}$C(g.s.)$=s_\Lambda \otimes {}^{12}$C(g.s.), the $\Lambda n \to nn$ weak process occurs on an s-shell neutron, leading to two neutrons in the final state, followed by ^{11}C* decay into three charged particles (^{3}He$+^4$He$+^4$He). The broad distribution of strength for the removal of an s-shell neutron from ^{12}C is centered [11] around 21 MeV in ^{11}C* and the threshold for $\alpha+\alpha+{}^3$He is at 9.1 MeV (the next threshold for three charged particles is for ^{6}Li$+\alpha+p$ at 13.1 MeV). Rough estimates, depending somewhat on the assignments for the three charged particles, for the center-of-mass kinetic energy of the recoiling ^{11}C* put the excitation energy of the decaying state at about 27 MeV for breakup into either $\alpha+\alpha+{}^3$He or ^{6}Li$+\alpha+p$. Note that the decay ^{11}C*$\to{}^3$He$+^3$He$+^4$He$+n$ is suppressed, since the energy required to break up ^{4}He into $n+{}^3$He is not available. The alternative decay mechanism $\Lambda(1s)+n(1p)\to n+n$ would give, in the absence of final-state interactions, only one track corresponding to bound states of ^{11}C, contrary to observation.

VI. ATTRACTIVE $\Lambda\Lambda$ INTERACTION IN $^1S_0$ STATE

A problem with the interpretation of Aoki *et al.* [5] [Eq. (2)] is that the resultant $\Lambda\Lambda$ interaction must be *strongly repulsive.* This is theoretically unacceptable, as we now indicate. Our alternative interpretation in Eq. (3) leads to a $\Lambda\Lambda$ interaction matrix element which is attractive, and in agreement with that extracted by Danysz *et al.* [2] for ${}^{10}_{\Lambda\Lambda}$Be.

First consider the medium and longer range parts of the $\Lambda\Lambda\to\Lambda\Lambda$ interaction, due to isoscalar meson exchange (scalar 0^+ mesons ϵ and S^*, pseudoscalar 0^- mesons η and η', and vector 1^- mesons ω and ϕ). The $\Lambda\Lambda$ meson-exchange potential is of the form [12–14]

$$V_{\Lambda\Lambda}(r)=V_c(r)+V_\sigma(r)\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 \ . \tag{6}$$

The nonzero components are

$$\begin{aligned} V^{\eta}_{\sigma}&=\frac{g^2_{\Lambda\Lambda\eta}}{4\pi}\frac{\mu^3_\eta}{12M^2_\Lambda}\phi(x_\eta)\ ,\\ V^{\epsilon}_{c}&=-\frac{g^2_{\Lambda\Lambda\epsilon}}{4\pi}\mu_\epsilon\phi(x_\epsilon)\ , \end{aligned}\tag{7}$$

for pseudoscalar and scalar exchange, and

$$\begin{aligned} V^{\omega}_{c}&=\frac{g^2_{\Lambda\Lambda\omega}}{4\pi}\mu_\omega\phi(x_\omega)\left[1+\left[\frac{f}{g}\right]_{\Lambda\Lambda\omega}\frac{\mu^2_\omega}{4M_NM_\Lambda}\right]^2 ,\\ V^{\omega}_{\sigma}&=\frac{g^2_{\Lambda\Lambda\omega}}{4\pi}\frac{\mu^3_\omega}{6M^2_\Lambda}\phi(x_\omega)\left[1+\left[\frac{f}{g}\right]_{\Lambda\Lambda\omega}\frac{M_\Lambda}{M_N}\right]^2 , \end{aligned}\tag{8}$$

for vector exchange, with the same forms for η', S^*, and ϕ exchange. In these equations, we have neglected some small recoil terms in the expressions given by Nagels *et al.* [12,13]. Spin-orbit and tensor terms are not considered, since they vanish in the $^1S_0$ state. Meson and baryon masses are denoted by μ and M, respectively, and $\phi(x)=\exp(-x)/x$, with $x=\mu r$. The coupling constants g and f in Eqs. (7) and (8) are related by SU(3) symmetry to those determined by Nagels *et al.* [12,13] from a fit to NN, ΛN, and ΣN scattering data.

Several points are worthy of note: The pseudoscalar and scalar $\Lambda\Lambda$ potentials are always attractive in the $^1S_0$ state, for any choice of coupling constants, while the vector exchange contributions $V^{\omega,\phi}_c-3V^{\omega,\phi}_\sigma$ involve a cancellation of central repulsion and spin-dependent attraction. For model D, each meson contribution is separately attractive, while for model F, all mesons give attraction except for the ω. In the latter case, the sizable negative value of $(f/g)_{\Lambda\Lambda\omega}$ reduces V^ω_σ considerably and the central repulsion V^ω_c dominates. However, for both models, the total $\Lambda\Lambda\to\Lambda\Lambda$ diagonal potential in the $^1S_0$ state is *attractive.*

The meson-exchange model is relevant for the medium- and long-range part of the $\Lambda\Lambda$ potential, say, $r\gtrsim 0.5-0.7$ fm. In the NN, ΛN, and ΣN systems, the Nijmegen models [12,13] employ phenomenological hard cores at short distances. There have been several attempts [15–17] to calculate $\Delta B_{\Lambda\Lambda}$ using a $\Lambda\Lambda$ effective interaction (G matrix) derived from models D and F. Fairly strong attraction is obtained for model D and weak repulsion for model F; neither model can obtain the strong $\Lambda\Lambda$ repulsion suggested by Aoki *et al.* [5] for ${}^{10}_{\Lambda\Lambda}$Be. A number of three- and four-body cluster calculations have been performed for ${}^{6}_{\Lambda\Lambda}$He and ${}^{10}_{\Lambda\Lambda}$Be, in which the sensitivity of the hypernuclear binding energy to the form of the $\Lambda\Lambda$ interaction is explored; see, for example, Ref. [18]. In these purely phenomenological treatments, an attractive $\Lambda\Lambda$ interaction is assumed, as indicated by the events of Refs. [1,2].

The simple hard-core prescription employed in models D and F for the short-range $\Lambda\Lambda$ interaction cannot be justified. At the microscopic level, the short-range baryon-baryon interaction arises from a delicate interplay of quark-gluon exchange (OGE) and the requirements of quark antisymmetrization [19]. For strangeness $S=-1,-2$ dibaryon systems, the short-range interaction at the quark level has been studied by several authors [20–23]. For $S=-1$, short-range repulsion is found in the equivalent local hyperon-nucleon potentials, but the effective core radius is quite strongly dependent on the spin-isospin quantum numbers. Thus the notion of a channel independent core radius, as adopted in model F, is not supportable.

For the $S=-2$ dibaryon interaction in the $^1S_0$ channel, the situation in the quark model is somewhat special. Jaffe [24] first speculated that there could be a bound state, the H dibaryon, in this channel. In the flavor-SU(3) symmetry limit, the H corresponds to the unitary singlet combination of $\Lambda\Lambda$, $\Sigma\Sigma$, and ΞN configurations. Hybrid models, where medium- and long-range pseudoscalar and scalar meson-exchange potentials are grafted onto the short-range OGE interaction [21,22], find such a bound state below $2M_\Lambda$, whereas if nonperturbative instanton effects are included [23], the bound state disappears. However, whether a bound state exists or not, a strong mixing of the $\Lambda\Lambda$, $\Sigma\Sigma$, and ΞN channels is established at short distances. Thus, although the single channel $\Lambda\Lambda\rightarrow\Lambda\Lambda$ phase shift due to the OGE interaction is repulsive, the effect of channel coupling is strong, and leads to a net attraction (this can be seen in Fig. 4 of Ref. [20], Fig. 1 of Ref. [21], and Fig. 4 of Ref. [22], for instance).

Our conclusion is the following: The meson-exchange potential for $\Lambda\Lambda\rightarrow\Lambda\Lambda$ in the $^1S_0$ channel is attractive in any reasonable model, and we do not expect strong short distance repulsion due to quark-gluon exchange in this channel. Hence $\Delta B_{\Lambda\Lambda}$ is very likely to be positive, corresponding to an attractive $\Lambda\Lambda$ interaction energy.

VII. SUMMARY

We have presented arguments which support our interpretation (3) of the $\Lambda\Lambda$ hypernucleus event observed by Aoki *et al.* [5]. Although the alternative (2) satisfies the kinematical constraints of energy-momentum conservation, the binding energy $B_{\Lambda\Lambda}$ for an interpretation as $^{10}_{\Lambda\Lambda}$Be disagrees violently with that obtained by Danysz *et al.* [2]. On theoretical grounds, we have argued that $(2A)$ is much less likely than $(3A)$ in terms of reaction mechanism, and that (2) requires $\Delta B_{\Lambda\Lambda}<0$, which contradicts any reasonable model of the $\Lambda\Lambda$ interaction. Clearly more experimental data on double Λ hypernuclei are required before any more quantitative statements can be made on the spin dependence of the $\Lambda\Lambda$ interaction, the implications for the existence of the $S=-2$ six quark H dibaryon [24], and the breaking of SU(3) symmetry in baryon-baryon interactions [25]. Further experiments with energetic K^- beams should be pursued at the KEK facility in Japan and/or the Brookhaven Alternating Gradient Synchrotron.

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