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SOME POSSIBILITIES FOR UNUSUAL LIGHT HYPERNUCLEI*

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ABSTRACT

Some possibilities are considered concerning the stability, formation, and identification of Λ -hypernuclei corresponding to core nuclei (generally with $I \geq 3/2$) away from the stability valley. The identification of such hypernuclei may be rather informative concerning the existence and properties of such little-known nuclei. For neutron-rich species, e.g. $\Lambda^6\text{H}$, $\Lambda^8\text{He}$, etc., the possible confusions of their major decay modes with (and their separation from) similar well-established modes of more abundant hypernuclei are discussed. The expectation that narrow resonance levels (with lifetimes $\geq 10^{-21}$ sec) should exist for certain hypernuclear systems (e.g. the $p - \Lambda^4\text{He}$ system) is also mentioned briefly, since the production and observation of such resonance states could be achieved with existing techniques.

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I. INTRODUCTION

In this note, we wish to point out that there are a number of Λ -hypernuclear species which are likely to be particle-stable but which are not usually considered as possible interpretations in the analysis of observed hypernuclear decay events. Although these species are not expected to be abundant, their existence may well account for some hypernuclear events whose identification has appeared quite certain but whose B_Λ values have disagreed rather strongly with the established values.

This note is prompted by the observation of the species ${}_\Lambda\text{Be}^7$ by several groups [1,2]. The core nucleus Be^6 has no particle-stable state, its lowest level Be^{6*} being 1.4 MeV above $\text{He}^4 + 2p$. The B_Λ value for ${}_\Lambda\text{Be}^7$ is (4.9 ± 0.5) MeV, relative to Be^{6*} ; this means that it is stable with respect to ${}_\Lambda\text{He}^5 + 2p$ by (0.4 ± 0.5) MeV. Such a hypernucleus is best thought of as consisting of a ${}_\Lambda\text{He}^5$ core, to which two protons are loosely bound. Although the two protons do not bind to He^4 , the additional attraction provided by their interaction with the Λ particle in ${}_\Lambda\text{He}^5$ leads to a bound state for the ${}_\Lambda\text{Be}^7$ system. The additional binding energy obtained in this way is, therefore, (0.9 ± 0.2) MeV per p-shell nucleon in ${}_\Lambda\text{Be}^7$; the two protons have zero total spin, so that this value corresponds to the spin average for the ΛN interaction.

Lawson and Rotenberg [3] and Iwao [4] have independently proposed the following expression for the B_{Λ} values for hypernuclei in the nuclear 1p-shell:

$$B_{\Lambda} = C + N_p \langle \bar{V} \rangle + \alpha_N \langle \Delta \rangle , \quad (1.1)$$

where $\langle \bar{V} \rangle$ denotes a mean expectation value for the spin-average interaction $(3V_t + V_s)/4$, and $\langle \Delta \rangle$ the mean expectation value for the spin-dependent interaction $(V_s - V_t)$, between a p-shell proton and a bound Λ particle. Here N_p denotes the number of p-shell nucleons and α_N is a coefficient whose value depends on the coupling scheme appropriate to the nuclear core. This expression (1.1) provides an adequate fit to the B_{Λ} data available for these hypernuclei: the values which have been obtained for these parameters [5] are $C = (3.0 \pm 1.0) \text{ MeV}$, $\langle \bar{V} \rangle = (0.90 \pm 0.03) \text{ MeV}$, and $\langle \Delta \rangle = (1.75 \pm 0.3) \text{ MeV}$. We note that the additional binding energy per p-shell nucleon observed in ${}_{\Lambda}\text{Be}^7$ agrees well with this mean value $\langle \bar{V} \rangle$. As pointed out in reference[5], this value $\langle \bar{V} \rangle$ also agrees with the value predicted from a direct calculation based on the ΛN potentials deduced from the binding energy data for the s-shell hypernuclei.

The identification and measurement of other such hypernuclei, corresponding to core nuclei which are unbound or weakly bound, would be of considerable interest in nuclear physics. These nuclei are generally well off the stability line and are often difficult to form and to identify through

the reaction processes most conveniently available to nuclear physicists, so that rather little is generally known about their properties. For proton-rich hypernuclei such as ${}_{\Lambda}\text{Be}^7$, there are generally possible a number of uniquely identifiable decay modes; for example,

For neutron-rich hypernuclei, on the other hand, many of the decay modes possible are readily confused with the decay modes of established hypernuclei and such misinterpretations may contribute appreciably to the straggling in the B_{Λ} distributions observed for some of the light hypernuclei.

Most of the hypernuclei to be discussed here have quite low binding for the last nucleon, and it may be thought that the formation of such hypernuclei would have low probability. Although there will certainly be an effect in this direction, experience has shown that some loosely-bound systems are formed quite frequently in elementary particle reaction processes. For ${}_{\Lambda}\text{Be}^7$, the π^- decay mode (1.2) is quite strongly suppressed by the restrictions of the Pauli principle for the final protons; the dominant decay processes will be the non-mesic modes (probably by a factor 5-10). The observation of two events of the type (1.2) suggests that the formation rate for ${}_{\Lambda}\text{Be}^7$ in K^- interactions in emulsion is quite appreciable. Similarly, the hypernucleus ${}_{\Lambda}\text{H}^3$ is rather well known, despite its low Λ -d separation energy, $B_{\Lambda} = (0.31 \pm 0.15) \text{ MeV}$. It is therefore

reasonable to expect that particle-stable hypernuclei of low binding may generally be produced at a non-negligible rate in the reaction processes which lead to hyperfragment production.

II. SOME Λ -HYPERNUCLEAR SPECIES OF POSSIBLE INTEREST

The lightest systems of possible interest here are the $I = 1$ systems ${}_{\Lambda}n^3$ and ${}_{\Lambda}\text{He}^3$. The possibility of such systems has been discussed extensively in the literature [6] in terms of our knowledge of the NN and AN potentials, with the conclusion that there is no good reason to expect the existence of any particle-stable state for these systems. No clear experimental evidence indicating their existence has yet been reported.

$A = 5$. Argan et al. [7] have recently found evidence for a sharp resonance ($\Gamma \leq 1$ MeV) in the $n\text{-H}^3$ system at c.m. kinetic energy 4.5 MeV. They have pointed out that this narrow width is difficult to understand unless this H^{4*} state has isotopic spin $I = 2$, in which case there is expected to occur a corresponding state with 4 MeV binding energy in the n^4 system. In this case, a stable system ${}_{\Lambda}n^5$ will certainly be expected to exist. The net Λ -nuclear attraction in this system is not less than that for ${}_{\Lambda}\text{He}^5$; however, the spatial distribution of this potential is not known, so that it is difficult to estimate B_{Λ} accurately. It is a reasonable estimate that B_{Λ} should not be less than 2 MeV for ${}_{\Lambda}n^5$. This system could be formed and identified in reactions of the type

This object Λ^n^5 could not have been produced in the studies of Λ decay in hydrogen or helium bubble chambers. It could be produced in a lithium target inserted in a hydrogen chamber, or directly in a propane chamber and detected as an anomalous Λ decay, with typical modes

The other components of the $I = 2$ state corresponding to Λ^n^5 will not be particle-stable. Λ^{H^5} will not be stable relative to $\Lambda^{\text{H}^4} + n$, nor $I = 2$ $\Lambda^{\text{He}^5^*}$ stable relative to $\Lambda^{\text{He}^4} + n$ and $\Lambda^{\text{H}^4} + p$. These decay processes violate charge-independence and will have correspondingly slow rates, just as the decay $\text{H}^{4*} \rightarrow n + \text{H}^3$ is observed to have a narrow width ($\Gamma \leq 1$ MeV). The $I = 2$ $\Lambda^{\text{He}^5^*}$ state may therefore be expected to appear as a narrow resonance for the $p - \Lambda^{\text{H}^4}$ and $n - \Lambda^{\text{He}^4}$ systems, for example. Such a resonance state may be studied by investigating the Q-value distribution for $p - \Lambda^{\text{H}^4}$ systems in hyperfragment production reactions, for example in the reaction

or more complicated reaction processes. The study of these Q-value distributions is not, of course, confined to reaction processes which can be completely analyzed and identified.

It is natural to inquire also whether an $I = 1$ Λ^5 state might also exist. There is at present no evidence for an $I = 1$ H^{4*} resonant state (which would be broad, since the decay $n + H^3$ is now allowed), or for any bound H^4 state, although it would appear rather surprising if there were not such an $I = 1$ state lying below the $I = 2$ state mentioned above. If such an $A = 4$ nuclear state does exist, it would then be quite conceivable that a corresponding Λ^5 should exist, describable essentially as a p-wave neutron loosely bound to Λ^4 . If such a system exists, it could be produced in Li^6 -loaded emulsion through the reaction

and identified through the decay process

This system would also have the decay modes $(\pi^- + He^4 + \bar{n})$, with $Q_0 = 57.39 \text{ MeV} - B_n$, which could readily be confused with $\Lambda^4 \rightarrow \pi^- + He^4$ decay and $(\pi^- + He^3 + 2n)$, with $Q_0 = 35.81 \text{ MeV} - B_n$, which could contaminate the $\Lambda^4 \rightarrow \pi^- + n + He^3$ decay events.

In view of the likelihood that Λ^5 exists with total binding energy about 6 MeV, it is natural to consider the possibility that Λ^4 may also have a particle-stable state. Although

Λn^3 does not have a bound state, this system certainly provides considerable attraction for a p-wave neutron, although it is not at all clear without considerable calculation whether this attraction is sufficient for the formation of a bound state Λn^4 . This possibility might be sought in the helium bubble chamber reactions:

A = 6. Strong experimental evidence for the existence of particle-stable H^5 has recently been reported by Nefkens [8]. The probable existence of this nucleus had previously been pointed out on theoretical grounds by Blanchard and Winter [9] and by Ajzenberg-Selove and Lauritsen [10], with an estimate of - 0.35 MeV for its energy relative to $H^3 + 2n$. It is therefore natural to expect the system $(\Lambda H^4 + 2n) = \Lambda H^6$ to be bound in an $I = 3/2$ state, with B_Λ value of about 4.2 MeV. This estimate corresponds to the value $B_\Lambda = 2.4$ MeV for ΛH^4 , with an additional 1.8 MeV estimated as above for the additional attraction exerted on the two neutrons by the Λ particle. This hyper-nucleus could conveniently be formed in Li^6 - or Li^7 - loaded emulsion, through the reactions

as well as in many other more complicated reactions.

The decay process

$$\Lambda^H{}^6 \rightarrow \pi^- + \text{He}^6, \quad Q_0 = 58.33 \text{ MeV} - B_{2n} \quad (2.8)$$

has appearance similar to the two-body mode for $\Lambda^H{}^4$, except that there is a shorter ($5.4 \mu\text{m}$), β -active recoil in the present case. The β -decay of He^6 has however not been detected in emulsion for several recoils resulting from $\Lambda^H{}^7 \rightarrow \pi^- + p + \text{He}^6$. Amongst an abundant sample of $\Lambda^H{}^4$, reaction (2.8) could be readily over-looked in favor of the $\Lambda^H{}^4$ interpretation. Since such misinterpretation would lead to a B_Λ value significantly higher than appropriate to $\Lambda^H{}^4$, $\Lambda^H{}^6$ events could probably be identified by careful examination of the recoil track for those events classed as $\Lambda^H{}^4$ but giving a high B_Λ value. The other identifiable decay modes are

$$\Lambda^H{}^6 \rightarrow \pi^- + p + \text{H}^5, \quad (2.9)$$

for which the recoil β^- has a spectrum whose maximum is not less than 15 MeV, and

$$\Lambda^H{}^6 \rightarrow \pi^- + \text{H}^3 + \text{H}^3, \quad Q_0 = 46.06 \text{ MeV} - B_{2n}. \quad (2.10)$$

The other decay processes involve neutrons, for example

$$\Lambda^H{}^6 \rightarrow \pi^- + \text{He}^4 + 2n, \quad Q_0 = 57.39 \text{ MeV} - B_{2n}, \quad (2.11a)$$

$$\rightarrow \pi^- + \text{He}^3 + 3n, \quad Q_0 = 36.81 \text{ MeV} - B_{2n}, \quad (2.11b)$$

and would generally have been included as a contaminant among the decay modes $(\pi^- + \text{He}^4)$ and $(\pi^- + \text{He}^3 + n)$, respectively, of ΛH^4 . We note also that the non-mesic decay process

can lead to H^3 momenta much higher than the momentum for the identified process $\Lambda\text{H}^4 \rightarrow \text{H}^3 + n$.

The corresponding $I = 3/2$ state ΛHe^6 has a high excitation energy (of order 20 MeV) relative to $\Lambda\text{He}^5 + n$; although forbidden by charge-independence, this decay will be rapid on the nuclear time scale (i.e. lifetime width of order 1 MeV or more). The stability of the $I = 1/2$ state of ΛHe^6 has frequently been considered in the literature [5,11,12] with conflicting conclusions; its existence has not yet been established experimentally. The $p_{3/2}$ level of He^5 is at +0.96 MeV for $n + \text{He}^4$; the question is whether the addition of a Λ particle to give a ΛHe^5 core provides sufficient attraction to bind a $p_{3/2}$ neutron. The simplest possible estimate, based on the calculation of the expectation value of the ΛN potential between the Λ particle of ΛHe^5 and a lightly bound neutron* in a p-orbit relative to He^4 , suggests that ΛHe^6 may form a bound state. An alternative

* We note here that, since the p-wavefunction for a lightly bound neutron has asymptotic radial form $\exp(-r\sqrt{2\mu B_n})/r^2$, this expectation value is convergent in the limit $B_n \rightarrow 0$ and is therefore not sensitive to the value of B_n if B_n is small.

argument makes appeal to the fact that B_{Λ} for ${}_{\Lambda}\text{Be}^7$ indicates that the additional Λ -binding energy per p-shell nucleon is about 0.9 in this system. This additional binding energy is already almost sufficient to ensure the stable binding of a p-shell neutron to ${}_{\Lambda}\text{He}^5$. This estimate refers only to the spin-independent attraction; for the $J = 1$ state of a $p_{3/2}$ neutron and $s_{1/2}$ Λ -particle, there is an additional spin-dependent attraction of amount $5/12 \langle \Delta \rangle \approx 0.75$ MeV expected, from which the prediction of particle-stable ${}_{\Lambda}\text{He}^6$ follows. More detailed calculations on the binding of $I = 1/2$ ${}_{\Lambda}\text{He}^6$ are rather desirable.

The decay mode ${}_{\Lambda}\text{He}^6 \rightarrow \pi^- + \text{Li}^6$ ($Q_0 = 42.23$ MeV) could be readily confused with the known decay process ${}_{\Lambda}\text{Li}^7 \rightarrow \pi^- + \text{Be}^7$. Two identifiable modes for ${}_{\Lambda}\text{He}^6$ decay are

$${}_{\Lambda}\text{He}^6 \rightarrow \pi^- + d + \text{He}^4, \quad Q_0 = 40.76 \text{ MeV}, \quad (2.13a)$$

$$\rightarrow \pi^- + \text{H}^3 + \text{He}^3, \quad Q_0 = 26.44 \text{ MeV}, \quad (2.13b)$$

but no examples have been clearly established.

If ${}_{\Lambda}\text{He}^6$ (and therefore also its mirror system ${}_{\Lambda}\text{Li}^6$) is not particle-stable, there is still to be expected a p-wave $n - {}_{\Lambda}\text{He}^5$ (and $p - {}_{\Lambda}\text{He}^5$) resonance at a low c.m. kinetic energy (less than 1 MeV). This resonance level would be quite sharp (as is the case for the $\bar{n} - \text{He}^4$ $p_{3/2}$ resonance) and could be sought by the study of the Q -value distribution for $p - {}_{\Lambda}\text{He}^5$ systems in ${}_{\Lambda}\text{He}^5$ production processes, for example

$$K^- + Li^6 \rightarrow \pi^- + (p + {}_{\Lambda}He^5). \quad (2.14)$$

A = 8. The stability of the nucleus He^7 has been discussed by Balashov [13]. Following Peaslee and Telegdi [14], Balashov identifies the 10.8 MeV level of Li^{7*} as its lowest $I = 3/2$ level, partly on theoretical grounds and partly from the absence of the $Li^7 (\gamma, H^3) He^4$ reaction at this energy (the reaction $Li^7 (\gamma, n)$ allowed for an $I = 3/2$ resonant state is observed). After allowance for the Coulomb energy, this identification corresponds to a ground-state He^7 stable by about 0.3 MeV relative to $He^6 + n$. If this identification is correct, ${}_{\Lambda}He^8$ will certainly exist. The additional binding energy expected for the last neutron due to the Λ particle is $(\bar{V} + 5/12 < \Delta >) \approx 1.6$ MeV, so that ${}_{\Lambda}He^8$ may then be expected to have $B_{\Lambda} \approx 6.5$ MeV and to be quite stable (by ≈ 2 MeV) relative to ${}_{\Lambda}He^7 + n$.

The two-body decay mode

$${}_{\Lambda}He^8 \rightarrow \pi^- + Li^8, \quad Q_0 = 49.61 \text{ MeV} - B_n \quad (2.15)$$

would have a rather distinctive appearance. However, the β^- particle from Li^8 decay could easily be overlooked, in which case the decay could be misinterpreted as due to

$${}_{\Lambda}Li^9 \rightarrow \pi^- + Be^{9*} \rightarrow \pi^- + n + 2He^4. \quad (2.16)$$

There are two other identifiable modes expected,

$${}_{\Lambda}He^8 \rightarrow \pi^- + H^2 + He^6, \quad Q_0 = 40.80 \text{ MeV} - B_n, \quad (2.17a)$$

$$\rightarrow \pi^- + H^2 + 2H^3, \quad Q_0 = 27.53 \text{ MeV} - B_n, \quad (2.17b)$$

while the decay

$$\Lambda \text{He}^8 \rightarrow \pi^- + n + \text{Li}^7, \quad Q_0 = 47.58 \text{ MeV} - B_n, \quad (2.17c)$$

could be confused with $\Lambda \text{He}^7 \rightarrow \pi^- + \text{Li}^7$.

A = 9. The $I = 1$ nucleus B^8 is particle-stable by 0.13 MeV relative to $p + \text{Be}^7$. Hence the hypernucleus ΛB^9 must necessarily exist, and is expected to have essentially the same B_Λ value as the mirror hypernucleus ΛLi^9 , namely 8.0 MeV. ΛB^9 is then stable by about 1.8 MeV relative to $p + \text{Be}^8$. The identification of ΛB^9 should be especially straightforward. If C^9 is particle-stable (as appears probable [10]), the two-body decay mode will follow the sequence

$$\Lambda \text{B}^9 \rightarrow \pi^- + \text{C}^9, \quad (Q_0 = 37.88 \text{ MeV}), \quad \text{C}^9 \rightarrow e^+ + \nu + p + 2\text{He}^4 \quad (2.18)$$

The three-body decay mode

$$\Lambda \text{B}^9 \rightarrow \pi^- + p + \text{B}^8, \quad \text{B}^8 \rightarrow e^+ + \nu + 2\text{He}^4 \quad (2.19)$$

is difficult to distinguish from $\Lambda \text{Li}^9 \rightarrow \pi^- + p + \text{Li}^8$, followed by Li^8 beta-decay, especially as charge symmetry requires the same B_Λ values for ΛB^9 and ΛLi^9 . Other ΛB^9 decay modes such as

$$\Lambda \text{B}^9 \rightarrow \pi^- + p + p + \text{Be}^7, \quad Q_0 = 37.29 \text{ MeV}. \quad (2.20a)$$

$$\rightarrow \pi^- + p + p + \text{He}^3 + \text{He}^4, \quad Q_0 = 35.50 \text{ MeV}. \quad (2.20b)$$

will be readily identifiable.

The lowest $I = 1$ level of ${}_{\Lambda}\text{Be}^{9*}$ forms a charge triplet with the ground states of ${}_{\Lambda}\text{B}^9$ and ${}_{\Lambda}\text{Li}^9$. This level has spin $J = 3/2 +$ and is unstable relative to the system $(\text{He}^4 + {}_{\Lambda}\text{He}^5)$ by 12.0 MeV. However, the disintegration

$$\text{Be}^{9*} (I = 1) \rightarrow \text{He}^4 + {}_{\Lambda}\text{He}^5 \quad (2.21)$$

is forbidden by the property of charge symmetry for strong interactions. The situation is quite similar to that for the $I = 1, J = 2+$ level of Be^{8*} at 16.9 MeV, which corresponds to the ground state of Li^8 . The decay of this Be^{8*} level to $(\text{He}^4 + \text{He}^4)$ is allowed by all of the conservation laws except that associated with charge symmetry. The violations of charge symmetry for nuclear interactions due to the electromagnetic couplings do permit the decay $\text{Be}^{8*} (I = 1) \rightarrow \text{He}^4 + \text{He}^4$ to take place at a correspondingly reduced rate, for the width observed for this Be^{8*} level is 0.12 MeV (to be compared with the width $\Gamma = 1.0$ MeV observed for the $I = 0, J = 2+$ level of Be^{8*} at 2.9 MeV, a much lower excitation energy). It is therefore reasonable to expect a similar inhibition for the decay process $\nearrow$ (2.21) for the lowest $I = 1$ level of ${}_{\Lambda}\text{Be}^{9*}$, so

$\nearrow$ As for the corresponding case of $I = 1 \text{ Be}^{8*}$, γ -emission provides the only competing decay process for this level.

that this state will be quite long-lived ($\tau \geq 10^{-20}$ sec.) and can generally escape before decay from a nuclear process in

which it is formed. It would therefore be of interest to study the Q-value distribution for $(\text{He}^4, \Lambda\text{He}^5)$ systems emitted in K^- or Σ^- interactions in emulsion, in order to establish the existence of a sharp resonance in this system corresponding to this level of ΛBe^{9*} . It should be mentioned here that several such long-lived $I = 1$ levels may be expected to exist for ΛBe^{9*} . Since $B_\Lambda = 6.5$ MeV for ΛLi^8 compared with $B_\Lambda = 8.0$ MeV for ΛLi^9 , the threshold $p + \Lambda\text{Li}^8$ lies 2.0 MeV above the lowest $I = 1$ level ΛBe^{9*} ; in consequence, the second $I = 1$ level ΛBe^{9*} corresponding to the second $I = 1$ level of Be^{8*} (and possibly higher $I = 1$ ΛBe^{9*} levels) will also be particle-stable, except for the inhibited decay to $(\text{He}^4 + \Lambda\text{He}^5)$.

At present, rather little is known concerning the stability of the $I = 2$ nucleus He^8 , or of the location of the first $I = 2$ level of Li^{8*} . If we denote by E^* the excitation energy of this $I = 2$ level of Li^{8*} (or Be^{8*}) relative to that of the first $I = 1$ level, then the energy of He^8 relative to $\text{He}^6 + 2n$ is given by $(E^* - 13.0)$ MeV, allowing 1.0 MeV for the Coulomb energy difference between corresponding He and Li states. Kurath [15] has estimated E^* using intermediate coupling for the configuration $(p)^4$, with parameters adjusted to fit the observed location of the $I = 1$ levels of Be^{8*} , giving the result $E^* \approx 13$ MeV; this estimate would probably be lowered to $E^* \approx 9$ -10 MeV by the inclusion of the s^2p^2 , sp^2d and p^2d^2 configurations. A simple-minded estimate in agreement with this result may also be obtained from the alpha-particle model of Be^8 . The lowest $I = 1$ level of Be^8 corresponds to the excitation of

one alpha-particle to an $I = 1$ state; the lowest $I = 1$ He^4_* state corresponds to threshold 20 MeV, whereas the observed $I = 1$ Be^{8*} level is at 17 MeV. The lowest $I = 2$ level of Be^8 is similarly reached most favorably by the excitation of one alpha-particle to its lowest $I = 2$ state. If the bound state n^4 exists at - 4.0 MeV (see above), this excitation requires 25.5 MeV (after allowance for Coulomb energy difference) and suggests $E^* < 8.5$ MeV; if not, the least excitation is 28.0 leading to a rather pessimistic estimate $E^* \leq 11$ MeV. In other words, if the $I = 2$ bound state n^4 does not exist, it appears quite reasonable to expect a particle-stable state for He^8 . If the n^4 bound state does exist, the condition on E^* is more severe; stability of He^8 relative to $(\text{He}^4 + n^4)$ requires $E^* < 9.0$ MeV, a possibility which is by no means excluded. The B_Λ value expected for ΛHe^9 would be the same as for ΛBe^9 , i.e. $B_\Lambda \approx 6.5$ MeV, since He^8 would also be a spinless nucleus. This large value for B_Λ means that ΛHe^9 could be particle-stable even if He^8 were not. For example, if He^8 were unstable by δ MeV relative to $\text{He}^4 + n^4$, ΛHe^9 would be stable relative to $(\Lambda\text{He}^5 + n^4)$ and $(\text{He}^4 + \Lambda n^5)$ provided $\delta < 3.4$ MeV; if n^4 does not exist, and He^8 were unstable by δ' MeV relative to $\text{He}^6 + 2n$, then ΛHe^9 would be stable by $(1.6 - \delta')$ MeV relative to $\Lambda\text{He}^7 + 2n$.

A strong mode for ΛHe^9 decay would be the two-body mode

$$\Lambda\text{He}^9 \rightarrow \pi^- + \text{Li}^9, \quad Q_0 = (53.19 B_{2n}) \text{ MeV.} \quad (2.22)$$

where B_{2n} denotes the binding energy of the last two neutrons

in He^8 . Since Li^9 is beta-active (half-life 0.2 sec.),

$$\text{Li}^9 \rightarrow e^- + \bar{\nu} + \text{Be}^{9*}, \quad \text{Be}^{9*} \rightarrow n + 2\text{He}^4, \quad (2.23)$$

the decay mode (2.22) could readily simulate the known ΛLi^9 decay process

$$\Lambda\text{Li}^9 \rightarrow \pi^- + n + 2\text{He}^4, \quad (2.24)$$

if the beta-particle from the Li^9 decay were not detected. The decay mode

$$\Lambda\text{He}^9 \rightarrow \pi^- + n + \text{Li}^8, \quad Q_0 = (49.61 - B_{2n}) \text{ MeV} \quad (2.25)$$

followed by Li^8 beta-decay can similarly simulate the ΛLi^9 decay (2.24). The πpr mode

$$\Lambda\text{He}^9 \rightarrow \pi^- + p + \text{He}^8 \quad Q_0 = 37.58 \text{ MeV} \quad (2.26)$$

could be distinguished from ΛHe^7 decay only if He^8 is particle-stable. In this case, He^8 would beta-decay to Li^8 , which in turn beta-decay to Be^8 , giving the well-known hammer track; this sequence can be distinguished from $\Lambda\text{Li}^9 \rightarrow \pi^- + p + \text{Li}^8$ decay only if both beta-particles are detected. If He^8 is not particle-stable, this mode appears as $(\pi^- + p + \text{He}^6 + 2n)$ which readily simulates ΛHe^7 decay. A uniquely identifiable decay mode, not expected to be frequent, may also be mentioned,

$$\Lambda\text{He}^9 \rightarrow \pi^- + 3\text{H}^3, \quad Q_0 = (33.79 - B_{2n}) \text{ MeV} \quad (2.27)$$

A = 10. Li^9 is a well-known beta-active nucleus, stable by 3.5 MeV relative to $\text{Li}^8 + n$, so that the hypernucleus ${}_{\Lambda}\text{Li}^{10}$ must exist, with B_{Λ} value about 9.0 MeV. Besides the two-body mode $(\pi^- + \text{Be}^{10})$, the mode

$${}_{\Lambda}\text{Li}^{10} \rightarrow \pi^- + p + \text{Li}^9, \quad \text{Li}^9 \rightarrow e^- + \bar{\nu} + n + 2\text{He}^4 \quad (2.28)$$

is quite striking; however, the neutron emitted will generally be of low momentum, so that a clear identification might not always be straightforward.

The mirror hypernucleus ${}_{\Lambda}\text{C}^{10}$ also appears a strong possibility for there is evidence [10] to suggest that the nucleus C^9 may be particle-stable. Even a pessimistic estimate for the energy of C^9 suggests that it is unlikely to be unbound (relative to $\text{B}^8 + p$) by more than 1.5 MeV. The additional binding energy expected for the last proton (assuming j-j coupling) due to the Λ particle is about $(\langle \bar{\nu} \rangle + 5/12 \langle \Delta \rangle) \approx 1.6$ MeV, so that the stability of ${}_{\Lambda}\text{C}^{10}$ seems virtually certain. Its decay modes generally involve only charged particles and should be readily identifiable.

A ≥ 11. For larger A values, there are many other hypernuclear species for which stability is to be expected and which should be considered as possibilities for the interpretation of hypernuclear-decay events. For example, ${}_{\Lambda}\text{C}^{11}$ will certainly exist, with $B_{\Lambda} \approx 8.5$ MeV expected. ${}_{\Lambda}\text{Be}^{12}$ will also be particle-stable, with quite strong total binding; its π -recoil decay should be quite distinctive, with $Q_0 = 51.71$ MeV. ${}_{\Lambda}\text{N}^{13}$ provides a further example.

III. DISCUSSION

The observation of hypernuclei corresponding to core nuclei far off the stability line will be of considerable interest, in that they would provide a further means for determining the properties of such unusual nuclei, of which little is known at present [10]. Generally speaking, the proton-rich hypernuclei will be the most readily identified since their decay will usually lead to a final state consisting of charged particles. However, these decay processes may often involve nuclei which β^+ -decay, so that a careful search for associated fast electrons is always desirable. The neutron-rich hypernuclei are more difficult to identify, since their decay will often lead to neutron emission. As a result, their decay would often be confused with the decay processes of established lighter hypernuclei; however, there are generally some modes available through which a unique identification will become possible in due course.

For the π -recoil modes, there is naturally appreciable straggling in the pion range (and in the corresponding B_Λ value) and in the associated recoil range. For those events where B_Λ is appreciably far from the accepted value for the interpretation proposed, it is desirable to look also for an associated anomaly in the recoil range, since this might then point to an alternative interpretation in terms of a rarer hypernuclear species. The possibility of ${}^6_\Lambda\text{H} \rightarrow \pi^- + \text{He}^6$

events confused with ${}_{\Lambda}H^4 \rightarrow \pi^- + He^4$ provides an illustration of this point. Similarly, for events which give anomalous B_{Λ} values, a careful search should be made for an associated beta-particle from beta-decay of the recoil nucleus. Even though the characteristics of the two hypernuclear decay processes may be very similar, with overlapping distributions for B_{Λ} and recoil range, the study of such correlations between the observed quantities may still allow a convincing identification of these rarer species.

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