Physics Letters B 736 (2014) 93–97

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Is there a bound ${}^{3}_{\Lambda}$n?

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ARTICLE INFO

Article history:
Received 27 April 2014
Received in revised form 1 July 2014
Accepted 7 July 2014
Available online 9 July 2014
Editor: J.-P. Blaizot

Keywords:
Faddeev equations
Hypernuclei

ABSTRACT

The HypHI Collaboration at GSI argued recently for a ${}^{3}_{\Lambda}$n (Λnn) bound state from the observation of its two-body $t + \pi^-$ weak-decay mode. We derive constraints from several hypernuclear systems, in particular from the $A = 4$ hypernuclei with full consideration of $\Lambda N \leftrightarrow \Sigma N$ coupling, to rule out a bound ${}^{3}_{\Lambda}$n.

1. Introduction

The lightest established Λ hypernucleus is known since the early days of hypernuclear physics to be ${}^{3}_{\Lambda}\mathrm{H}^{T=0}$, in which the Λ hyperon is weakly bound to the $T = 0$ deuteron core, with ground-state (g.s.) separation energy $B_\Lambda({}^{3}_{\Lambda}\mathrm{H}) = 0.13 \pm 0.05$ MeV and spin-parity $J^P = \frac{1}{2}^+$. There is no evidence for a bound spin-flip partner with $J^P = \frac{3}{2}^+$. For a brief review on related results deduced from past emulsion studies of light hypernuclei, see Ref. [1].

As for ${}^{3}_{\Lambda}\mathrm{H}^{T=1}$, given the very weak binding of the Λ hyperon in the $T = 0$ g.s., and that the $T = 1$ NN system is unbound, it is unlikely to be particle stable against decay to $\Lambda + p + n$. Similarly, assuming charge independence, Λnn is not expected to be particle stable. As early as in 1959 just six years following the discovery of the first Λ hypernucleus, it was concluded by Downs and Dalitz upon performing variational calculations of both $T = 0, 1$ ΛNN systems that the isotriplet (${}^{3}_{\Lambda}$n, ${}^{3}_{\Lambda}\mathrm{H}^{T=1}$, ${}^{3}_{\Lambda}$He) hypernuclei do not form bound states [2]. This issue was revisited in Refs. [3–5] using various versions of Nijmegen hyperon–nucleon (YN) potentials within ΛNN Faddeev equations for states with total orbital angular momentum $L = 0$ and all possible values of total angular momentum J and isospin T. Again, no Λnn bound state was found in any of these studies as long as ${}^{3}_{\Lambda}\mathrm{H}^{T=0}$ ($J^P = \frac{1}{2}^+$) was only slightly bound. Similar conclusions were reached in Refs. [6–8] based on chiral constituent quark model YN interactions, and in Ref. [9] based on recently constructed NLO chiral EFT YN interactions [10]. Note that $\Lambda N \leftrightarrow \Sigma N$ coupling was fully implemented in the more recent ${}^{3}_{\Lambda}$n studies [4–9]. A more general discussion of stability vs. instability for ${}^{3}_{\Lambda}$n in the context of neutral hypernuclei with strangeness -1 and -2 has been given very recently in Ref. [11].

A claim for particle stability of ${}^{3}_{\Lambda}$n has been made recently by the HypHI Collaboration [12] observing a signal in the $t + \pi^-$ invariant mass distribution following the bombardment of a fixed graphite target by ^{6}Li projectiles at $2A$ GeV in the GSI laboratory. The binding energy of the conjectured weakly decaying ${}^{3}_{\Lambda}$n is $0.5 \pm 1.1 \pm 2.2$ MeV, with a large standard deviation $\sigma = 5.4 \pm 1.4$ MeV. As noted above, there is unanimous theoretical consensus based on ΛNN bound-state calculations that ${}^{3}_{\Lambda}$n cannot be particle stable. However, possible connections to other hypernuclear systems, in particular the $A = 4$ bound isodoublet hypernuclei (${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He), need to be explored. The present work addresses this issue by establishing connections that make it clear why a bound ${}^{3}_{\Lambda}$n cannot be accommodated into hypernuclear physics. Assuming charge-symmetric ΛN interactions, $V_{\Lambda p} = V_{\Lambda n}$, we demonstrate some unacceptable implications of a bound ${}^{3}_{\Lambda}$n to Λp scattering in Section 2, and to ${}^{3}_{\Lambda}\mathrm{H}^{T=0}$ in Section 3. Consequences of $A = 4$ hypernuclear spectroscopy with full consideration of charge-symmetric $\Lambda N \leftrightarrow \Sigma N$ couplings are derived for ${}^{3}_{\Lambda}$n in Section 4 by applying methods that differ from those used in the combined analysis of $A = 3$ and $A = 4$ hypernuclei by Hiyama et al. [5], reaffirming that ${}^{3}_{\Lambda}$n is unbound. Our results are discussed and summarized in Section 5, with additional remarks made on the possible role of charge-symmetry breaking (CSB) and ΛNN interaction three-body effects, concluding that a bound ${}^{3}_{\Lambda}$n interpretation of the $t + \pi^-$

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http://dx.doi.org/10.1016/j.physletb.2014.07.009
0370-2693/

Table 1
Values of the spin-independent ΛN scattering length a required to bind $T=0$ and $T=1$ ΛNN states as indicated, for two representative values of the spin-independent effective range r, and calculated values of the Λp total cross section at $p_\Lambda = 145$ MeV/c. The measured value at the lowest momentum bin available is $\sigma^{tot}_{\Lambda p}(p_\Lambda = 145 \pm 25 \text{ MeV}/c) = 180 \pm 22$ mb [13]. Calculated values of $B_\Lambda({}^3_\Lambda\text{H}^{T=0})$ are listed in the last column for ΛN interactions that just bind ${}^3_\Lambda$n, in contrast to $B^{exp}_\Lambda({}^3_\Lambda\text{H}) = 0.13 \pm 0.05$ MeV.

	$B^{T=0}_\Lambda = 0$		$B^{T=0}_\Lambda = 0.13$ MeV		$B^{T=1}_\Lambda = 0$ (${}^3_\Lambda$n just bound)		
r (fm)	a (fm)	$\sigma^{tot}_{\Lambda p}$ (mb)	a (fm)	$\sigma^{tot}_{\Lambda p}$ (mb)	a (fm)	$\sigma^{tot}_{\Lambda p}$ (mb)	$B^{T=0}_\Lambda$ (MeV)
2.5	−1.185	129.7	−1.498	192.5	−4.491	953.8	2.59
3.5	−1.405	152.4	−1.895	239.7	−5.930	943.1	1.74

signal in the HypHI experiment is outside the scope of present-day hypernuclear physics.

2. ${}^3_\Lambda$n vs. Λp scattering

To make a straightforward connection between the low-energy ΛN scattering parameters and the three-body ΛNN system we follow the method of Ref. [3] in solving YNN Faddeev equations with two-body YN input pairwise separable interactions constructed directly from given low-energy YN scattering parameters. For simplicity we neglect in this section the spin dependence of the low-energy ΛN scattering parameters, setting $a_s = a_t$ for the scattering length and $r_s = r_t$ with values $r = 2.5$ or 3.5 fm for the effective range, spanning thereby a range of values commensurate with most theoretical models and also with the analysis of measured Λp cross sections at low energies [13]. By using Yamaguchi form factors within rank-one separable interactions, we then compute critical values of scattering length a required to bind successively the $T=0$ and $T=1$ ΛNN systems, with results shown in Table 1.

Exceptionally large values of ΛN scattering lengths are seen to be required to bind ${}^3_\Lambda$n, and the low-energy Λp cross sections thereby implied exceed substantially the measured cross sections as shown by the ΛN cross sections evaluated at the lowest momentum bin reported in Ref. [13]. Of the three B_Λ values tested in the table, only $B^{T=0}_\Lambda = 0.13$ MeV is consistent with the reported Λp cross sections, including their uncertainties. In the last column of the table we also listed the Λ separation energies in ${}^3_\Lambda$H that result once ${}^3_\Lambda$n has just been brought to bind. These calculated values are much too big to be reconciled with $B^{exp}_\Lambda({}^3_\Lambda\text{H}) = 0.13 \pm 0.05$ MeV.

3. ${}^3_\Lambda$n vs. ${}^3_\Lambda$H

The ${}^3_\Lambda$n vs. ${}^3_\Lambda$H discussion in this section is limited to using s-wave ΛN effective interactions, providing a straightforward extension of earlier studies [2,3]. Effects of possibly substantial $\Lambda N \leftrightarrow \Sigma N$ coupling, as generated by strong one-pion exchange in Nijmegen meson-exchange potentials [14] and in recent chirally based potentials [10], are discussed in Section 4.

Following Ref. [3] we solve Faddeev equations for ${}^3_\Lambda$n and ${}^3_\Lambda$H using simple Yamaguchi separable s-wave interactions fitted to prescribed input values of singlet and triplet scattering lengths a and effective ranges r, thereby relaxing the spin-independence assumption of the preceding section. Of the four Nijmegen interaction models A, B, C, D studied there, only C reproduces the observed binding energy of ${}^3_\Lambda$H, binding also the $\frac{3}{2}^+$ spin-flip excited state just 11 keV above the $\frac{1}{2}^+$ g.s. To get rid of this excited state, we have slightly changed the input parameters of model C. In this model, denoted C′, the input ΛN low-energy parameters are (in fm):

Table 2
Λ separation energies $B_\Lambda({}^3_\Lambda\text{H}^{T=0})$ (in MeV) calculated for both $J^P = \frac{1}{2}^+, \frac{3}{2}^+$, using ΛN separable interactions based on the low-energy parameters Eq. (1) with V_t multiplied by a factor x up to values allowing ${}^3_\Lambda$n to become bound, as indicated by following the values of its Fredholm determinant (FD) at $E = 0$.

x	${}^3_\Lambda$n FD ($E=0$)	$B_\Lambda[{}^3_\Lambda\text{H}^{T=0}(\frac{1}{2}^+)]$	$B_\Lambda[{}^3_\Lambda\text{H}^{T=0}(\frac{3}{2}^+)]$
1.00	0.55	0.096	unbound
1.10	0.47	0.147	0.124
1.20	0.39	0.211	0.448
1.30	0.31	0.288	0.986
1.40	0.21	0.381	1.704
1.50	0.12	0.488	2.598
1.60	+0.015	0.612	3.659
1.61	+0.004	0.625	3.772
1.62	−0.006	0.638	3.890

$$a_s = -2.03, \qquad r_s = 3.66, \qquad a_t = -1.39, \qquad r_t = 3.32. \qquad (1)$$

The ${}^3_\Lambda\text{H}^{T=0}(J^P = \frac{1}{2}^+, \frac{3}{2}^+)$ separation energies obtained by solving the appropriate ΛNN Faddeev equations are listed in Table 2. The row marked $x = 1$ corresponds to using ΛN interaction based on the low-energy parameters Eq. (1), and subsequent rows correspond to multiplying the ΛN triplet interaction V_t by $x > 1$ in order to bind ${}^3_\Lambda$n(${}^3_\Lambda\text{H}^{T=1}$).

Inspection of Table 2 shows that while the Λ separation energies increase upon varying x, a by-product of this increase is that ${}^3_\Lambda\text{H}^{T=0}(\frac{3}{2}^+)$ quickly overtakes ${}^3_\Lambda\text{H}^{T=0}(\frac{1}{2}^+)$ becoming ${}^3_\Lambda$H g.s. This is understood by observing that the weights with which V_t and the singlet interaction V_s enter a simple folding expression for the Λ–core interaction are given by

$$J^P = \frac{1}{2}^+ : \left(T + \frac{1}{2}\right)V_t + \left(\frac{3}{2} - T\right)V_s, \qquad J^P = \frac{3}{2}^+ : 2V_t, \quad (2)$$

so that V_t is the only ΛN-interaction component affecting ${}^3_\Lambda\text{H}^{T=0}(\frac{3}{2}^+)$ besides being more effective in binding ${}^3_\Lambda$n than binding ${}^3_\Lambda\text{H}^{T=0}(\frac{1}{2}^+)$. Subsequently, beginning with $x = 1.614$, ${}^3_\Lambda$n becomes bound as indicated by the corresponding Fredholm determinant at $E = 0$ going through zero. Note that the $(2J+1)$-averaged $B^{T=0}_\Lambda({}^3_\Lambda\text{H})$ is then ≈2.76 MeV, in rough agreement with the spin-independent analysis of the previous section (cf. first row in Table 1). Similar results are obtained when replacing the parameters (1) of model C′ by those of model C, used in Ref. [3], and repeating the procedure summarized in Table 2. A bound ${}^3_\Lambda$n is therefore in strong disagreement with the binding energy $B^{exp}_\Lambda({}^3_\Lambda\text{H}) = 0.13 \pm 0.05$ MeV determined for ${}^3_\Lambda\text{H}_{g.s.}$ and with its spin-parity $J^P = \frac{1}{2}^+$.

4. ${}^3_\Lambda$n vs. ${}^4_\Lambda$H

$\Lambda N \leftrightarrow \Sigma N$ coupling cannot be ignored in quantitative calculations of Λ hypernuclear binding energies. One-pion exchange induces a strong coupling in the YN ${}^3S_1$–${}^3D_1$ channel which dominates the effective V_t contribution in ${}^3_\Lambda$H three-body calculations, independently of whether using NSC97-related YN interactions as in Refs. [4,5] or NLO chiral YN interactions in Ref. [15]. In the YN ${}^1S_0$ channel, in contrast, $\Lambda N \leftrightarrow \Sigma N$ coupling is weak. Here we employ G-matrix $0s_N 0s_Y$ effective interactions devised by Akaishi et al. [16] from the Nijmegen soft-core interaction model NSC97 and used in binding energy calculations of the $A = 4, 5$ Λ hypernuclei. Of particular significance in the present context is the ≈1.1 MeV splitting of the $0^+_{g.s.}$–1^+_{exc} spin-doublet levels in the isodoublet hypernuclei ${}^4_\Lambda$H–${}^4_\Lambda$He which cannot be reconciled with theory without substantial $\Lambda N \leftrightarrow \Sigma N$ contribution. These $0s_N 0s_Y$ effective interactions were extended by Millener to the p shell