1 of 1

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NUCLEAR ASPECTS OF FEW-BARYON SYSTEMS

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Abstract

Recent progress in understanding the bound state properties of the trinucleons and the alpha particle in terms of a hadron picture of the nucleus is reviewed. The role of three-body forces and meson exchange currents is examined. Novel aspects of few-body hypernuclei as well as unresolved issues in this $S \neq 0$ sector are summarized.

I thank the organizers for their invitation to speak at this convocation of European few-body physicists. The topic of few-baryon bound states covers a wide range of intriguing problems, many more than I will be able to touch upon today. Therefore, for a detailed summary of the trinucleon physical observables and model properties, the audience is referred to a review in the proceedings of the Adelaide International Few-Body Conference.[1] Also, a summary of the work by Sasakawa and collaborators will appear shortly in Few-Body Systems.[2] The trinucleon discussion is based upon calculations by a number of people: Friar, Gibson, Payne, ..., Tjon, ..., Glöckle, Witala, ..., Sauer, Stadler, ..., Sasakawa, Ishikawa, ..., Kim, Pickelsimer, Brandenburg, ..., deSwart & Stoks, My brief remarks on ^4He are based upon the work of Tjon, Carlson, and Glöckle & Kamada, My comments in this area will be concentrated on recent results and our growing understanding of the physics. The primary emphasis in the talk will be the strangeness ($S = -1$ & -2) sector, where hyperons can act as tagged probes of the nucleus. The focus will be on the physics of hypernuclei, where a number of novel features are to be found and a number of unresolved issues remain.

I. The Strangeness-Zero Sector

Before summarizing the status of our understanding of the low energy physical observables for the conventional ($S = 0$) $A = 3$ & 4 bound states, a brief glimpse of the history of calculational developments is in order. Tjon [3] gave us the early calculations of $^3\text{H}/^3\text{He}$ properties using a realistic potential. The analysis of those impulse approximation charge form factors is still valid today: triton underbinding implies radii that are too large, and the diffraction minima occur at too high a momentum transfer in nonrelativistic Hamiltonian model calculations. Afnan [4] produced the initial $^3\text{S}_1$ - $^3\text{D}_1$, $^1\text{S}_0$ (5-channel) calculation for the existing realistic force models, using the Adhikari-Sloan expansion;

the Ernst-Shakin-Thaler expansion has since been used [5] for contemporary potential model calculations. Recently, the W-matrix expansion of Sandhas, Haberzettl, . . . [6] has been shown to give reliable results for a low-rank, small-basis solution and holds promise for speedy $nd \rightarrow nnp$ breakup calculations. Finally the coordinate-space approach of Kok and Schellingerhout [7] appears to be a computationally efficient means of attacking the 3-body and 4-body problem.

Traditional Model

The traditional approach to nuclear physics can be defined in terms of the constraints placed upon the complexity of the model assumptions:

- Nuclei consist only of nucleons – other degrees of freedom are suppressed.
- Nucleons move slowly within the nucleus – nonrelativistic dynamics prevails.
- Nucleons interact primarily via pairwise (two-body) forces.

This is an enormous simplification of the physics, but it accounts amazingly well for much of the experimental data. Nonetheless, our calculational ability has achieved the precision required to see differences between traditional model predictions and experiment, and much research during the past decade has been focussed upon extensions: meson exchange currents (MEC), three-body forces (3BF), $NN-N\Delta$ coupling, relativistic dynamics, quark-gluon substructure, I will concentrate on results from the traditional model for binding energies (and implicitly other low energy observables) and address only briefly the MEC, 3BF, and relativity aspects of extensions.

Before turning to specific systems, let us take a quick look at the nonrelativistic assumption. The $A = 3$ & 4 bound states have charge radii of the size of 1.5-1.8 fm, the same order as the pion compton wave length ($1/m_\pi$). The uncertainty principle permits one to estimate Δp from the size of the system: $\langle p \rangle \approx 120$ MeV/c. Also, from the triton kinetic energy of ≈ 40 MeV, one can estimate $\langle p^2 \rangle^{1/2} \approx 160$ MeV/c. Thus, the average momentum of the system is of the order of m_π , and

$$\left(\frac{v}{c}\right)^2 \approx \left(\frac{\langle p \rangle / M}{c}\right)^2 \approx \left(\frac{m_\pi}{M}\right)^2 \approx 2\%.$$

Caveat: This is an average. It should reflect accurately relativistic corrections to the low energy observables, which are averages over the nuclear volume. However, processes involving high momentum wave function components can suffer much larger relativistic effects.

Status of the Trinucleons

It has now been reasonably well established that the low energy observables “scale” with the trinucleon binding energy.[8, 9] A summary of results for charge radii, wave function probabilities, magnetic moments, Coulomb energy, asymptotic normalization constants, and Nd scattering lengths can be found in Ref. [1]. Because of this scaling property, the discussion will be limited to results for the triton binding energy.

Benchmark results exist from a number of groups [8, 9, 10, 11, 12, 13, 14, 15, 16] for a variety of realistic potentials [17, 18, 19, 20, 21]. In this context realistic implies

- strong spin-isospin dependence ($V_{nn} \neq V_{np}$),
- strong tensor force (OPEP is essential, providing up to 3/4 of the potential energy in ${}^3\text{H}$ and ${}^4\text{He}$),
- strong short range repulsion (the probability of NN overlap at such separations should be small),

in addition to a reasonable fit to the NN scattering data. Somewhat surprisingly, the explicitly momentum-dependent models such as Paris and Nij78 are more repulsive in the negative-parity partial waves in a triton binding energy calculation than are the RSC and AV14 models.[22]

The latest development of consequence is a set of local potential models by the Nijmegen group with a $\chi^2/f \approx 1$ for the scattering observables.[23] These charge dependent potential models (with $V_{nn} \neq V_{np}^s \neq V_{np}^t$) have now been used to estimate the triton binding energy to be $B({}^3\text{H}) = 7.62 \pm .01$ MeV.[24] Thus, a local potential model of the NN interaction that fits the NN observables as well as any phase shift analysis leads to underbinding of the triton by about 0.85 MeV.

Previously such underbinding of the triton by local potential models had led investigators to raise the question of the role of 3BF.[25] Various groups demonstrated that adding a two-pion-exchange ($\pi\pi$) three-body force [26, 27] to the Hamiltonian led to overbinding of the triton when the πNN vertex cutoff of $5.8m_\pi$, as recommended by the authors of Ref. [26], was used.[28, 29, 30, 31] For example, for the combined RSC/TM model one obtains $B({}^3\text{H}) \simeq 8.9$ MeV for $j \leq 2$ (or 9.1 MeV for $j \leq 4$). Recently Coon and Peña completed the TM 3BF by deriving the $\pi\rho$ and $\rho\rho$ terms.[32] Now, Stadler *et al.*[31] have calculated the ${}^3\text{H}$ binding energy for the full TM 3BF. Just as the ρ cancels part of the π contribution to the NN force, the $\pi\rho$ term cancels part of the $\pi\pi$ term in the NNN force. The result for the RSC/TM model is that $8.9 \text{ MeV} \rightarrow 8.4 \text{ MeV}$. (Similarly, for the Paris/TM combination one finds $9.1 \rightarrow 8.5$ and for the Nij78/TM model one finds $9.3 \rightarrow 8.7$.) *Apparently, a nonrelativistic Hamiltonian composed of a local NN potential plus a comparable 3BF can yield approximately the correct value for $B({}^3\text{H})$.*

Where do the Bonn potentials fit in this picture? Let me remind everyone that the Bonn q-space potentials (as approximations to the full Bonn energy-dependent interaction) are not local. That is, they do not depend solely upon the difference $|\vec{p}-\vec{p}'|$. Nonlocal interactions have an added degree of flexibility, which may well be partially mimicked in local Hamiltonians by a 3BF. Recall the theorem by Polyzou and Glöckle [33] that relates the three-body potential and on-shell equivalent two-body interactions. Paraphrasing: If there exist two-body Hamiltonians $H_{12} (= T_1 + T_2 + V_{12})$ and $\bar{H}_{12}$ which have the same binding energies and scattering matrices, are complete, and are related by a unitary transform, then there is a three-body interaction W which relates the three-body Hamiltonians $(T_1 + T_2 + T_3 + V_{12} + V_{13} + V_{23})$ given by H and $\bar{H}' = \bar{H} + W$ such that they have the same binding energies and scattering matrices. In other words, it is quite conceivable that if

a local potential plus 3BF describes the physics of the trinucleons, then there is also a nonlocal potential plus different 3BF (perhaps identically zero) that will also describe the physics. The Bonn potentials may already incorporate certain 3BF effects in their nonlocal nature. Using the TM 3BF with the Bonn NN potential is likely double counting at some level, as the result for the Bonn-Q/TM calculation [31] indicates. However, it is also worth noting that the difference between the charge-dependent Bonn-B potential triton, $B(^3\text{H}) = 7.92$ MeV, [16] and the nonlocal Nijmegen charge-dependent potential (Nijm I) result, $B(^3\text{H}) = 7.72$ MeV [24] is only some 200 keV. Are the model differences so great? The Graz group is examining the electromagnetic response of the NN system in an effort to pin down the proper off-shell behavior.[34]

For the experimentalists, let me reiterate that three-body forces is a “game” for theorists. On the other hand, we now have understood much about the “rules of the game.”

The Alpha Particle

Tjon first established that the $A = 3$ & 4 nucleon system binding energies are strongly correlated.[35] This is in part due to the fact that the $^3\text{S}_1$ - $^3\text{D}_1$ interaction is so dominant. That is, $\langle V_{np}^t \rangle \gg \langle V_{np}^s \rangle \Rightarrow$ the physics of all the s-shell nuclei must be similar.

The GFM results of Carlson [36] confirm that underbinding for ^3H ($\simeq 7.7$ MeV for the AV14 model) and for ^4He ($\simeq 24.9$ MeV) follows the Tjon line. Adding a phenomenological 3BF to fit the triton implies a corresponding fit for the α particle.

Integral equation solutions by Glöckle and Kamada for realistic force models have just appeared.[37] In addition to binding energies for the AV14 model (7.68 MeV and 24.62 MeV), they quote results for several other potentials for $j \leq 3$ NN partial waves. One should note Kamada’s talk [38] later in the week as well as Fonseca’s review [39] of the $A = 4$ system.

Meson Exchange Currents

The deviation of the $^3\text{H}/^3\text{He}$ magnetic moments from the Schmidt limits provided an early indication of the need to include subnucleon degrees of freedom when nucleons are embedded within the nuclear medium. In one language these effects are due to MEC. Isovector corrections [40] are estimated to be of the order of 15% and are reasonably model independent.[41] The isoscalar MEC contributions to the magnetic moments are expected to be small, of the order of relativistic corrections. Indeed, the isoscalar magnetic moment combination for ^3H and ^3He appears to be reasonably described by impulse approximation.[41]

What is known in the case of MEC corrections to the charge operator? It is tempting to invoke them to obtain a fit to the charge form factor data. An *ad hoc* addition to the impulse approximation form factor of a term which vanishes at $q^2 = 0$ and is negative in the region of the diffraction minimum and beyond will certainly improve the fit to the data. Such a procedure is far from unique. In the case of the deuteron, an isoscalar object, we have seen [42, 43] that the difference between relativistic results and the nonrelativistic impulse approximation is small for a significant range of momentum transfer. This is in contrast with the large effect that one sees when relativistic current corrections are

included as a perturbation. In his *Les Houches* lectures, Tjon dissected the relativistic calculation for OPE.[44] He demonstrated that including the relativistic corrections to the current operator alone can be extremely misleading. The effect is large, but incorrect. Specifically, the MEC correction is cancelled by a corresponding dynamical correction to the ${}^2\text{H}$ wave function – the nucleon can be offshell. When modeling isoscalar (relativistic) corrections to the ${}^3\text{H}/{}^3\text{He}$ form factors, the practitioner should first check the model results for the ${}^2\text{H}$ form factor.

II. Hypernuclei

A hypernucleus is a baryon system comprised of conventional (nonstrange) nucleons and one or more strange hyperons ($Y = \Lambda$, Σ , or Ξ). The presence of the strangeness degree of freedom (flavor) adds a new dimension to our evolving picture of nuclear physics. Because the $S = -1$ hyperon masses differ markedly from those of the neutron and proton, $SU(3)$ symmetry is clearly broken. How it is broken is a question of fundamental importance to our understanding of the baryon-baryon interaction. The search for the $S \neq 0$ dibaryon states directly bears upon this. Certainly the investigation of strangeness in few-baryon systems will play a significant role in our understanding the strong force.

The physics of hypernuclei has proven to be both novel and puzzling, stretching our intuition and analysis capability beyond that developed during the more than half century that we have explored conventional nuclear physics. The hypernuclear sector of hadronic physics is not just a simple extension of zero-strangeness phenomena. The discoveries have been new; the physics is different. We have observed such novel aspects as:

- obvious charge symmetry breaking in the ${}^4_\Lambda\text{He}$ - ${}^4_\Lambda\text{H}$ isodoublet,[45, 46]
- anomalously small binding of ${}^5_\Lambda\text{He}$,[45, 47, 48, 49, 50]
- surprisingly narrow structure in the ${}^4\text{He}(\text{K}^-, \pi^\pm)$ reactions, a possible ${}^4_\Xi\text{He}$ hypernucleus.[51, 52, 53]

These phenomena stand out clearly without the need for sophisticated theoretical analysis of the data. Furthermore, the following aspects are also interesting:

- The “H” dibaryon ($S = -2$ *uuddss* object) is a unique prediction of the QCD Bag model.[54]
- Theoretical calculations imply a significant role for 3BF effects in the hypertriton ${}^3_\Lambda\text{H}$. [55, 56]
- A spin inversion between the $A = 4$ ground states and excited states would explain unobserved γ rays in heavier hypernuclei.[57, 58, 59]
- Confirmation of a claim for the observation of ${}^6_{\Lambda\Lambda}\text{He}$ would argue strongly against the existence of a deeply bound “H”. [60]

Λ hypernuclear physics has been established as an interesting subject, one which deserves concentrated effort to comprehend. The prospect of exploring Σ hypernuclei and the more exotic $S = -2$ systems makes the strange physics sector that much more attractive.

The available data on the few-body Λ hypernuclei come primarily from emulsion experiments [45] – binding energies and weak decay properties. We shall discuss only the binding energies today, for we have seen in the $S = 0$ sector that binding energy determines the low energy observables. In the study of hypernuclei, it is customary to quote the Λ -separation energies

$$B_{\Lambda}(\Lambda A) = B(\Lambda A) - B(A-1).$$

The accepted values for the s-shell systems are quoted in Table 1 along with the measured γ -ray deexcitation energies for the two species with particle-stable excited states. The $A = 6$ entry is $B_{\Lambda\Lambda} = B({}_{\Lambda\Lambda}^6\text{He}) - B({}^4\text{He})$. [60] I would point out that Don Davis of University College London is a great source of information about the emulsion data. [61, 62]

Table 1. Hypernuclear Λ -separation energies and excitation energies in MeV

hypernucleus	B_{Λ}	E_{γ}
${}_{\Lambda}^3\text{H}$	$0.13 \pm .05$	
${}_{\Lambda}^4\text{H}$	$2.04 \pm .04$	$1.04 \pm .04$
${}_{\Lambda}^4\text{He}$	$2.39 \pm .03$	$1.15 \pm .04$
${}_{\Lambda}^5\text{He}$	$3.10 \pm .02$	
${}_{\Lambda\Lambda}^6\text{He}$	10.6	

The YN Interaction

Several novel features of the YN interaction come into play in hypernuclear physics. The Λ ($T = 0$) and N ($T = 1/2$) cannot exchange a π ($T = 1$), so that there is no dominant OPE tensor force in ΛN scattering. Shorter range properties of the baryon-baryon interaction play a more important role than in NN scattering. The longest range components are due to the exchange of two pions or one kaon. The shorter range K-exchange potential does admit a tensor-force component, but it is largely cancelled by that from K^* -exchange. Thus, tensor-force effects in the ΛN interaction are expected to be smaller than those in the NN interaction. [63, 64, 65, 66, 67, 68]

On the other hand, ΛN - ΣN coupling effects are expected to be much more important in the hypernuclear sector than are NN - $N\Delta$ coupling effects in the nonstrange sector. The m_{Σ} - m_{Λ} mass difference is only some 75 MeV, and the width of the Σ is small compared to that of the Δ . Formally eliminating the Σ channel from the problem leads to an energy dependent ΛN effective interaction and to ΛNN three-body forces. Both of these effects have been the subject of recent research in the nonstrange sector. [14]

The experimental data for ΛN and ΣN scattering consist of some 600 events in the low energy range (momenta of less than 300 MeV/c) [69, 70, 71] and another 250 events

in the momentum range 300-1500 MeV/c [72]. A phase shift analysis is not a practical possibility. The low energy data fail to adequately define even the relative sizes of the dominant s-wave spin-triplet and spin-singlet scattering lengths.[69] The limited cross section measurements have been grouped with the abundant NN data in a combined analysis to constrain the YN OBE potential models. The Nijmegen group has developed several OBE models by simultaneously fitting the NN and YN data and employing $SU(3)$ constraints among the coupling constants. In addition, the Jülich group has now constructed YN potential models with a different character. In particular, the assumption about the F/D ratio (scalar singlet and scalar octet coupling) differs, which affects the relative strengths in the ΛN and ΣN channels.

The scattering lengths and effective ranges for five of these models are collected in Table 2. The scatter among the parameters gives an indication of how poorly the potentials are constrained by the data. The scattering lengths are clearly negative, so that there is no bound hyperdeuteron. However, one can not determine whether the interaction in the spin-singlet state or the spin-triplet state is the stronger. A cusp is expected in the region of the threshold for Σ production, although neither the position nor the magnitude of the peak in this energy region is determined by the data; the cross sections in this energy region exhibit uncertainties of a factor of 2-4. The strong ΛN - ΣN coupling combined with the sizeable Σ^- - Σ^+ mass difference and the charge dependence of the ΣN OBE force implies a measurable charge symmetry breaking in the YN interaction, which is clearly seen in the $A = 4$ isodoublet.

Table 2. The scattering lengths and effective ranges in fm for the YN potential models listed

Model	Ref.	a^s	r_o^s	a^t	r_o^t
Nijmegen D	[63]	-1.90	3.72	-1.96	3.24
Nijmegen F	[64]	-2.29	3.17	-1.88	3.36
Nijmegen SC	[65]	-2.78	2.88	-1.41	3.11
Jülich A	[68]	-1.56	1.43	-1.59	3.16
Jülich $\tilde{A}$	[68]	-2.04	0.64	-1.33	3.91

Λ Hypernuclei

The question remains open as to whether we can successfully calculate the properties of the few-body Λ hypernuclei utilizing realistic YN and NN interactions. Because neither the ΛN nor ΣN forces possess sufficient strength to support a bound state, the ground state of the ΛNN system (the hypertriton) plays the role of the deuteron. The spin and parity of ${}^3_\Lambda\text{H}$ were determined to be $J^\pi = \frac{1}{2}^+$ from an analysis of the angular distribution of pions emitted during its weak mesonic decay. The small Λ -separation energy (130 ± 50 keV) leads one to expect a loosely bound system — essentially a Λ clinging tenuously to a deuteron. As such, one expects the hypertriton to be sensitive to the long range properties of the YN interaction. Because ΛN - ΣN coupling plays a large role in that

interaction, one is also led to speculate whether ${}^3_\Lambda\text{H}$ is bound only because of the $\Lambda N N$ 3BF that results when the Σ channel is eliminated from the formalism.

Because of the weak binding and lack of definitive YN scattering data, many theorists have studied ${}^3_\Lambda\text{H}$ using separable potentials fitted to the approximate ΛN low energy parameters. (For a partial list, see Ref. [55].) The essential physics can be summarized as follows: 1) The spin-averaged ΛN interaction is $V_{\Lambda N} = \frac{1}{4}V'_{\Lambda N} + \frac{3}{4}V''_{\Lambda N}$; that is, the spin-singlet interaction dominates. 2) The dispersive energy dependence that results from embedding the ΛN - ΣN coupled-channel potential in a three-body system is repulsive, as is that from the NN - $N\Delta$ interaction in the triton. 3) The true 3BF due to the coupling of ΣNN states to ΛNN states is attractive. 4) The YN tensor force interacts with the NN tensor force in a complex manner, which depends upon the relative sign of the 3S_1 - 3D_1 mixing parameters. This analysis has been confirmed by the recent calculation of Miyagawa and Glöckle [56] using the Jülich $\tilde{A}$ model in combination with various realistic NN potentials. Surprisingly, the model ${}^3_\Lambda\text{H}$ was found to be unbound. This is surprising because the low energy scattering parameters for $\tilde{A}$ in Table 2 would imply that the ΛNN system should bind; thus, one must conclude that the short range properties of the realistic potential play an unexpected role in this weakly bound system. The binding of the hypertriton is clearly a balancing act. A 4% enhancement in the strength of $V'_{\Lambda N}$ would yield a bound state [56], but such a change in the spin-singlet interaction would destroy the model $\tilde{A}$ fit to the YN data.

The ${}^4_\Lambda\text{He}$ - ${}^4_\Lambda\text{H}$ isodoublet provides an even stronger test of our modeling of the YN interaction. The quality of the calculations for the (ground and excited) states of the $A = 4$ system should approach that demonstrated for the α particle. Even greater precision should be obtained for the charge-symmetry-breaking (CSB) difference

$$\Delta B_\Lambda = B_\Lambda({}^4_\Lambda\text{He}) - B_\Lambda({}^4_\Lambda\text{H}) .$$

The nominal $\Delta B_\Lambda \simeq 350$ keV is much larger than the $\simeq 100$ keV CSB effect seen in the ${}^3\text{He}$ - ${}^3\text{H}$ binding energy difference after correcting for the pp Coulomb energy in ${}^3\text{He}$. A key question is whether the CSB can be understood in terms of the free ΛN interaction. The question is not trivial. Consider a simple separable-potential model fitted to the Λp and Λn scattering parameters of Nijmegen D listed in Table 3. A folding model approximation for the Λ -nucleus potential

$$V_{\Lambda A}(\mathbf{k}) = \int d^3p \rho_A(\vec{p}) V_{\Lambda N}(\mathbf{p}, \mathbf{k}) ,$$

which provides effective two-body dynamics in a Schrödinger equation solution, yields a value of $\Delta B_\Lambda = 0.21 \rightarrow 0.24$ MeV when a core compression of $0 \rightarrow 5\%$ is used. In contrast, an exact four-body calculation for the identical potentials yields a value of $\Delta B_\Lambda = 0.43$ MeV – almost twice the folding model result.[46] Few-body dynamics does matter.

The existence of particle-stable excited states for the $A = 4$ system provides a further strong constraint upon our models of the YN interaction. Fitting both the 0^+ and 1^+ states within the same model is not a trivial exercise. The spin structure is more complex than one might naively expect; the ${}^4_\Lambda\text{H}$ states are not simply $[\Lambda \otimes {}^3\text{H}]^{[J]}$ configurations. Furthermore, ΛN - ΣN coupling plays an important role because of the composite

Table 3. The charge-dependent scattering lengths and effective ranges in fm for Nijmegen D

channel	a^s	r_p^s	a^t	r_p^t
Λp	-1.77	3.78	-2.06	3.18
Λn	-2.03	3.66	-1.84	3.32

nature of the trinucleon core states. A simple example follows from the Stepien-Rudza and Wycech [73] separable potential approximation to Nijmegen D. The spin-averaged potential combination that determines the 0^+ state is $\frac{1}{2}V_{\Lambda N}^s + \frac{1}{2}V_{\Lambda N}^t$, whereas for the 1^+ state it is $\frac{1}{6}V_{\Lambda N}^s + \frac{5}{6}V_{\Lambda N}^t$. If explicit ΛN - ΣN coupling is neglected, and the ΛN effective interactions are constructed from the scattering lengths and effective ranges, then one finds in an exact four-body calculation that

$$B(0^+) \simeq 10.7 \text{ MeV} \quad \text{and} \quad B(1^+) \simeq 11.7 \text{ MeV};$$

the ground state and excited states are inverted, the 1^+ being more bound. However, if one takes into account the composite nature of the $A = 3$ core states and suppresses the $T = 3/2$ trinucleon excited states that couple to the Σ but lie 10s of MeV higher in energy, then one finds

$$B(0^+) \simeq 9.6 \text{ MeV} \quad \text{and} \quad B(1^+) = 8.2 \text{ MeV},$$

which places the states in proper order.[59] This simplified schematic-model calculation emphasizes the importance of ΛN - ΣN coupling. That has been born out in variational calculations using Nijmegen SC for the YN interaction. For the 0^+ state, where the singlet and triplet interactions are of equal importance, one finds $B_\Lambda(0^+) \simeq 1.5 \text{ MeV}$, in qualitative agreement with the data. However, the 1^+ state is unbound.[74] The spin-triplet interaction which dominates the 1^+ system derives much of its attraction in Nijmegen SC from the $\Lambda \leftrightarrow \Sigma$ transition term $v_{\Lambda N}$ in the coupled channel potential

$$\begin{bmatrix} v_{\Lambda N} & v_{\Lambda \Sigma} \\ v_{\Sigma N} & v_{\Sigma \Sigma} \end{bmatrix}$$

which is less effective "in medium" than in free space, just as is tensor coupling in the NN interaction.

The anomalously small binding of ${}^5_\Lambda\text{He}$ remains an enigma. In the baryon picture, the four nucleons and Λ can coexist in $1s$ states. Simple model calculations based upon ΛN potentials parameterized to account for the low energy scattering data, as well as the binding energies of the $A = 3$ & 4 systems, overbind ${}^5_\Lambda\text{He}$ by 2-3 MeV.[48, 49, 50] Explanations of the model overbinding have been proposed in terms of tensor forces that bind ${}^3\text{H}$ and ${}^4\text{He}$ less than do central forces,[47] and in terms of ΛN - ΣN coupling that is weakened when the nucleon is part of a composite core.[75] The variational calculations by Carlson again fail to bind, because of the strength in the $\Lambda \leftrightarrow \Sigma$ transition potential.

The spin averaged interaction is $\frac{1}{4}V_{\Lambda\Lambda} + \frac{3}{4}V_{\Lambda\Lambda}^s$; the spin-triplet potential dominates as it does for the $A = 4, 1^+$ states. It should also be noted that the reduction needed in the binding has been modeled as a repulsive 3BF,[76] and as a manifestation of quark effects.[77]

A total of three $\Lambda\Lambda$ hypernuclei events have been reported [78, 60, 79]. The ${}^6_{\Lambda\Lambda}\text{He}$ event [60] is the most controversial,[80] although the exact interpretation of the most recent event has been called question.[81] However, the value for $B_{\Lambda\Lambda}({}^6_{\Lambda\Lambda}\text{He})$ is consistent with the trend from the other two events and not unreasonable. The 10.6 MeV implies a value for $\langle V_{\Lambda\Lambda} \rangle \equiv B_{\Lambda\Lambda} - 2B_{\Lambda}({}^3\text{He}) \simeq 4$ MeV, which is a matrix element comparable to that from the ΛN potential. That is, the overall strength of the $\Lambda\Lambda$ interaction appears comparable to that of the ΛN interaction.[49] Because one would expect a $\Lambda\Lambda$ hypernucleus to decay quickly into an "H" if the "H" mass were much smaller than $2m_{\Lambda}$, the observation of $\Lambda\Lambda$ hypernuclei argues against the existence of a deeply bound "H". If the existence of ${}^6_{\Lambda\Lambda}\text{He}$ is confirmed, then one can surmise that

$$m_H \geq 2m_{\Lambda} - 10 \text{ MeV}.$$

If it is then bound, the "H" would be more of a nuclear bound state of two Λ s rather than a deeply bound *uuddss* exotic.

Σ Hypernuclei

While the existence of Λ hypernuclei is well established from the observation of many bound states, such is not the case for Σ hypernuclei. It was surprising when Hayano [51] reported that the π^- spectrum from the ${}^4\text{He}(\text{stopped } K^-, \pi^+)$ reactions exhibited narrow structure below the threshold for Σ emission. An analysis by Dover and Gal [82] had noted that, if a bound state were to exist, then the $(T = \frac{1}{2}, S = 0)$ $\Sigma N N N$ configuration should lie lower in energy than the $(T = \frac{3}{2}, S = 0)$ configuration, although the latter state was expected to be narrower. The (K^-, π^-) reaction can lead to both $T = \frac{1}{2}$ and $T = \frac{3}{2}$ $\Sigma N N N$ states, whereas the (K^-, π^+) reactions leads only to $T = \frac{1}{2}$. Thus, because no structure was observed in the ${}^4\text{He}(K^-, \pi^+)$ reaction and the (K^-, π^-) spin-flip reaction is small, the structure was interpreted as a ${}^4_{\Sigma}\text{He}$ state having quantum numbers $(T = \frac{1}{2}, J^{\pi} = 0^+)$. New results, which confirm the earlier spectra with stopped kaons, have recently been reported from in-flight experiments at the Brookhaven AGS [83]. Furthermore, the data are consistent with the recently reanalyzed bubble chamber data from the exclusive $K^- {}^4\text{He} \rightarrow \pi^- \Lambda p d$ measurements,[84] which appear to show a cusp-like enhancement near the Σ^+ production threshold. The peak of the π^- spectrum appears to be centered at $B_{\Sigma^+} = 4 \pm 1$ MeV. (The width is about 10 MeV.) The Σ in the inferred hypernucleus would be more bound than is the Λ in ${}^4_{\Lambda}\text{He}$, implying that the Σ^+ interaction with ${}^3\text{H}$ must be more attractive than the corresponding Λ interaction with ${}^4\text{H}$ or ${}^4\text{He}$. Data were taken at the same time on ${}^3\text{He}$,[85] but no claim for structure has been made.

Following the work of Dover and Gal but prior to the experiment, Harada *et al* predicted the existence of an $A = 4$ $\Sigma N N N$ bound state with $B_{\Sigma^+} \simeq 4.5$ MeV and a width of about 8 MeV. They predicted no other "bound state" for $A = 2-5$. The only true continuum calculation was published for Λd scattering in the region of the $\Sigma N N$

threshold.[86] Surprisingly, it was found that structure in the elastic scattering cross section would appear *below* the ΣNN threshold whether the resonance pole corresponding to a ΣNN eigenstate lies above or below the ΣNN threshold. That is, although structure in the cross section below threshold does imply the existence of a resonance, it does not guarantee that the pole lies below threshold (that one has a "bound state").

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