LA-UR-82-1744

LA-UR--82-1744

DE82 017589

CONF-820635--4

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

TITLE: ON THE A=4 0^+-1^+ BINDING-ENERGY DIFFERENCE

AUTHOR(S): B. F. Gibson, T-5
D. R. Lehman, The 'ashington University

SUBMITTED TO: Presented at 1982 Int'l. Conference on Hypernuclear and Kaon Physics, Heidelberg, W. Germany, June 21-24, 1982.

ON THE A=4 0^+-1^+ BINDING-ENERGY DIFFERENCE

B. F. Gibson
Theoretical Division, Los Alamos National Laboratory
Los Alamos, New Mexico 87545

D. R. Lehman
Department of Physics, The George Washington University
Washington, D. C. 20052

The A=4 Λ-hypernuclei provide a rich source of information about the s-wave properties of the fundamental hyperon-nucleon (YN) force as well as offer a unique opportunity to investigate the complications that arise in calculations of the properties of bound systems in which one baryon (here the Λ) with a given isospin couples strongly to another (the Σ) with a different isospin.[1] (Implications for NN-NΔ coupling are apparent.) The $^4_\Lambda$H-$^4_\Lambda$He isodoublet ground-state energies are not consistent with a charge symmetry hypothesis for the YN interaction. The (spin-flip) excitation energies are quite sensitive to the ΛN-ΣN coupling of the YN interaction. In particular, when one represents the free YN interaction in terms of one-channel effective ΛN potentials, the resulting 0^+ (ground) state and 1^+ (excited) spin-flip state are inversely ordered in terms of binding energies, the 1^+ state being more bound. It is the "Σ suppression" that results from the reduced strength of the ΛN-ΣN off-diagonal coupling potential when the trinucleon core is restricted to isospin-1/2 which we study here. We find this spin-isospin suppression of the Λ-Σ conversion, which is due to the composite nature of the nuclear cores of the $^4_\Lambda$H and $^4_\Lambda$He hypernuclei, to be a significant factor in understanding the 0^+-1^+ binding energy relationship.

Lack of precision YN scattering data is a severe limitation upon any attempt to characterize that interaction. Commendable attempts have been made to parameterize potentials using 1) a combined analysis of all existing YN data plus the extensive NN data and 2) various symmetry assumptions concerning meson coupling in an OBE model of the YN and NN interactions.[2,3] We shall for convenience make use of the ΛN-ΣN separable potential model of Stepein-Rudzka and Wycech[4] in our four-body calculations; it is based upon the main features of the OBE potential model described in Ref.

In order to put our results into perspective, let us first consider the model that results when one assumes that the YN force is independent of explicit ΛN-ΣN coupling; in other words, it is assumed that the free YN force acts in an unmodified manner in composite systems. This model has been extensively employed in the literature in s-shell hypernuclear studies. Such a phenomenological approach leads to the following spin-isospin combinations of the effective ΛN spin-singlet and spin-triplet potentials $\bar{V}^s_{\Lambda N}$ and $\bar{V}^t_{\Lambda N}$ (neglecting any charge-symmetry-breaking differences between Λp and Λn interactions):

$$^4_\Lambda\text{H}: \quad V_{YN} = \frac{1}{2}\bar{V}^s_{\Lambda N} + \frac{1}{2}\bar{V}^t_{\Lambda N}$$

$$^4_\Lambda\text{H}^*: \quad V_{YN} = \frac{1}{6}\bar{V}^s_{\Lambda N} + \frac{5}{6}\bar{V}^t_{\Lambda N} \quad .$$

(It has been assumed that the singlet interaction is stronger than the triplet interaction.[5]) The YN subscript denotes the fact that the potential describes the full effective ΛN-ΣN interaction. The implicit assumption is that the ΛN-ΣN coupling is identical in each state. That is, one has assumed that the 2×2 matrix potentials

$$V^s_{YN} = \begin{pmatrix} V^s_{\Lambda N} & V^s_{XN} \\ V^s_{XN} & V^s_{\Sigma N} \end{pmatrix} \quad \text{and} \quad V^t_{YN} = \begin{pmatrix} V^t_{\Lambda N} & V^t_{XN} \\ V^t_{XN} & V^t_{\Sigma N} \end{pmatrix}$$

can be represented by unique effective one-channel potentials $\bar{V}^s_{\Lambda N}$ and $\bar{V}^t_{\Lambda N}$ independent of the spin and isospin of the hypernuclear states being studied. Such is not the case. For the A=4 hypernuclei the $J^\pi=0^+$ ground-state potentials have the form

$$V^s_{YN} = \begin{pmatrix} V^s_{\Lambda N} & \frac{-1}{3}V^s_{XN} \\ \frac{-1}{3}V^s_{XN} & V^s_{\Sigma N} \end{pmatrix} \quad \text{and} \quad V^t_{YN} = \begin{pmatrix} V^t_{\Lambda N} & V^t_{XN} \\ V^t_{YN} & V^t_{\Sigma N} \end{pmatrix} ,$$

while the $J^\pi=1^+$ excited state potentials are of the form

$$V^s_{YN} = \begin{pmatrix} V^s_{\Lambda N} & V^s_{XN} \\ V^s_{XN} & V^s_{\Sigma N} \end{pmatrix} \quad \text{and} \quad V^t_{YN} = \begin{pmatrix} V^t_{\Lambda N} & \frac{1}{5}V^t_{XN} \\ \frac{1}{5}V^t_{XN} & V^t_{\Sigma N} \end{pmatrix} .$$

(See, for example, Ref. 6 and 7.) In neither case is the coupling of the Λ-Σ system to the composite isospin-1/2 trinucleon core the same as the coupling to an elementary isospin-1/2 nucleon. The singlet potential differs from the free interaction in the ground state. The triplet potential differs from the free interaction in the excited state. In each case the magnitude of the ΛN-ΣN coupling is reduced, weakening the YN interaction relative to its free strength.[1] Both 0^+ and 1^+ state binding energies are less than those calculated in terms of a model based entirely upon free ΛN interaction parameters.

The measurement of the γ-transitions in the A=4 hypernuclei has been described by Piekarz[8] see also Ref. 9 and 10. Bound state transitions of this type provide invaluable data because our ability to treat properly bound systems is much more highly developed than that for continuum states. In addition, the precision possible in such experiments is normally much greater than that obtained in a continuum measurement. The reported spin-flip γ-transition energies are[8]

$$E_\gamma({}^4_\Lambda H) = B({}^4_\Lambda H) - B({}^4_\Lambda H^*) = 1.04 \pm .04 \text{ MeV}$$

$$E_\gamma({}^4_\Lambda He) = B({}^4_\Lambda He) - B({}^4_\Lambda He^*) = 1.15 \pm .04 \text{ MeV} .$$

These excitation energies (of approximately the same 1 MeV magnitude) imply that the mechanism leading to this particular 0^+-1^+ splitting must be similar for each member of the isodoublet. The question which we address is whether E_γ can be understood, at least qualitatively, in terms of the known properties of the free YN interaction.

In order to carry out our calculations within the context of the an exact four-body formalism,[11] we utilize separable potential representations of both the NN and YN interactions. We employ rank-one potentials of the form

$$V^i = -\frac{\lambda_i}{2\mu}\; g_i(k)g_i(k') \qquad i = s,t \quad ,$$

where $g_i(k) = (k^2 + \beta_i^2)^{-1}$ when there is no tensor component and where

$$g_t = g_C + \frac{S_{mn}}{\sqrt{8}} g_T$$

$$g_C = (k^2 + \beta_C^2)^{-1}$$

$$g_T = \xi_T k^2 (k^2 + \beta_T^2)^{-2}$$

$$S_{mn} = 3\vec{\sigma}_m \cdot \hat{k}\; \vec{\sigma}_n \cdot \hat{k} - \vec{\sigma}_m \cdot \vec{\sigma}_n$$

when a spin-triplet tensor force is used. (The quantity μ is the appropriate two-body reduced mass.) In our previous ground-state studies,[11,12] we restricted our consideration to rank-one effective YN potentials, the potential parameters being chosen to describe the low-energy free scattering data. In the case of the singlet potential this was rationalized on the basis that ΛN-ΣN coupling was very weak[13] so that $V^s_{XN} = 0$ was a good approximation; see also Ref. 1-3. We now assume that the free interactions are defined by the rank-two potentials of Ref. 4, modify the off-diagonal coupling terms as noted above for the ground state ($V^s_{XN} \rightarrow -\frac{1}{3}V^s_{XN}$) and the excited state ($V^t_{XN} \rightarrow \frac{1}{5}V^t_{XN}$), and generate effective rank-one potentials which reproduce the same scattering length and effective range as the appropriately modified singlet and triplet rank-two potentials. The result is a reasonable qualitative description of the spin-isospin suppressed (compared to the free interaction) ground-state and excited-state binding energies from which to estimate E_γ.

The exact coupled two-variable integral equations that must be solved, when the NN and YN interactions are represented by separable potentials, are described in Ref. 11. The integral equations are solved numerically without resort to separable expansions of the kernels. The resulting solutions possess the characteristics of true few-body calculations: for an attractive potential with a negative scattering length, $|a| > |a'|$ implies that V is more attractive that V′ in two-body, three-body, and four-body calculations, whereas $r > r'$ implies that V is more attractive than V′ in a two-body calculation but less attractive in both three-body and four-body calculations. Even though this is an oversimplified picture, it is possible to understand qualitatively the E_γ results described below in terms of the scattering lengths and effective ranges of the various potential models.

The potential parameters used in our numerical studies are listed in Table I. The first two columns are devoted to the free YN singlet and triplet interactions; the potentials as modified for the 0^+ and 1^+ state calculations due to coupling to the composite trinucleon cores are described in the last two columns. In the first five rows we list the parameters from Ref. 4 for the coupled ΛN-ΣN potentials; note that their definitions of the potential strengths differ from ours. In the next two rows we list the ΛN scattering lengths and effective ranges for each of the rank-two potentials; our values for the free interactions differ slightly from those reported in Ref. 4. The rank-one effective potentials, as defined above, which reproduce these scattering lengths and effective ranges are given in the last two rows. It is the rank-one effective potentials which are actually utilized in obtaining the numerical estimates of the A=4 binding energies reported here. The singlet potential is stronger than the triplet in the two-body sense discussed above: $|a_s| > |a_t|$ and $r_s > r_t$. However, the significant difference in size between r_s and r_t ensures that the triplet-dominated 1^+ state is more bound than the 0^+ state when one uses the potentials which describe free scattering in a true four-body calculation. Indeed, we find that $E_\gamma \cong -1$ MeV which has the wrong sign; i.e., the 1^+ state is an MeV more bound than the 0^+ state if effective interactions corresponding to the free scattering parameters are used. To obtain a correct picture, one must take into account the spin-isospin suppression of the off-diagonal potentials outlined above. When the modified singlet potential (corresponding to $\frac{-1}{3}V^s_{XN}$) is used in the 0^+ state calculation, the binding energy is lowered to about 9 MeV; in contrast, when the modified triplet potential (corresponding to $\frac{1}{5}V^t_{XN}$) is used in the triplet-dominated 1^+ state calculation, the binding energy is lowered much further to around 7.7

Table I. The YN potential parameters with corresponding scattering lengths and effective ranges.

	V^s_{YN}	V^t_{YN}	$V^s_{YN}(0^+)$	$V^t_{YN}(1^+)$
$\lambda_\Lambda(fm^{-1})$	-0.7251	-0.5298	-0.7251	-0.5298
$\lambda_X(fm^{-1})$	-1.0970	-0.6777	0.3657	-0.1355
$\lambda_\Sigma(fm^{-1})$	0.8916	-0.9871	0.8916	-0.9871
$\beta_\Lambda(fm^{-1})$	1.18	1.6	1.18	1.6
$\beta_\Sigma(fm^{-1})$	1.44	2.0	1.44	2.0
a (fm)	1.97	-1.95	-1.33	-0.95
r_o(fm)	3.80	2.45	4.68	3.51
λ (fm^{-3})	0.1022	0.3194	0.0741	0.1801
β (fm^{-1})	1.2260	1.7142	1.1839	1.6028

MeV. In summary, we obtain the following estimates of the Λ-separation energy and the γ-transition energy:

$$\Delta B_\Lambda = B({}^4_\Lambda H) - B({}^3H) \cong 2.0 \text{ MeV}$$

$$E_\gamma(1^+ \to 0^+) = B({}^4_\Lambda H) - B({}^4_\Lambda H^*) \cong 1.3 \text{ MeV} .$$

(The triton core has been treated in the truncated t-matrix approximation using the 7% D-state deuteron model of Phillips along with a rank-one singlet potential.[14]) These results are a clear indication of the importance of treating more explicitly the ΛN-ΣN coupling in hypernuclear studies than is possible when one merely fits effective potentials to the free scattering data.

References

1. B. F. Gibson and D. R. Lehman, Proceedings of the Workshop on Nuclear and Particle Physics up to 31 Gev: New and Future Aspects, LA-8775-C (1981), p. 460.
2. M. M. Nagels, T. A. Rijken, and J. J. deSwart, Ann. Phys. (NY) 79, 338 (1973); Phys. Rev. D 15, 2547 (1977).
3. M. M. Nagels, T. A. Rijken, and J. J. deSwart, Phys. Rev. D 20, 1633 (1979).
4. W. Stepien-Rudza and S. Wycech, Nucl. Phys. A362, 349 (1981).
5. R. C. Herndon and Y. C. Tang, Phys. Rev. 153, 1091 (1967), 159, 853 (1967); 165, 1093 (1968); R. H. Dalitz, R. C. Herndon, and Y. C. Tang, Nucl. Phys. B47, 109 (1972).
6. B. F. Gibson, A. Goldberg, and M. S. Weiss, Phys. Rev. C 6, 741 (1972); 8, 837 (1973).
7. J. Dabrowski, Phys. Rev. C 8, 835 (1973).
8. H. Piekarz, Nukleonika 25, 1091 (1980).
9. A. Bamberger, M. A. Faessler, U. Lynen, H. Piekarz, J. Piekarz, J. Pniewski, B. Povh, H. G. Ritter, and V. Soergel, Nucl. Phys. B60, 1 (1973).
10. M. Bedjidian, E. Descroix, J. Y. Grossiord, A. Guichard, M. Gusakow, M. Jacquin, M. I. Kudla, H. Piekarz, J. Piekarz, J. R. Pizzi, and J. Pniewski, Phys. Lett. 83B, 252 (1979).
11. B. F. Gibson and D. R. Lehman, Nucl. Phys. A329, 308 (1979); Phys. Lett. 83B, 289 (1979).
12. B. F. Gibson and D. R. Lehman, Phys. Rev. C 23, 404 (1981); 23, 573 (1981).
13. J. Dabrowski and E. Fedorynska, Nucl. Phys. A210, 509 (1973).
14. B. F. Gibson and D. R. Lehman, Phys. Rev. C 18, 1042 (1978).