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The ΛN Effective Interaction

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THE ΛN EFFECTIVE INTERACTION

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ABSTRACT

A combination of theoretical estimates, based on a ΛN potential model, and phenomenological analysis of hypernuclear data is used to determine a set of four $p_N s_\Lambda$ two-body matrix elements which characterize the spin dependence of the ΛN interaction in the p shell. The central spin-spin and the Λ spin-orbit matrix elements are most strongly constrained by existing data. The spin dependence is weak in the sense that s_Λ doublet splittings are predicted to be of order 100 keV except for the special case of $^7_\Lambda$Li where the central spin-spin interaction dominates and the ground-state doublet separation is likely to be about 600 keV. The results of recent $(K^-,\pi^-\gamma)$ experiments at the Brookhaven AGS are interpreted in terms of the ΛN effective interaction.

INTRODUCTION

Since the sizes of p-shell nuclei determined from measurements of r.m.s. charge radii do not vary greatly it is a reasonable approximation to attempt a description of p-shell hypernuclei in terms of a constant set of ΛN two-body, and possibly ΛNN three-body, matrix elements. Past phenomenological analyses[1] have demonstrated that a data set consisting of ground state information only (Λ binding energies, some spins, etc.) is too limited to permit a characterization of the spin dependence of the ΛN interaction. Excited states have been observed at CERN and Brookhaven in (K^-,π^-) reactions using magnetic spectrometers with an important deduction being that the ΛN spin-orbit interaction is weak[2,3]. Much more precise excitation energies have been obtained at Brookhaven[4] using the $(K^-,\pi^-\gamma)$ reaction with NaI detectors following earlier results obtained with stopped kaons[5,6]. The most direct evidence on the spin dependence of the ΛN interaction lies[7] in the separation of s_Λ doublets based on core states with non-zero spin. Recent $(K^-,\pi^-\gamma)$ experiments[8] have searched for the doublet transitions using germanium detectors.

CALCULATIONS

The basic philosophy behind these calculations is very similar to that of Gal, Soper and Dalitz[1]. Shell-model calculations are performed for $\{s^4p^{A-5}s_\Lambda\}$ configurations using the interaction of Cohen and Kurath for the core wave functions; the formalism follows a recent treatment[10] for $\{s^4p^{A-5}p_\Lambda\}$ configurations. The two-body ΛN interaction can be expressed[1,9] in terms of five radial integrals, one associated with each term in

$$V_{\Lambda N}(r) = V_o(r) + V_\sigma(r) s_N \cdot s_\Lambda + V_\Lambda(r) \ell_{N\Lambda} \cdot s_\Lambda + V_N(r) \ell_{N\Lambda} \cdot s_N + V_T(r) S_{12} \qquad (1)$$

These parameters, denoted by $\bar{V}$, Δ, S_Λ, S_N and T, are taken to be constant throughout the shell. In terms of Talmi integrals for the appropriate radial interaction,

$$\bar{V} = -1/2(I_o + I_1), \quad \Delta = 1/2(I_o + I_1), \quad S_\Lambda = 1/2\ I_1\ , \quad S_N = 1/2\ I_1, \quad T = 1/3\ I_1 \qquad (2)$$

In a simplified model the doublet splittings at the beginning of the shell ($p^{-1}_{3/2N} s_{1/2\Lambda}$) and at the end of the shell ($p^{-1}_{1/2N} s_{1/2\Lambda}$) are given in terms of the parameters δ and δ' respectively where

$$\delta = 2/3\ \Delta + 4/3\ S_\Lambda - 8/5\ T$$
$$\delta' = -1/3\ \Delta + 4/3\ S_\Lambda + 8T \qquad (3)$$

For a standard interaction[9], the spin-dependence of which is given by $\Delta = 0.5$, $S_\Lambda = -0.04$, $S_N = -0.08$ and $T = 0.04$ (all in MeV), δ and δ' are small.

The case of ${}^{12}_{\Lambda}C$ represents a typical calculation. The spectrum of core states to which a Λ or a Σ is coupled (s_Λ, p_Λ or p_Σ are of most interest) is shown in Fig. 1. Also given are

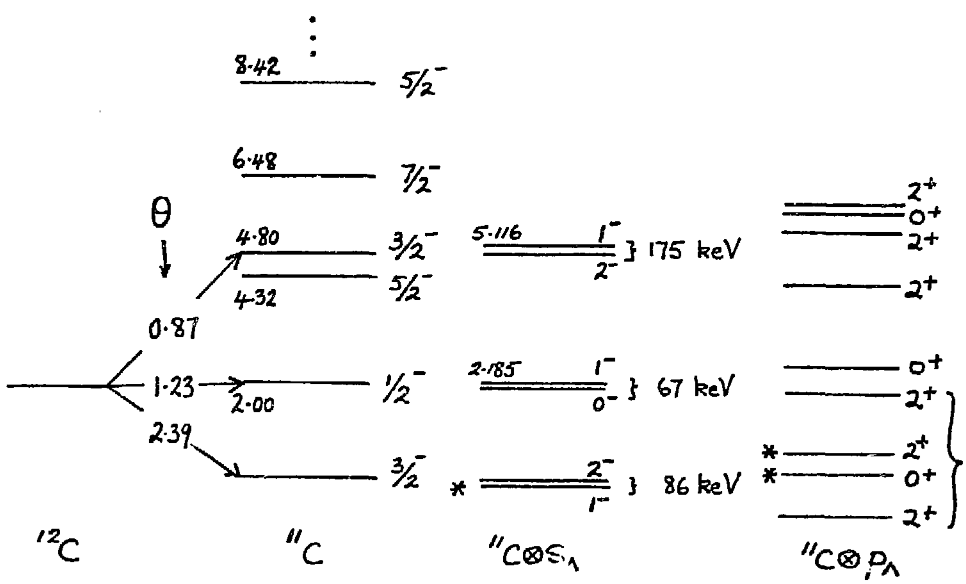

Fig. 1. Low-lying levels of ${}^{11}C$ and of the hypernuclear states formed by coupling s_Λ or p_Λ to this core.

the spectroscopic amplitudes for nucleon pickup which govern[10] the formation cross sections of hypernuclear states in the (K^-,π^-) reaction (for a weak-coupling state $d\sigma/d\Omega \propto \theta^2$). The low-lying states for $^{11}C \times s_\Lambda$ and $^{11}C \times p_\Lambda$ are also shown in Fig. 1. For $^{11}C \times s_\Lambda$ a weak-coupling structure with small doublet splittings is evident. The ground state wave function is quite pure ^{11}C gs $\times s_\Lambda$ with admixtures at the 1% level; nevertheless the (K^-,π^-) formation strengths for the upper 1^- levels are reduced by destructive admixtures (for $\Delta>0$, $S_\Lambda<0$) to levels which are not observable in magnetic spectrometer experiments. For $^{11}C \times p_\Lambda$, on the other hand, there is considerable mixing of the basis configurations to form states with particular symmetries[10], all the $\Delta L=0$ formation strength being concentrated in the lowest 0^+ state (see §5.3.4 of Ref. 10).

Theoretical estimates for the interaction parameters have been obtained using the Model D potential of Nagels et al.[11] to obtain explicit expressions for the radial forms in Eq. (1). In addition to the first order boson-exchange potentials for the ΛN channel, second order $\Lambda N \to \Sigma N \to \Lambda N$ coupling terms and second order tensor terms are included. An effective interaction is obtained[9] by cutting the potentials off inside a separation distance r_0. For $r_0 = 1.2$ fm, $S_\Lambda = -0.037$, $S_N = 0.075$ and $T = 0.035$. These estimates for S_N and T are used informing the standard $p_N s_\Lambda$ interaction while Δ and S_Λ are estimated from hypernuclear data.

The spin-orbit splitting, $\epsilon_p = \epsilon_{p1/2}(\Lambda) - \epsilon_{p3/2}(\Lambda)$, is related to S_Λ by $\epsilon = -6S_\Lambda$. The first deduction of the smallness of this splitting come from analysis of the $^{16}O(K^-,\pi^-)^{16}_\Lambda O$ reaction[2]. Subsequently, an analysis[3] of $^{13}C(K^-,\pi^-)^{13}_\Lambda C$ data gave $\epsilon_p = 0.36 \pm 0.30$ MeV and hence $S_\Lambda = -0.06 \pm 0.05$. A new estimate of S_Λ comes from the recent observation[4] of a 3.08 MeV γ ray in $^9_\Lambda Be$. This line corresponds to the deexcitation of the first excited $3/2^+$, $5/2^+$ doublet to $^9_\Lambda Be$ g.s. An upper limit of 100 keV for the separation of the doublet gives

$$\left|2.48S_\Lambda - 0.73T\right| < 0.1 \qquad (4)$$

For $T > 0$, $S_\Lambda < 0$ a conservative upper limit is $|S_\Lambda| \le 0.04$.

The $1^+,0^+$ doublet splitting in the A=4 hypernuclei[6], if naively attributed to the spin-spin interaction, is equal to I_0. Using a potential of range $\mu = 1$ fm to estimate the Talmi integrals gives $0.40 \le \Delta \le 0.64$ based on extreme assumptions about the size of the A=4 hypernuclei relative to the p-shell hypernuclei. In the case of $^7_\Lambda Li$ (see Fig. 2 of R.E. Chrien's contribution[8] to this conference) the ground state doublet splitting depends mainly on Δ since the ^6Li g.s. has $L = 0$, $S = 1$. Unfortunately the $3/2^+$ member is difficult to populate, particularly if the $1/2^+$; $T = 1$ level is particle unstable. However, the 0^+; $T = 1$ core state has $L = 0$, $S = 0$ so that $B_\Lambda(^7_\Lambda Be)$ receives little contribution from spin-dependent ΛN forces. Consequently

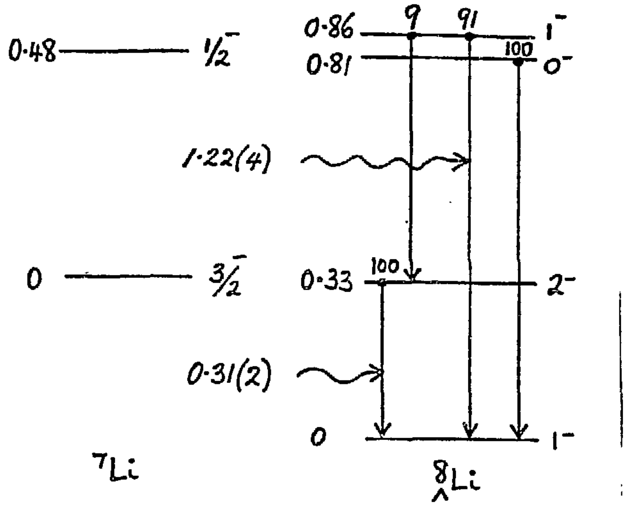

Fig. 2 Levels of ^{7}Li and $^8_\Lambda$Li; possible identifications of observed γ rays are indicated.

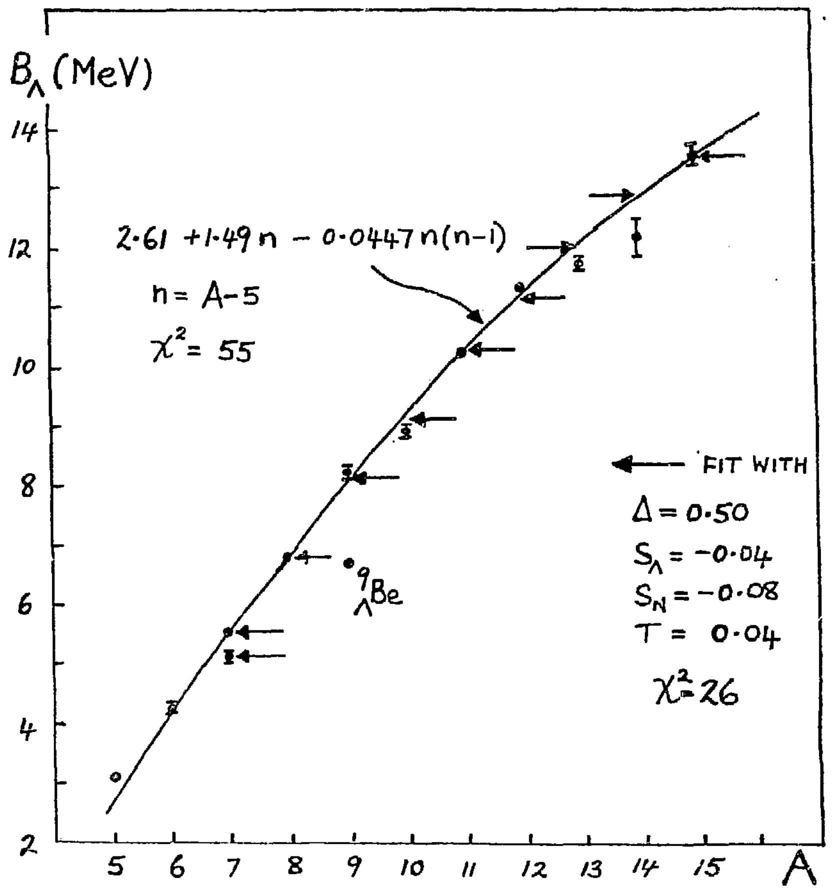

Fig. 3 Binding energies of p-shell hypernuclei.

$$3/2[B_\Lambda({}^7_\Lambda\mathrm{Li}) - B_\Lambda({}^7_\Lambda\mathrm{Be})] = 3/2[0.42 \pm 0.09]\ \mathrm{MeV}$$

$$\approx E(3/2^+) - E(1/2^+) = 1.35\Delta + 0.15S_\Lambda - 1.29T - 0.06S_N \qquad (5)$$

from which we deduce $\Delta \approx 0.50 \pm 0.11$ in agreement with the estimate from A=4. Also, the $5/2^+ \rightarrow 1/2^+$ γ transition has been observed[4] with $E_\gamma = 2.18 + 0.07\Delta - 1.00\ S_\Lambda + 0.22T + 0.95S_N =$ 2.034 ± 0.023 MeV. For the standard parameters only S_N lowers the energy, $S_N \approx -0.25$ being required to give the observed transition energy.

In the case of ${}^{10}_\Lambda$B only the members of the ground state doublet will be particle stable and it is the 2^- member which will be formed in the (K^-,π^-) reaction. A separation $E(2^-) - E(1^-) =$ 170 keV [$\approx \delta$; Eq. (3)] is obtained from the full calculation in good agreement with the preliminary measurement of 156 keV reported by R. E. Chrien[8].

The ${}^8_\Lambda$Li states based on the ^{7}Li ground and first excited states are shown in Fig. 2. The mixing angle governing the structure of the 1^- ground state is constrained by an analysis[12] of ${}^8_\Lambda\mathrm{Li} \rightarrow \pi^- + {}^8\mathrm{Be}^* \rightarrow \pi^- + \alpha + \alpha$ data to $-0.40 < \varepsilon < -0.13$ or $-1.2 < \varepsilon < -0.9$ (ε in radians). This result has been difficult to reconcile with the solutions found by Gal, Soper and Dalitz[1]. The present calculations give $\varepsilon = -0.35$. Two tentative assignments[5] of γ rays to ${}^8_\Lambda$Li are indicated in Fig. 2. While it is difficult to obtain a separation as large as 1.22 MeV for the 1^- levels the energy of the second γ ray is close to the predicted separation of the ground state doublet.

Finally it is interesting to ask how well the B_Λ values for the p shell hypernuclei can be fitted. In Fig. 3 the solid line represents a fit by a quadratic in the number of p shell nucleons to the data[1,13] omitting ${}^5_\Lambda$He, ${}^6_\Lambda$He and ${}^9_\Lambda$Be, the first on the grounds that ${}^5_\Lambda$He is probably more compact than the heavier hypernuclei and the latter two on the grounds that the core nucleus, the mass of which enters into B_Λ, is unbound. The constant term represents the single particle energy for s_Λ relative to a ^{4}He core, the linear term $\bar{V}$ and the quadratic term provides a crude approximation to a (repulsive) three-body ΛNN interaction. The χ^2 of 55 drops to 26 when the data are refitted with the spin-dependent ΛN terms included and fixed at the standard values (the fitted values are indicated by arrows in Fig. 3). Any attempt to improve χ^2 by varying one of Δ, S_Λ, S_N or T leads to a very small change in the parameter and little change in χ^2.

SUMMARY

It has been possible to find a set of parameters for the $p_N s_\Lambda$ interaction which fits all available data—such as ground state spins, excitation energies, B_Λ values etc.—on p-shell hypernuclei. This interaction is also consistent with $p^n p_\Lambda$ data[10]. There is a need for data at the end of the shell where there is a strong sensitivity to the tensor force [see δ', Eq. (3)]. The present calculations give 84 keV for the ground state doublet splitting in $^{16}_{\Lambda}O$ (and $J^\pi = 0^-$ for the ground state). However, a very small splitting, such that the excited level would undergo predominantly weak decay, could occur for a perfectly reasonable value of T. In general more data will provide consistency checks and c[illegible]ld test the basic assumption of a constant two-bo[illegible].

[illegible]NTS

This w[illegible]form[illegible]ation with A. Gal, C. B. Dover and R. [illegible] Dalitz. A [illegible]plete account can be found in Ref. 9 and many details are c[illegible]ained in Ref. 7. We have benefitted from many conversations with R. E. Chrien and M. May. Work supported by U.S. Department of Energy under contract DE-AC02-76CH00016.

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