STRUCTURE OF P-SHELL HYPERNUCLEI

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New γ-ray data for $^7\Lambda$Li from KEK E419 and new (s+, K+) data on $^{12}$C, $^{13}$C, and $^{16}$O targets from KEK E336 and E369 is used to update Millener, Gal, Dover and Dalitz's 1985 analysis of the spin dependence of the effective ΛN interaction.

1 Introduction

With only very limited YN two-body scattering data available, baryon-baryon potential models based on meson exchange rely heavily on the extension of NN potential models to the strangeness -1 sector by use of symmetry schemes to relate the coupling constants at different baryon-baryon-meson vertices, cutoff parameters in form factors, and so on. When applied to hypernuclei in the form of G-matrix interactions derived from the potentials by solving the ΛN-ΣN coupled channels problem, the YN interactions give a qualitative description of the overall binding energies of Λ hypernuclei characterized by the depth of the Λ-nucleus potential well required to describe the binding energies of Λ single-particle states for a wide range of orbits and masses. However, the spin-dependence of the YN interactions, particularly the central spin-spin interaction, varies greatly.

In this situation, it has long been recognized that the energy spectra of Λ hypernuclei can provide rather direct information on the spin dependence of the effective AN interaction. Given that the AN interaction is weaker than the NN interaction and that the Pauli principle is absent for the Λ in a Λ hypernucleus, the properties of the in-medium ΛN effective interaction are more simply related to the properties of the free YN interaction than in the corresponding case for ordinary nuclei. For the particular case of p-shell hypernuclei with the Λ in a 0s orbit, there are only five radial integrals which characterize the $p_Ns_\Lambda$ effective interaction. Of these one characterizes the strength of the spin-independent central interaction while the remaining four characterize the overall strengths of the central spin-spin, symmetric spin-orbit, antisymmetric spin-orbit, and tensor interactions.

Experimentally, an important step forward has been made with the development of a 14 element array (Ge ball) of BGO suppressed Ge detectors for hypernuclear γ-ray spectroscopy. The results of a very successful first experiment on $^7\Lambda$Li, performed at KEK in the summer of 1998, are reported at this meeting by Tanida. Two γ rays with energies of 2.05 MeV and 0.69 MeV, corresponding to the ground-state transitions from the first 5/2$^+$ and 3/2$^+$ states of $^7\Lambda$Li, have been observed; the latter transition represents the first measurement of an $s_\Lambda$ doublet splitting in a p-shell hypernucleus. In addition, the lifetime of the 5/2$^+$ level has been measured.

After a brief review of the parametrization of the $p_Ns_\Lambda$ effective interaction in Sec. 2, it is shown in Sec. 3 how the new data on $^7\Lambda$Li from KEK E419 affects the values of the parameters used by Millener, Gal, Dover, and Dalitz in their 1985 fit to the then available data on p-shell hypernuclei. The remaining
sections examine the consistency of the parametrization which fits the $^7\text{Li}$ data with recent ($\pi^+, K^+$) data on $^{12}\text{C},^{13}\text{C}$, and $^{16}\text{O}$ targets from KEK E336 (presented at this meeting by Hashimoto) and from KEK E369 for a $^{12}\text{C}$ target (presented at this meeting by Nagae).

2 Effective Interaction Parameters

By taking the appropriate linear combinations of the symmetric and antisymmetric spin-orbit interactions, the AN effective interaction may be written as

$$V_{\text{NA}}(r) = V_0(r) + V_s(r)s_N.s_A + V_A(r)l_NA.s_A + V_N(r)l_NA.s_N + V_T(r)S_{12}.$$ 

In shell-model calculations for $s^4p^{4-5}s_A$ configurations, the two-body AN interaction can be expressed in terms of five radial integrals, one associated with each term in the above expression and conventionally denoted by $V$, $\Delta$, $S_A$, $S_N$, and $T$. If the same harmonic oscillator (HO) wave functions are used for the N and the A, then $V$ and $\Delta$ are the average of radial integrals in relative 0s and 0p states while only relative $p$-state integrals contribute for the non-central interactions. If, on the other hand, it is assumed that $\hbar w_N = \hbar w_A$, the relative $s$-state and $p$-state intensities are weighted by factors $m_N/(m_N + m_A)$ and $m_A/(m_N + m_A)$, respectively. The choice does not affect the phenomenological parametrization of the $p_Ns_A$ interaction but does affect the relationship to matrix elements which involve $p_A$ orbits.

A selection of parametrizations of the $p_Ns_A$ interaction is given in Table 1. The first line contains the MGDD parametrization in which the spin-spin parameter $\Delta$ is chosen to be consistent with the average $0^+, 1^+$ separation in the $A = 4$ hypernuclei while the remaining spin-dependent parameters are chosen to be roughly consistent with estimates based on the Nijmegen model D potential. The parametrization of Fetisov et al. takes into account the non-observation of a $\gamma$ ray between the members of the ground-state doublet of $^{15}\text{B}$, and the assignment of a 440-keV $\gamma$ ray to a transition between the members of the ground-state doublet in $^{7}\text{Li}$ (this assignment is now invalidated by the results of KEK E419). The next three lines of Table 1 show parameters deduced from the finite-nucleus G-matrix calculations.

<table>
<thead>
<tr>
<th>parametrization</th>
<th>$V$</th>
<th>$\Delta$</th>
<th>$S_A$</th>
<th>$S_N$</th>
<th>$T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGDD</td>
<td>0.50</td>
<td>-0.04</td>
<td>-0.08</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Fetisov</td>
<td>0.30</td>
<td>-0.02</td>
<td>-0.10</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>G(JA)</td>
<td>-0.992</td>
<td>0.020</td>
<td>-0.005</td>
<td>-0.327</td>
<td>0.063</td>
</tr>
<tr>
<td>G(JB)</td>
<td>-1.099</td>
<td>-1.316</td>
<td>0.014</td>
<td>-0.324</td>
<td>0.066</td>
</tr>
<tr>
<td>G(JB)*</td>
<td>-1.183</td>
<td>-1.590</td>
<td>0.044</td>
<td>-0.413</td>
<td>0.056</td>
</tr>
<tr>
<td>G(NSC89)</td>
<td>-0.901</td>
<td>1.106</td>
<td>-0.200</td>
<td>-0.190</td>
<td>0.058</td>
</tr>
<tr>
<td>3-body</td>
<td>0.131</td>
<td>0.470</td>
<td>0.013</td>
<td>0.009</td>
<td>0.002</td>
</tr>
<tr>
<td>$V_{\text{eff}}$</td>
<td>-0.840</td>
<td>1.414</td>
<td>-0.160</td>
<td>-0.230</td>
<td>0.055</td>
</tr>
</tbody>
</table>

Table 1. $p_Ns_A$ interaction parameters, radial integrals in MeV.

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for the energy-independent versions of the Jülich A and B potential models\(^8\) (\(h\omega_N = h\omega_A = 11\) MeV, except for the case marked by an asterisk, for which \(h\omega_N = 14\) MeV). The next line shows similar G-matrix results\(^8\) for the Nijmegen soft-core potential\(^9\), followed by the contribution of the lowest-order 3-body diagram in which a \(\Lambda\) converts to a \(\Sigma\) one one nucleon and converts back on another nucleon. The final line shows the result of summing the folded-diagram series to obtain an energy-independent effective interaction.

As is well-known\(^1\), the JB and NSC89 interactions represent extremes for the spin-spin interaction, which is basically unconstrained by the existing YN data. As discussed by Rijken at this meeting, the strength of the spin-spin interaction is strongly correlated with value of the magnetic \(F/(F + D)\) ratio \(\alpha_F\) for the vector mesons, a fact which has been exploited in the construction of a new set of six NSC97 potential models\(^11\). For three of these (NSC97\(a,b,c\)) \(\Delta < 0\) while for the remaining three (NSC97\(d,e,f\)) \(\Delta > 0\), with models e and f favored by the empirical value of \(\Delta\) required to fit the data from light hypernuclei. It is interesting to note that for NSC89 the 3-body diagram makes a repulsive contribution to \(V\) and a substantial contribution to \(\Delta\). The 3-body contribution in this case should represent an upper limit because it is believed\(^1\) that the \(\Lambda - \Sigma\) coupling for NSC89 is too strong. There is a need to calculate finite-nucleus effective interactions for NSC97 models using the methods represented by the last three lines of Table 1. The NSC97 models also exhibit substantial odd-state repulsion in the central interaction, a fact which is of importance when the \(\Lambda\) is in a \(0p\) orbit.

The Jülich interactions have the feature that the symmetric and antisymmetric spin-orbit forces are comparable in magnitude and opposite in sign, leading to a small value for \(S_A\) and a substantial value for \(S_N\). As will be seen, this feature seems to be consistent with the existing data on p-shell hypernuclear spectra. In the Nijmegen interactions, the same type of coherence exists but the ordinary (symmetric) spin-orbit interaction is dominant. Finally, the tensor matrix element \(T\) is about the same for all interactions.

\[ \Lambda \text{Li} \]

A spectrum of \(\Lambda \text{Li}\) which reflects the new information on \(\gamma\)-ray transitions from KEK E419, namely the energies of 2050 keV and 690 keV for the \(5/2^+ \rightarrow gs\) and \(3/2^+ \rightarrow gs\) transitions, is shown in Fig. 1. Fig. 1 is an update of the corresponding figure of MGDD in two respects. First, a p-shell effective interaction (hereafter labelled DJM) from a fit to energy levels of the \(A = 6 - 9\) nuclei is used in place of the CK616 interaction (see later for the rationale for this change). Second, the value of \(S_N\) for MGDD in Table 1 is increased in magnitude to \(-0.47\) MeV to fit the experimental excitation energy of 2.05 MeV for the \(5/2^+\) level; the need for a similar but smaller change in \(S_N\) was noted by MGDD for the case of the CK616 interaction. Fig. 1 also incorporates information from a very recent \(\Lambda\)He + \(N + N\) three-body calculation\(^12\), reported on at this meeting by Kamimura, in that the \(\gamma\)-ray branching ratios use the B(M1) and B(E2) values of Hiyama et al.\(^12\) and the "experimental" energies. The calculated \((\pi^+, K^+)\) cross sections (in \(\mu b\)) integrated from \(0^\circ - 15^\circ\) are taken from the appendix of Hiyama et al. From the information
in Fig. 1, one can calculate the relative yields of \(\gamma\)-rays (ignoring a small \(\sim 2\%\) weak-decay branch for the \(5/2^+\) level)

\[
\frac{5}{2}^+ \rightarrow gs = (1.23 + 0.08 \times 0.85) \times 0.962 = 1.249
\]

\[
\frac{3}{2}^+ \rightarrow gs = 0.13 + 1.298 \times 0.038 + 0.08 \times 0.15 + 0.60 \times 0.52 = 0.503
\]

\[
\frac{1}{2}^+ \rightarrow \frac{3}{2}^+ = 0.60 \times 0.52 = 0.312
\]

\[
\frac{1}{2}^+ \rightarrow gs = 0.60 \times 0.48 = 0.288
\]

Taking into account the fact that the detector efficiency for 0.69 MeV \(\gamma\) rays is 2.3 times higher than for 2.05 MeV \(\gamma\) rays, it can be seen that the yields of the two \(\gamma\) rays should be comparable, which is indeed the case. This is strong evidence that the \(T = 1\) \(1/2^+\) state \(\gamma\) decays, whether or not it lies above the \(\Lambda He + d\) threshold.
5.65 ———— 1+  
4.31 ———— 2+  
3.700 ———— 4He + n + p  
3.563 ———— 0+  
2.186 ———— 3+  
1.475 ———— 4He + d  
0 ———— 1+  
  T = 0  S = 1  
  T = 1  S = 0

Figure 2. Spectrum of $^6$Li.

It also means that Doppler-broadened γ-ray lines with energies of ~ 3.3 MeV and ~ 4 MeV should be present in the spectrum but with intensities somewhat below the detection efficiency of E419.

The spectrum of the core nucleus $^6$Li, to which the $s_A$ is coupled to form $^7$Li, is shown in Fig. 2. The Cohen and Kurath interactions$^{13}$ do not fit the $^6$Li spectrum particularly well and exhibit the peculiarity that the single-particle spin-orbit splitting at $A = 5$ is small but grows to ~ 6 MeV to fit $A = 15$. This is achieved by having a one-body spin-orbit interaction masquerade as a two-body interaction, its effective strength therefore increasing linearly with the number particles; all 6 two-body spin-orbit matrix elements (4 ALS) can be substantial in contrast to the dominant role of the odd-state spin-orbit interaction in a G-matrix. The DJM interaction represents a fit to 32 energy levels for $A = 6 – 9$, much in the spirit of Kumar$^{14}$ ($A = 5$ spin-orbit splittings of ~ 3.5 and ~ 4 MeV, respectively). The $^6$Li LS coupling ground-state wave functions for the CK616 and DJM interactions are shown in Table 2.

The small quadrupole moment of $^6$Li ($Q = -0.083$ fm$^2$) provides a tight constraint on the wave function, as discussed by Elliott$^{15}$ in 1953 (then, $|Q| < 0.1$ fm$^2$), via

$$Q(^6$Li) = e^0 \sqrt{2/5}(-\sqrt{5}a/\beta + \sqrt{5}/2\gamma^2 - 7/2\sqrt{10}/\beta^2)b^2$$
Table 2. Ground-state wave functions for $^6$Li.

<table>
<thead>
<tr>
<th>$^6$Li(gs) =</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CK616</td>
<td>0.9576</td>
<td>0.2777</td>
<td>0.0761</td>
</tr>
<tr>
<td>DJM</td>
<td>0.9873</td>
<td>0.0422</td>
<td>0.1532</td>
</tr>
</tbody>
</table>

where $e^0 = (1 + \delta e_p + \delta e_n)/2$ and $b$ is the harmonic oscillator length parameter. Independent of $e^0$ and $b$, CK616 gives an order of magnitude larger $Q$ than DJM (which gives $Q = -0.133$ fm$^2$ for $e^0 = 0.815$ and $b = 1.77$ fm). The point is that direct mixing of $^3S_1$ and $^3D_1$ via the tensor force gives $\alpha/\beta > 0$ while indirect mixing via the one-body spin-orbit interaction gives the opposite sign. This is in exact analogy to the famous cancellation for $^{14}$C $\beta$ decay; a similar interplay leads to small mixings between the dominantly $^2F$ and $^4P$ $5/2^-$ states in $^7$Li and $^7$Be.

The smaller $^3D$ admixture in the DJM wave function has a substantial effect on the energy separation of the ground-state doublet in $^7$Li, as can be seen from Table 3 where the coefficients of the AN interaction parameters are listed for both MGDD and DJM. The separation is raised from 610 keV for MGDD to 712 keV for DJM, which is close to the measured separation of $\sim 690$ keV. As the last line of Table 3 shows, the spin-spin contribution is dominant.

Table 3. Splitting of $^7$Li gs doublet $\Delta E_{AN}$.

<table>
<thead>
<tr>
<th>$\Delta$</th>
<th>$S_A$</th>
<th>$S_N$</th>
<th>$T$</th>
<th>$\Delta E_{AN}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGDD</td>
<td>1.348</td>
<td>0.152</td>
<td>-0.059</td>
<td>-1.301</td>
</tr>
<tr>
<td>DJM</td>
<td>1.444</td>
<td>0.054</td>
<td>0.016</td>
<td>-0.271</td>
</tr>
<tr>
<td></td>
<td>722</td>
<td>-2</td>
<td>-7</td>
<td>-11</td>
</tr>
</tbody>
</table>

Table 4 shows a similar breakdown for the excitation energy of the $5/2^+$ state. Here $S_N$ is the only contribution which lowers the excitation energy (unless $S_A > 0$), and a value of $-0.47$ MeV is required to obtain agreement with the experimental excitation energy of 2.05 MeV for the DJM case if the other parameters remain at their MGDD values. The enhanced nuclear spin-orbit interaction due to $S_N$ increases the separation of states in the $L = 2$, $S = 1$ triplet in the $^6$Li core (see Fig. 2), thus lowering the $3^+$ level.

Table 4. $5/2^+ - 1/2^+$ separation $\Delta E = 2186 + \Delta E_{AN}$.

<table>
<thead>
<tr>
<th>$\Delta$</th>
<th>$S_A$</th>
<th>$S_N$</th>
<th>$T$</th>
<th>$\Delta E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGDD</td>
<td>0.075</td>
<td>-1.003</td>
<td>0.952</td>
<td>0.226</td>
</tr>
<tr>
<td>DJM</td>
<td>0.154</td>
<td>-1.105</td>
<td>0.678</td>
<td>1.095</td>
</tr>
<tr>
<td></td>
<td>77</td>
<td>44</td>
<td>-319</td>
<td>44</td>
</tr>
</tbody>
</table>

An interesting question to ask is whether the $5/2^+$ and $3/2^+$ states based on the
2+; 1 core state are likely to γ decay in 7Li. To isospin mix the 1D2 and 3P2 basis states with the 3D2 2+; 0 state requires the electromagnetic spin-orbit interaction, and an estimate by Bray et al.\textsuperscript{16} gives an admixture of $2 \times 10^{-4}$. Using an $\alpha + d$ potential well which accounts for the widths of the 3+ and 2+ levels in 6Li, gives an estimate of 28 eV for $\Gamma_2$ in 7Li, a value which is much greater than the estimated $\Gamma_\gamma$ of $\sim 2$ eV. The DJM calculation gives a separation of only 10 keV for the 5/2+ and 3/2+ $T = 1$ levels so that, in this case, both levels would be expected to weak decay in 7He.

In this section, it has been shown that the calculated spin-dependent splittings in 7Li are quite sensitive to the choice of core wave functions. If the DJM $p$-shell interaction (non-central interactions fixed, central and one-body spin-orbit interactions fitted to $A = 6 - 9$) is used, the only change needed in the MGDD parametrization of the AN effective interaction is to increase $S_N$ from $-0.08$ to $-0.47$ MeV (the necessity for a change to $\sim -0.25$ MeV when using the CK616 interaction was noted by MGDD). This change lowers the excitation energy of the 5/2+ level in 7Li. The new set of parameters which define the modified MGDD interaction are

$$\Delta = 0.50 \quad S_A = -0.04 \quad S_N = -0.47 \quad T = 0.04$$

In the next sections, it is asked whether the change in $S_N$ is consistent with recent ($\pi^+, K^+$) data from KEK on 12C, 13C, and 16O targets.

4 13C

Although the spectrum of 13C observed in $(K^-, \pi^-)$ and $(\pi^+, K^+)$ reactions is rather complex\textsuperscript{17} because the neutron removal parentage from the 13C ground state goes to widely-separated states of both [44] and [431] spatial symmetry in 12C, the 1/2+ ground state and the 3/2+ state based on the 4.44-MeV 2+ level of 12C are strongly populated and well separated from each other and higher states. From the high-statistics ($\pi^+, K^+$) data from KEK E336\textsuperscript{18} it is possible to obtain an accurate value for the separation energy of these two states, the preliminary value from E336 being 4.89(7) MeV. This excitation energy is considerably larger than the unperturbed separation energy of 4.44 MeV and the MGDD value of 4.49 MeV, and is primarily sensitive to $S_N$, as may be seen from

$$E_x(3/2^+) = 4.44 - 0.044\Delta - 1.455S_A - 0.803S_N - 1.142T$$

with the modified MGDD interaction (CKPOT for the core) which gives an excitation energy of 4.81 MeV for the 3/2+ state.

5 12C

In this case, the neutron removal spectrum is rather simple with the parentage to the 11C ground state being strongest and the only other significant parentage being to the 2.00-MeV 1/2– and 4.80-MeV 3/2– states, leading to three 1– states which can be populated by non-spin-flip transitions in the $(\pi^+, K^+)$ reaction. The
energies of the $1^-$ excited states are again sensitive to $S_N$ and are given by

\[ E_1(1^-) = 2.00 + 0.336\Delta + 1.130S_A - 0.909S_N + 0.703T \]

\[ E_2(1^-) = 4.80 + 0.383\Delta - 0.397S_A - 1.336S_N + 0.488T \]

Results for the excitation energies and formation strengths, represented by the square of the $L=1, S=0$ one-body density-matrices, are given in Table 5 for the weak-coupling limit, the MGDD interaction, and the modified MGDD interaction. As noted in MGDD, $\Delta > 0$ leads to constructive admixtures for the ground-state cross section and destructive admixtures for the excited states.

<table>
<thead>
<tr>
<th>$S_N$</th>
<th>$\rho^2(1^-)$</th>
<th>$E(1^-)$</th>
<th>$\rho^2(1^-)$</th>
<th>$E(1^-)$</th>
<th>$\rho^2(1^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC</td>
<td>0.475</td>
<td>2.00</td>
<td>0.125</td>
<td>4.80</td>
<td>0.063</td>
</tr>
<tr>
<td>-0.08</td>
<td>0.540</td>
<td>2.19</td>
<td>0.075</td>
<td>5.12</td>
<td>0.048</td>
</tr>
<tr>
<td>-0.47</td>
<td>0.527</td>
<td>2.54</td>
<td>0.083</td>
<td>5.66</td>
<td>0.054</td>
</tr>
</tbody>
</table>

Table 5. Excitation energies and formation strengths for $1^-$ states in $^{12}$C.

The increase in the excitation energies shown in the last line of Table 5 gives much better agreement with the results from three KEK experiments, namely 2.58(17) MeV from E140, 2.71(13) MeV from E336, and 2.83(9) MeV from E369 (Nagae, this meeting) for the second $1^-$ level. This is also true for the energy of the third $1^-$ level, although in this case there is no clear separation from higher positive-parity levels based on $1h\omega$ positive-parity states of the $^{11}$C core.

6 $^{16}$O

The splitting between the lowest two $1^-$ states, based on the $p_{1/2}$ and $p_{3/2}$ neutron hole states, in $^{16}$O is substantially increased with the modified MGDD interaction, as can be seen from the expression below

\[ E(1^-) - E(1^-) = 6.176 - 0.24\Delta - 1.25S_A - 1.50S_N - 0.73T . \]

In this case, the predicted energy separation of 6.75 MeV is considerably larger than the preliminary value of 6.26 MeV from KEK E336, which is puzzling given the evidence from $^{15}$C and $^{13}$C. The energy centroid of the peak associated with the $1^-_2$ level should be lowered somewhat by the population of a $2^+$ level built on the the 5.24-MeV $5/2^+$ level of $^{15}$O but this effect should modest because the cross section estimated from the spectroscopic factor deduced from the $^{18}$O($e,e'p$) reaction is only 10% of that for the $1^-_2$ level.

As is well known, the splitting of the ground-state doublet is very sensitive to the $\Lambda N$ tensor interaction

\[ E(1^-_1) - E(0^-) = -0.38\Delta + 1.37S_A + 7.87T . \]

and, if the splitting is as small as predicted (86 keV), will have to be measured by observing the difference between the energies of the $\gamma$ rays deexciting the $1^-_2$.
level. Of course, this measurement will also provide an accurate measurement of the separation of the 1− levels.

7 Summary

Experiment E419 at KEK has made the first observation of a γ-ray transition between the members of an sA doublet in a p-shell hypernucleus, namely the ground-state doublet in 7Li. This doublet separation (690 keV) is primarily sensitive to the central spin-spin component of the effective AN interaction, although the transition energy is in fact quite sensitive to the fine details of the 6Li core wave function, and, through a simple shell-model analysis, is in quantitative agreement with the 0+ − 1+ energy separation in the A = 4 hypernuclei. It is clear that only (e) and (f) of the NSC97 potential models have a central spin-spin interaction of the correct sign and approximately the correct magnitude (the Jülich interactions are not satisfactory in this regard). In the above cases, the effective ANN interaction which arises from the AN−ZN coupling contributes to the energy separations (see Sec. 2) and needs to be evaluated by many-body effective interaction theory for finite nuclei, as discussed by Kuo in these proceedings.

The A-spin dependent component of the effective AN spin-orbit interaction is known to be small, the best upper limit coming from the separation of the 5/2+, 3/2+ doublet in 6Be (new data from BNL E930, which uses the Ge ball, is currently under analysis). The energy separations of states belonging to different sA doublets are generally sensitive to the nucleon-spin dependent component of the AN spin-orbit interaction. This is the case for the 5/2+ − 1/2+ transition in 7Li, measured previously with NaI detectors at BNL but more precisely in KEK E419. Again, the value of SN required to fit the transition energy is sensitive to details of the 6Li core wave functions. An interesting observation is that the large value SN = −0.47 MeV required to fit the the 5/2+ − 1/2+ transition energy raises the energies of the 1− and 3/2+ excited states in 12C and 13C, respectively, bringing them into much better agreement with the energies deduced from recent (π+, K+) experiments at KEK. For unknown reasons, the Jülich potentials, but not the Nijmegen potentials, qualitatively reproduce the empirical feature of SA small and SN large (comparable magnitudes for the symmetric and antisymmetric spin-orbit interactions).

The influence of the tensor force is strongest at the end of the p-shell, the proposed BNL E930 measurement being that of the 1− 3/2− → 0+ 1− and 1− 3/2− → 1+ 1− transitions, with intensities in the ratio of ~ 3 : 1, in 16O. In addition, the 1− 3/2− → 1+ 1− transition energy provides another check on the value of SN.

In summary, a rather consistent picture of the spin dependence of the effective AN interaction is emerging, although the measurement of several more key γ-ray transition energies in p-shell hypernuclei is required to overdetermine the spin dependence and provide strict consistency checks. Nuclear many-body theory is probably reliable enough to use the measured spin dependence to put very good constraints on AN−ZN potential models. Of course, the empirically determined pNSA matrix elements relate only to an integrated strength for various components of the AN interaction. Sensitivity to odd-state components and quadrupole components of the central force requires the consideration of pNP and other matrix
elements, as noted for $p_A$ states in $p$-shell hypernuclei$^{17}$. Full $1\hbar\omega$ shell-model calculations are needed to properly eliminate spurious center-of-mass states and to account for all the low-lying states which arise from the coupling and an $s_A$ to low-lying non-normal-parity states of the core nucleus. The codes should also include both the effective $\Delta N$ and $\Delta NN$ interactions.

Acknowledgments

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References

9. T.T.S. Kuo, in these proceedings.