Tensor coupling effects on spin symmetry in anti-Lambda spectrum of hypernuclei

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Abstract

The effects of $\bar{\Lambda}\Lambda\omega$-tensor coupling on the spin symmetry of $\bar{\Lambda}$ spectra in $\bar{\Lambda}$-nucleus systems have been studied with the relativistic mean-field theory. Taking $^{12}\text{C}+\bar{\Lambda}$ as an example, it is found that the tensor coupling enlarges the spin-orbit splittings of $\bar{\Lambda}$ by an order of magnitude although its effects on the wave functions of $\bar{\Lambda}$ are negligible. Similar conclusions has been observed in $\bar{\Lambda}$-nucleus of different mass regions, including $^{16}\text{O}+\bar{\Lambda}$, $^{40}\text{Ca}+\bar{\Lambda}$ and $^{208}\text{Pb}+\bar{\Lambda}$. It indicates that the spin symmetry in anti-lambda-nucleus systems is still good irrespective of the tensor coupling.

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Spin symmetry and pseudo-spin symmetry in single particle spectrum of atomic nuclei have been discussed extensively in the literature. In atomic nuclei, there are a very large spin-orbit splitting, i.e., pairs of single particle states with opposite spin \((j = \ell \pm \frac{1}{2})\) have very different energies. This fact has allowed the understanding of magic numbers in nuclei and forms the basis of nuclear shell structure\[1\]. More than thirty years ago pseudo-spin quantum numbers have been introduced by \(\tilde{\ell} = \ell \pm 1\) and \(\tilde{j} = j\) for \(j = \ell \pm \frac{1}{2}\) and it has been observed that the splitting between pseudo-spin doublets in nuclear single particle spectrum is an order of magnitude smaller than the normal spin-orbit splitting \[2, 3\].

Pseudo-spin symmetry (PSS) is an important general feature in the nuclear energy spectra and has been extensively discussed in the framework of the relativistic mean-field (RMF) theory \[4–8\]. Since the relation between the pseudospin symmetry and the RMF theory was first noted in Ref. \[4\], the RMF theory has been extensively used to study the pseudospin symmetry in the nucleon spectrum. In Ref. \[5\], it suggested that the origin of pseudospin symmetry is related to the strength of the scalar and vector potentials. Ginocchio took a step further to reveal that pseudo-orbital angular momentum is nothing but the “orbital angular momentum” of the small component of the Dirac spinor, and showed clearly that the origin of pseudo-spin symmetry in nuclei is given by a relativistic symmetry in the Dirac Hamiltonian \[6\]. The quality of pseudo-spin symmetry has been found to be related to the competition between the centrifugal barrier and the pseudo-spin orbital potential \[7, 8\] within the RMF theory.

Recently, the possibility of producing a new nuclear system with one or more anti-baryons inside normal nuclei has gained renewed interest \[9–13\]. It motivates us to study the spin symmetry in the single \(\bar{\Lambda}\) spectrum, which can provide more information on the antiparticles and their interaction with nuclei.

As the negative energy solutions to the Dirac equation are interpreted as antiparticles under G parity transformation, the RMF theory has been used to investigate the antinucleon spectrum, and a well developed spin symmetry has been found in the antinucleon spectrum \[14\]. The spin symmetry for anti-Lambda spectrum in atomic nuclei has been examined and a better spin symmetry than that in antinucleon has been reported in Ref. \[15\]. However, the impurity effects of \(\bar{\Lambda}\) and tensor coupling effects were neglected there. Here in this work, the spin symmetry in anti-Lambda hypernuclear system will be investigated with both the impurity of \(\bar{\Lambda}\) and tensor coupling included.
The tensor force has been discussed over many decades. Its contribution to the spin-orbit splitting has been discussed by Arima and Terasawa in terms of the second-order perturbation [16]. The importance of the tensor force for the nuclear binding energy has been demonstrated in Ref. [17]. Recently, the tensor force was shown to have a distinct effect on the evolution of the nuclear shell structure [18–22] and appropriate conservation of pseudo-spin symmetry [21, 23, 24]. The importance of tensor coupling effects in reducing the spin-orbit splitting of Λ single particle energy spectrum has been extensively discussed in the single-Λ hypernuclei [25, 27, 28]. Therefore, it is essential to examine further the spin symmetry of ¯Λ in ¯Λ-nucleus system with the presence of ¯Λ ¯Λ ω-tensor coupling with the RMF theory.

For ¯Λ-nucleus system, the corresponding Lagrangian density $\mathcal{L}$ can be written into two parts,

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_{\bar{\Lambda}},$$  \hspace{1cm} (1)

where $\mathcal{L}_N$ is the standard Lagrangian density that has already been extensively and successfully applied to ordinary nuclei [29]. The second part $\mathcal{L}_{\bar{\Lambda}}$ for ¯Λ hyperon with the ¯Λ ¯Λ ω-tensor coupling is given by,

$$\mathcal{L}_{\bar{\Lambda}} = \bar{\psi}_{\bar{\Lambda}} (i\gamma^\mu \partial_\mu - m_{\bar{\Lambda}} - g_{\sigma\bar{\Lambda}} \sigma - g_{\omega\bar{\Lambda}} \gamma^\mu \omega_\mu) \psi_{\bar{\Lambda}} - \frac{f_{\omega\bar{\Lambda}}}{4m_{\bar{\Lambda}}} \bar{\psi}_{\bar{\Lambda}} \sigma^{\mu\nu} \Omega_{\mu\nu} \psi_{\bar{\Lambda}},$$  \hspace{1cm} (2)

where $m_{\bar{\Lambda}}$ is the mass of ¯Λ and chosen as $m_{\bar{\Lambda}} = 1115.7$ MeV, $g_{\sigma\bar{\Lambda}}, g_{\omega\bar{\Lambda}}$ are the coupling strengths of ¯Λ and $\sigma, \omega$ meson fields, and $f_{\omega\bar{\Lambda}}$ is the ¯Λ ¯Λ ω tensor coupling strength. The field tensor $\Omega_{\mu\nu}$ for the $\omega$-meson is defined as $\Omega_{\mu\nu} \equiv \partial_{\mu} \omega_{\nu} - \partial_{\nu} \omega_{\mu}$.

With the mean field and no-sea approximations as well as the stationary condition for hypernuclear system, one obtains the Dirac equation for the ¯Λ,

$$\{ \alpha \cdot \mathbf{p} + \beta (m_{\bar{\Lambda}} + S_{\bar{\Lambda}}) + V_{\bar{\Lambda}} + T_{\bar{\Lambda}} \} \psi_{\bar{\Lambda}} = \epsilon_{\bar{\Lambda}} \psi_{\bar{\Lambda}},$$  \hspace{1cm} (3)

where the scalar potential is $S_{\bar{\Lambda}} = g_{\sigma\bar{\Lambda}} \sigma$, the vector potential $V_{\bar{\Lambda}} = g_{\omega\bar{\Lambda}} \omega_0$ and the tensor coupling potential $T_{\bar{\Lambda}} = -\frac{1}{2m_{\bar{\Lambda}} g_{\omega\bar{\Lambda}}} i \gamma \cdot \nabla V_{\bar{\Lambda}}$. The set of $\epsilon_{\bar{\Lambda}}$ values forms the single-particle energy spectrum of ¯Λ.

According to the G-parity transformation, the coupling strengths for ¯Λ and mesons are related to those for Λ. Taking into account the many-body effects, an universal reduction
factor $\xi$ ($0 < \xi \leq 1$) is introduced as that in Refs. [11, 12],

$$g_{\sigma \Lambda} = \xi g_{\sigma N}, \quad (4)$$
$$g_{\omega \Lambda} = -\xi g_{\omega N}, \quad (5)$$

It has been found that the choice of $\xi = 0.3$ is consistent with the empirical $\bar{p} - A$ optical potential [12] and will be used in the following studies. According to the Okubo-Zweig-Iizuka (OZI) rule in naive quark model, the ratio $\alpha(\equiv f_{\omega \Lambda}/g_{\omega \Lambda})$ of $\Lambda \Lambda \omega$ tensor coupling strength to $\Lambda - \omega$ coupling is taken as $\alpha = -1$ [27, 30].

With the restriction of spherical symmetry, the Dirac spinor of $\Lambda$ has the following form,

$$\psi_{\Lambda}(r) = \frac{1}{r} \left( \begin{array}{c} iG_{n\kappa}(r)Y_{jm}^\ell(\theta, \phi) \\ -F_{n\kappa}(r)Y_{jm}^\ell(\theta, \phi) \end{array} \right), \quad j = l \pm \frac{1}{2}, \quad (6)$$

where $Y_{jm}^\ell(\theta, \phi)$ are the spin spherical harmonics, $G_{n\kappa}(r)/r$ and $F_{n\kappa}(r)/r$ form the radial wave functions for the upper and lower components with $n$ and $\tilde{n}$ radial nodes, and $\kappa = \langle 1 + \sigma \cdot \ell \rangle = (-1)^{j+\ell+1/2}(j + 1/2)$ characterizes the spin orbit operator and the quantum numbers $\ell$ and $j$.

With the restriction of spherical symmetry, the Dirac spinor of $\Lambda$ has the following form,

$$-\frac{1}{2M_{++}^* r^2} \frac{d^2}{dr^2} + \frac{1}{2M_{++}^*} \frac{dV_+}{dr} - \frac{\ell(\ell + 1)}{r^2} G_{n\kappa}(r)$$
$$+ \left\{ \left( \frac{T(r)}{M_{++}^*} - \frac{1}{4M_{++}^* r^2} \frac{dV_+}{dr} \right) \kappa + \frac{1}{2M_{++}^*} \left[ T^2(r) - T'(r) \right] - \frac{1}{4M_{++}^* r^2} \frac{dV_+}{dr} T + m + V_+ \right\} G_{n\kappa}(r) = \epsilon_{\Lambda} G_{n\kappa}(r), \quad (7)$$

with $V_\pm \equiv V_{\Lambda}(r) \pm S_{\Lambda}(r)$, $2M_{\pm}^* \equiv m_\Lambda \pm \varepsilon \mp V_\mp$, $T(r) = -\frac{\alpha}{2m_\Lambda} \partial_r V_{\Lambda}$, and $T'(r)$ is the first derivative of $T(r)$.

One notices in Eq.(7) that the total spin-orbit potential (the term $\sim \kappa$, denoted as “Total”), which determines the energy difference between the spin-orbit partner states, is composed of two terms. The first term is from the contribution of tensor coupling $\left( \frac{T(r)}{M_{++}^*} \right)$, denoted as “Tensor”, and the second term is the original spin-orbit potential from the derivative of central potential $\left( -\frac{1}{4M_{++}^*} \frac{dV_+}{dr} \right)$, denoted as “Central”.

Recently, a new set of parameters for effective $\Lambda$-nucleon interaction with $\Lambda \Lambda \omega$-tensor coupling, PK1-Y1 ($g_{\sigma \Lambda}/g_{\sigma N} = 0.580$, $g_{\omega \Lambda}/g_{\omega N} = 0.620$, $\alpha = -1$) is obtained by global
fitting the binding energies of single-Λ hypernuclei in different mass regions, based on the PK1 effective interaction \[31\] for the nucleon part. The PK1-Y1 set is shown great success in the description of both the single-Λ binding energies and Λ spin-orbit splittings \[32\] and will be adopted in subsequent calculations.

Taking \(^{12}\text{C}+\bar{\Lambda}\) as the first example, the effects of tensor coupling on the spin symmetry in single-\(\bar{\Lambda}\) energy spectrum are studied. Figure 1 shows the single particle spectrum for \(\bar{\Lambda}\) in \(^{12}\text{C}+\bar{\Lambda}\). In order to illustrate the tensor coupling effects on the spin-orbit splittings, the single particle energy spectrum for \(\bar{\Lambda}\) without\((\alpha = 0)\) tensor coupling is also plotted in Fig. 1. For comparison, the corresponding results for Λ in \(^{13}\Lambda\text{C}\) are given as well in the insets. It shows clearly that the spin-orbit splittings of each spin doublet for \(\bar{\Lambda}\) are much smaller than those for Λ if the tensor coupling is not considered \((\alpha = 0)\). However, the opposite phenomena occurs after taking into account the tensor coupling \((\alpha = -1)\), i.e., the spin-orbit splitting size becomes very small for Λ states as found in Refs. \[27, 30, 33, 34\], but significant for \(\bar{\Lambda}\) states.

We show in Fig. 2 the potentials of scalar \(S(r)\), vector \(V(r)\) types and their difference \(S(r) - V(r)\) (cf. Eq.(3)) as well as the spin-orbit potentials (cf. Eq.(7)) for \(\bar{\Lambda}\) in \(^{12}\text{C}+\bar{\Lambda}\) from the RMF calculations without and with the \(\bar{\Lambda}\bar{\Lambda}\omega\)-tensor coupling. For comparison, the
FIG. 2: The comparison of scalar, vector and total potentials (upper panels) and spin-orbit potentials for Λ in \(^{13}\text{C}\) and \(^{\bar{\Lambda}}\text{C}\) from the RMF calculations without (\(\alpha = 0\), dashed line) and with (\(\alpha = -1\), solid line) the tensor coupling.

corresponding results for Λ in \(^{13}\text{C}\) are given as well. As seen in Fig. 2, the vector potential of \(^{\bar{\Lambda}}\text{C}\) changes its sign because of G-parity symmetry. The derivative of the difference between the vector and scalar potentials changes dramatically with the radial coordinate \(r\) only for \(r\) smaller than 1.5 fm, which leads to the central part of spin-orbit potential decreasing rapidly to zero at \(\sim 1.5\) fm. However, for Λ in \(^{13}\text{C}\), it is shown that the difference between the vector and scalar potentials is quite large. As the consequence, the corresponding central part of spin-orbit potential is much larger than that for \(^{\bar{\Lambda}}\text{C}\).

Of particular interesting is the onset of almost opposite phenomena after taking into account the tensor coupling effects. The contribution from tensor coupling ("Tensor") reduces the spin-orbit potential for Λ, but enhances that for \(^{\bar{\Lambda}}\text{C}\). These effects can be observed on the splitting size of spin-orbit partner states, as partly shown in Fig. 1.

In Tab. I, we give the values of spin-orbit splittings,

\[ \Delta E = \epsilon(j = \ell - 1/2) - \epsilon(j = \ell + 1/2) \]  

for Λ in \(^{13}\text{C}\) and for \(^{\bar{\Lambda}}\text{C}\) from the RMF calculations both without (\(\alpha = 0\)) and with (\(\alpha = -1\)) the tensor couplings. To show the tensor coupling effects on the splitting
TABLE I: Spin-orbit splittings of $\Lambda$ in $^{13}_{\Lambda}\Lambda$C and of $\bar{\Lambda}$ in $^{12}\bar{\Lambda}C+\bar{\Lambda}$ from the RMF calculations without ($\alpha = 0$) and with ($\alpha = -1$) tensor coupling. In the calculations with tensor coupling, the expectations of the spin-orbit potentials labeled with “Central”, “Tensor” and “Total” in Fig. 2 are calculated with the dominant components in the Dirac spinors of spin doublets. Their differences are shown respectively in column “$\Delta SOP$”. All energies are in units of MeV. The experimental value of the spin-orbit splitting for $p_\Lambda$ states in $^{13}_{\Lambda}\Lambda$C is $152 \pm 54 \pm 36$ keV [35].

|       | $\Delta E^{\alpha=0}$ | $\Delta SOP$ | $\Delta E^{\alpha=-1}$ |
|-------|------------------------|--------------|-----------------------|
|       |                        | Central      | Tensor                | Total                  |
| $^{13}_{\Lambda}\Lambda$C | $1p$ 1.51 | 1.47 | -1.20 | 0.27 | 0.26 |
|       | $1p$ 0.64 | 0.64 | 1.85 | 2.49 | 2.49 |
| $^{12}C+\bar{\Lambda}$ | $2p$ 0.33 | 0.32 | 1.03 | 1.35 | 1.37 |
|       | $1d$ 0.48 | 0.50 | 2.87 | 3.37 | 3.37 |
|       | $1f$ 0.28 | 0.30 | 3.18 | 3.48 | 3.47 |

quantitatively, we calculate the expectations of the spin-orbit potentials with the dominant components in the Dirac spinors of spin doublets,

$$ SOP \equiv \int dr G(r)^2 \left( \frac{T}{M^2_+} - \frac{1}{4M^2_+} \frac{dV_-}{dr} \right) \frac{\kappa}{r} $$

$$ = - \int dr G(r)^2 \frac{1}{4M^2_+} \frac{d(V - S)}{dr} \frac{\kappa}{r} $$

$$ - \int dr G(r)^2 \frac{1}{M^2_+} \frac{\alpha}{2m_Y} \frac{\partial}{r} \frac{\kappa}{r}. $$

(9)

where the first term is labeled with “Central”, and the second term is labeled with “Tensor”, as indicated in Fig. 2. The difference of the expectations of total spin-orbit potentials between the spin doublets ($\Delta SOP$) gives mainly the observed spin-orbit splittings.

As seen in Tab. I, the spin-orbit splitting for $p_\Lambda$ states of $^{13}_{\Lambda}\Lambda$C is 0.26 MeV, which is in agreement with the corresponding data $152 \pm 54 \pm 36$ keV [35]. For $\bar{\Lambda}$, the spin-orbit splittings of $1p, 2p, 1d, 1f$ states with the tensor coupling contribution are found to be $(1.37 \sim 3.47)$ MeV, which is an order of magnitude larger than those without the tensor coupling $(0.28 \sim 0.64)$ MeV.

It is noted that the spin-orbit splitting without the tensor coupling is almost the same as
FIG. 3: Radial wave functions for $p_{\Lambda}$ states in $^{13}\Lambda C$ (left panel) and $p_{\bar{\Lambda}}$ states in $^{12}C+\bar{\Lambda}$ (right panel). In each case, the top panel represents results without tensor coupling ($\alpha = 0$) and the lower part displays results with tensor coupling ($\alpha = -1$).

the “Central” part of the spin-orbit splitting in the calculations with the tensor coupling. It indicates that the tensor coupling has negligible contribution to the “Central” part of spin-orbit potential through the rearrangement of mean-fields. However, the addition contribution from the tensor coupling to the spin-orbit potential of $\bar{\Lambda}$, corresponding to the “Tensor” term, dominates the final spin-orbit splittings in the calculations with the tensor coupling. Table I shows clearly that the “Tensor” part of the spin-orbit splitting almost cancels the “Central” part for $\Lambda$ states in $^{13}\Lambda C$, but enhances that for $\bar{\Lambda}$ states greatly in $^{12}C+\bar{\Lambda}$.

In Fig. 3, we plot the radial wave functions for $p_{\Lambda}$ states in $^{13}\Lambda C$ and $p_{\bar{\Lambda}}$ states in $^{12}C+\bar{\Lambda}$ from the RMF calculations with and without the tensor couplings. It shows clearly that the tensor coupling effect is significant on the dominant components of Dirac spinors for $\Lambda$ spin-orbit partner states. It recovers the spin symmetry on the wavefunctions of $p_{\Lambda}$ spin-orbit partner states. For $\bar{\Lambda}$, the same good spin symmetry is observed from the calculations with and without the tensor couplings for the dominant components of wavefunctions of spin-orbit partner states, because the spin-orbit potential of $\bar{\Lambda}$ ($\sim 1$ MeV) is much smaller than the corresponding total potential $V_{\bar{\Lambda}} + S_{\bar{\Lambda}}$ ($\sim 280$ MeV). Therefore, the changing of spin-orbit potentials due to the tensor coupling has negligible influence on the final wavefunctions of $\bar{\Lambda}$ states.

The tensor coupling effects on the spin-orbit splittings for $\bar{\Lambda}$ have been studied system-
TABLE II: Spin-orbit splittings for different single-particle states of $\bar{\Lambda}$ in $^{16}\text{O}+\bar{\Lambda}$, $^{40}\text{Ca}+\bar{\Lambda}$, and $^{208}\text{Pb}+\bar{\Lambda}$ from the RMF calculations without ($\alpha = 0$) and with ($\alpha = -1$) tensor coupling. All energies are in units of MeV.

| Energy Level | $\Delta E^{\alpha=0}$ | $\Delta SOP$ | $\Delta E^{\alpha=-1}$ |
|--------------|------------------------|--------------|------------------------|
|              | Central | Tensor | Total | Central | Tensor | Total | Central | Tensor | Total |
| $1p$         | 0.39    | 0.40   | 1.48   | 1.88    | 1.88    | 1.88    | 1.88    | 1.88    | 1.88    |
| $2p$         | 0.23    | 0.22   | 0.89   | 1.11    | 1.12    | 1.12    | 1.11    | 1.12    | 1.12    |
| $^{16}\text{O}+\bar{\Lambda}$ | $1d$ | 0.29    | 0.30   | 2.11   | 2.41   | 2.41   | 2.41    | 2.41    |
|              | $1f$    | 0.18    | 0.19   | 2.30   | 2.49   | 2.48   | 2.48    | 2.48    |
| $^{40}\text{Ca}+\bar{\Lambda}$ | $1d$ | 0.08    | 0.09   | 0.73   | 0.82   | 0.82   | 0.82    | 0.82    |
|              | $2d$    | 0.17    | 0.18   | 1.29   | 1.47   | 1.46   | 1.46    | 1.46    |
|              | $1f$    | 0.05    | 0.05   | 0.70   | 0.75   | 0.75   | 0.75    | 0.75    |
| $^{208}\text{Pb}+\bar{\Lambda}$ | $1d$ | 0.00    | 0.00   | 0.05   | 0.05   | 0.05   | 0.05    | 0.05    |
|              | $2d$    | 0.03    | 0.03   | 0.27   | 0.30   | 0.30   | 0.30    | 0.30    |
|              | $1f$    | 0.00    | 0.01   | 0.06   | 0.07   | 0.06   | 0.06    | 0.06    |

Attractically for $\bar{\Lambda}$-nucleus in different mass regions, including $^{16}\text{O}+\bar{\Lambda}$, $^{40}\text{Ca}+\bar{\Lambda}$ and $^{208}\text{Pb}+\bar{\Lambda}$ as shown in Tab. II. The tensor coupling effects on the spin-orbit splitting for $^{16}\text{O}+\bar{\Lambda}$, $^{40}\text{Ca}+\bar{\Lambda}$ and $^{208}\text{Pb}+\bar{\Lambda}$ are similar as those for $^{12}\text{C}+\bar{\Lambda}$. Specifically, the spin-orbit splittings of $\bar{\Lambda}$ in the calculations with the tensor coupling are found to be $(1.12 \sim 2.48)$ MeV in $^{16}\text{O}+\bar{\Lambda}$, $(0.75 \sim 1.48)$ MeV in $^{40}\text{Ca}+\bar{\Lambda}$, and $(0.05 \sim 0.76)$ MeV in $^{208}\text{Pb}+\bar{\Lambda}$, which are an order of magnitude larger than those from the calculations without the tensor coupling, i.e., $(0.16 \sim 0.39)$ MeV in $^{16}\text{O}+\bar{\Lambda}$, $(0.05 \sim 0.26)$ MeV in $^{40}\text{Ca}+\bar{\Lambda}$, and $(0 \sim 0.15)$ MeV in $^{208}\text{Pb}+\bar{\Lambda}$. Moreover, it is noted that the spin-orbit splittings for $\bar{\Lambda}$ decrease with the mass
number $A$ no matter the tensor coupling is considered or not.

In summary, the tensor coupling effects on the spin symmetry of $\bar{\Lambda}$ in several anti-Lambda-nucleus systems have been studied in the RMF theory with the new effective hyperon-nucleon interaction PK1-Y1 for $\Lambda$. The coupling strengths of $\bar{\Lambda}$ with meson fields are obtained using G-parity transformation, where, as usual, an universal reduction factor $\xi = 0.3$, consistent with the empirical $\bar{p} - A$ optical potential, is introduced to take into account the many-body effects.

For $^{12}$C+$\bar{\Lambda}$, the spin-orbit splittings with tensor coupling are found to be $(1.37 \sim 3.47$ MeV for $\bar{\Lambda}$) an order of magnitude larger than those without the tensor coupling $(0.28 \sim 0.64$MeV). The contribution from the tensor coupling has the dominant contribution to the splittings. Since the mean-field potentials for $\bar{\Lambda}$ are greatly large than the corresponding spin-orbit potential, the dominant components of the Dirac spinors for spin-orbit partner states are almost identical irrespective of the tensor coupling. It indicates that the tensor coupling effects on the wave functions are negligible for $\bar{\Lambda}$. Therefore, the spin symmetry for $\bar{\Lambda}$ in $^{12}$C+$\bar{\Lambda}$ system is still quite good even with the consideration of the tensor coupling. Similar phenomena has also been observed in $\bar{\Lambda}$-nucleus of different mass regions, including $^{16}$O+$\bar{\Lambda}$, $^{40}$Ca+$\bar{\Lambda}$ and $^{208}$Pb+$\bar{\Lambda}$, and the conclusion remains.

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