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Polarization effect on the spin symmetry for anti-Lambda spectrum in $^{16}O+\bar{\Lambda}$ system*

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Abstract The polarization effect on the spin symmetry for anti-Lambda spectrum in $^{16}O+\bar{\Lambda}$ system has been studied in relativistic mean-field theory. The PK1 effective interaction is used for nucleon-meson couplings and G-parity symmetry with a reduction factor $\xi=0.3$ is adopted for anti-Lambda-meson couplings. The energy differences between spin doublets in the anti-Lambda spectrum are around 0.10-0.73 MeV for $p_{\bar{\Lambda}}$ state. The dominant components of the Dirac spinor for the anti-Lambda spin doublets are found to be near identical. It indicates that the spin symmetry is still well-conserved against the polarization effect from the valence anti-Lambda hyperon, which leads to a highly compressed cold nucleus with the central density up to $2-3$ times of saturated density.

Key words lambda and anti-lambda, hypernuclei, relativistic mean field, spin symmetry

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1 Introduction

Symmetries in single particle spectrum of atomic nuclei have been discussed extensively in the literature, as the violation of spin-symmetry by the spin-orbit term and approximate pseudo-spin symmetry in nuclear single particle spectrum: atomic nuclei are characterized by a very large spin-orbit splitting, i.e., pairs of single particle states with opposite spin $\left(j=l\pm\frac{1}{2}\right)$ have very different energies. This fact has allowed the understanding of magic numbers in nuclei and forms the basis of nuclear shell structure. More than thirty years ago pseudo-spin quantum numbers have been introduced by $\tilde{l}=l\pm1$ and $\tilde{j}=j$ for $j=l\pm\frac{1}{2}$ and it has been observed that the splitting between pseudo-spin doublets in nuclear single particle spectrum is by an order of magnitude smaller than the normal spin-orbit splitting [1, 2].

The relativistic mean field (RMF) theory has been widely used for describing nuclear matter, finite nuclei and hypernuclei [3]. 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 describe 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 lower component of the Dirac wave function, 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] with the RMF theory.

The possibility of producing a new nuclear system with one or more anti-baryons inside normal nuclei has recently gained renewed interest [9–13]. In Ref. [14], the RMF theory has been used to investigate the antinucleon spectrum, which corresponds to the negative energy solutions to the Dirac equation,

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and a well developed spin symmetry has been found in the antinucleon spectrum. Recently, we have examined the spin symmetry for anti-Lambda spectrum in atomic nuclei [15]. An even better spin symmetry than that in antinucleon has been found. It stimulates us to take a step further to study the polarization effect from valence anti-Lambda hyperon on the spin symmetry for the anti-Lambda spectrum, which was not taken into account in Ref. [15].

In this work, the polarization effect of $\bar{\Lambda}$ and the spin symmetry for single $\bar{\Lambda}$ spectrum in $\bar{\Lambda}$-nucleus system will be discussed in detail.

2 Framework

In the RMF theory for $\bar{\Lambda}$-nucleus system, the Dirac equations for (anti)baryon can be written as,

$$\{\alpha\cdot P_{\rm j}+\beta[M_{\rm j}+S_{\rm j}(r)]+V_{\rm j}(r)\}\,\psi_{\rm j}^{\alpha}=\mathcal{E}_{\rm j}^{\alpha}\psi_{\rm j}^{\alpha}, \qquad (1)$$

where, $\rm j=N,\bar{\Lambda}$, and α denotes various single-particle states.

The presence of $\bar{\Lambda}$ in atomic nucleus will modify the source term in the Klein-Gordon equations for mesons,

$$(-\nabla^2+m_\sigma^2)\,\sigma_0 \;=\; -g_{\sigma\rm N}\bar{\Psi}_{\rm N}\Psi_{\rm N}-g_{\sigma\bar{\Lambda}}\bar{\Psi}_{\bar{\Lambda}}\Psi_{\bar{\Lambda}}, \qquad (2)$$

$$(-\nabla^2+m_\omega^2)\,\omega_0 \;=\; g_{\omega\rm N}\bar{\Psi}_{\rm N}\gamma^0\Psi_{\rm N}+g_{\omega\bar{\Lambda}}\bar{\Psi}_{\bar{\Lambda}}\gamma^0\Psi_{\bar{\Lambda}}. \qquad (3)$$

According to the G-parity transformation, the coupling strengthes of $\bar{\Lambda}$ and mesons are related to those of Λ and mesons. Since the many-body effects will cause deviations from the G-parity symmetry in finite atomic nuclei, an overall reduction factor ξ $(0<\xi\leqslant 1)$ is adopted to consider these effects [11, 12],

$$g_{\sigma\bar{\Lambda}} \;=\; \xi g_{\sigma\Lambda}, \qquad (4)$$

$$g_{\omega\bar{\Lambda}} \;=\; -\xi g_{\omega\Lambda}. \qquad (5)$$

It has been found that the choice of $\xi=0.3$ is consistent with the empirical $\bar{\rm p}-{\rm A}$ optical potential [12].

The Schrödinger-like equation for the upper (dominant) component of $\bar{\Lambda}$ is derived from the Dirac equation (1),

$$\left[-\frac{1}{2M_+}\left(\frac{{\rm d}^2}{{\rm d}r^2}+\frac{1}{2M_+}\frac{{\rm d}V_-}{{\rm d}r}\frac{\rm d}{{\rm d}r}-\frac{l(l+1)}{r^2}\right)-\frac{1}{4M_+^2}\frac{\kappa}{r}\frac{{\rm d}V_-}{{\rm d}r}+M_{\bar{\Lambda}}-V_+\right]G(r)=\epsilon_{\bar{\Lambda}}G(r), \qquad (6)$$

where $2M_+=M_{\bar{\Lambda}}+\epsilon_{\bar{\Lambda}}-V_-$ and

$$V_\pm(r)=V_{\bar{\Lambda}}(r)\pm S_{\bar{\Lambda}}(r).$$

The spin-orbit term $-\dfrac{1}{4M_+^2}\dfrac{\kappa}{r}\dfrac{{\rm d}V_-}{{\rm d}r}\sim$ determines the size of energy difference between the spin doublets.

With the mean-field and no-sea approximations, the coupled Dirac equations for nucleons and $\bar{\Lambda}$ together with the modified Klein-Gordon equations for mesons can be self-consistently solved by iteration. The effective interaction PK1 [16] is used for the nucleon-meson couplings, and

$$g_{\sigma\Lambda}=\frac{2}{3}g_{\sigma\rm N},\quad g_{\omega\Lambda}=\frac{2}{3}g_{\omega\rm N}$$

are chosen for Λ-meson couplings according to the $SU(3)$ symmetry in naive quark model.

3 Results and discussion

In the first part of this work [15], the spin symmetry of the anti-Lambda spectrum in ^{16}O were studied with exact G-parity symmetry $\xi=1$. The depth of the potential for $\bar{\Lambda}$ was found to be $V_0^{\xi=1}\simeq 450$ MeV. The splittings between spin doublets of $\bar{\Lambda}$ (0.1–0.8 MeV) were found to be little smaller than those of anti-neutron (0.2–1.9 MeV). Moreover, the dominant components of Dirac spinors for $\bar{\Lambda}$ are almost identical for spin partner states. It implies that the spin symmetry in anti-Lambda spectra is even better conserved than that in anti-neutron spectra. However, it has to be pointed out that the polarization effect caused by the valence $\bar{\Lambda}$ has not been taken into account.

In this section, the polarization effect on the spin symmetry for anti-Lambda spectrum in ^{16}O+$\bar{\Lambda}$ system will be studied in relativistic mean-field theory with the reduction factor $\xi=0.3$ for anti-Lambda-meson couplings.

Figure 1 displays the distribution of potential and single particle spectrum for $\bar{\Lambda}$ in ^{16}O+$\bar{\Lambda}$ system. For each pair of spin doublets, the left levels are with $\kappa<0$ and the right ones with $\kappa>0$. It shows that the single $\bar{\Lambda}$ energies for each spin doublets are almost identical, and the energy differences between spin doublets $\epsilon_{\bar{\Lambda}(nl_{j=l-1/2})}-\epsilon_{\bar{\Lambda}(nl_{j=l+1/2})}$ are around 0.10–0.73 MeV for $p_{\bar{\Lambda}}$ states, which is a little bit larger than the results (0.09–0.17 MeV) without polarization effect, but still much smaller than the value in Λ spectrum (2.26 MeV) [15].

The polarization effect due to the $\bar{\Lambda}$ on the nuclear density distribution of ^{16}O is illustrated in Fig. 2. For comparison, the density distribution for neutron in ^{16}O is given as well. As seen in Fig. 2, the presence of $\bar{\Lambda}$ compresses the protons and neutrons into the center of the nucleus with the central nuclear density (the sum of densities for proton and neutron) up to $2-3$ times of saturated density.

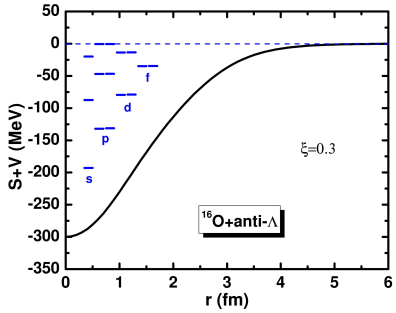

Fig. 1. (color online). The distribution of potential $S+V$ and single particle spectrum for $\bar{\Lambda}$ in ^{16}O+$\bar{\Lambda}$ system.

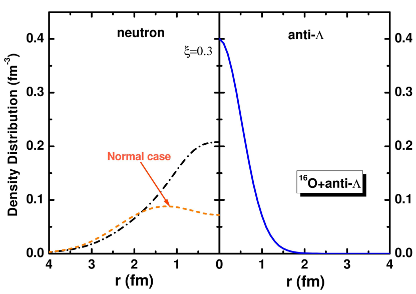

Fig. 2. (color online). Density distribution for $\bar{\Lambda}$ (solid line) and neutron (dashed-dotted line) in ^{16}O+$\bar{\Lambda}$. For comparison, the density distribution for neutron in ^{16}O is plotted as well (dashed line).

Radial wave functions $G(r)$ and $F(r)$ for several $\bar{\Lambda}$ spin doublets in ^{16}O+$\bar{\Lambda}$ are shown in Fig. 3. The dominant components $G(r)$ are nearly identical for the two spin partners. It indicates that the spin symmetry is still well-conserved against the polarization effect from the valence anti-Lambda.

It is known that the tensor coupling will cancel with the spin-orbit potential originated from scalar and vector fields and give a small spin-orbit splitting in Lambda hypernucleus [17–19]. For anti-Lambda hypernuclei, however, the tensor coupling is expected to increase the spin-orbit splitting. As the tensor couplings is comparable in magnitude with the original spin-orbit potential for $\bar{\Lambda}$, the spin-orbit splittings are not expected to be very large. The detailed quantitative studies of this effect will be given elsewhere.

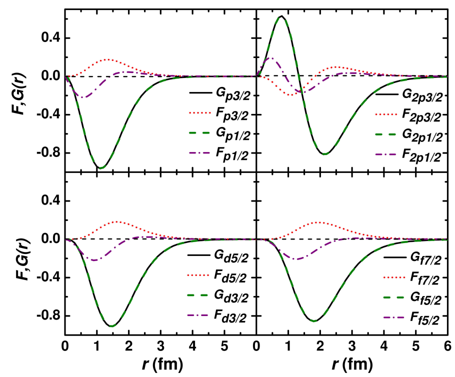

Fig. 3. (color online). Radial wave functions of $\bar{\Lambda}$ spin doublets with different orbits in ^{16}O+$\bar{\Lambda}$.

4 Summary

The polarization effect on the spin symmetry for anti-Lambda spectrum in ^{16}O+$\bar{\Lambda}$ system has been studied in relativistic mean-field theory. The PK1 effective interaction is used for nucleon-meson couplings and G-parity symmetry with a reduction factor $\xi=0.3$ is adopted for anti-Lambda-meson couplings. The energy differences between spin doublets in the anti-Lambda spectrum are around 0.10–0.73 MeV for $p_{\bar{\Lambda}}$ state. The dominant components of the Dirac spinor for the anti-Lambda spin doublets are found to be near identical. The results show that the polarization effect can worse the spin symmetry for anti-Lambda spectrum. However, the spin symmetry is still well-conserved even with the consideration of polarization effect from the valence anti-Lambda hyperon, which leads to a cold highly compression of nucleus with the central density up to $2-3$ times of saturated density.

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