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Spin Symmetry for Anti-Lambda Spectrum in atomic nucleus

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Introduction I

- Symmetries in the single particle spectra of nuclei,
  - violation of spin-symmetry Mayer:1955
  - with $\tilde{l} = l \pm 1$, the approximation of pseudo-spin symmetry Arima:1969, Hecht:1969
- The relativistic mean field (RMF) theory has been widely used for nuclear matter, finite nuclei and hypernuclei. Serot:1986, Reinhard:1989, Ring:1996, Meng:2006, Ma:1996, Vretenar:1998,...
- RMF been used to investigate pseudospin symmetry in nuclei spectrum.
  - The relation was first noted by Bahri *et al.*; found that the origin related to the strength of the scalar and vector potentials. Bahri:1992, Blokhin:1995
  - Ginocchio show that pseudo-orbital angular momentum is nothing but the "orbital angular momentum" of the lower component of the Dirac wave function . Ginocchio:1997 & 2005
  - Meng reveal that the quality of pseudospin symmetry. Meng:1998 & 1999

Introduction II

- The spin symmetry in antinucleon spectrum been investigated with RMF; a well developed spin symmetry in the antinucleon spectrum has been found. Zhou:2003

- Recently, nuclear system with anti-baryons($\bar{p}, \bar{\Lambda}$) gain renewed interest. Bürvenich:2002 Mishustin:2005 Friedman:2005 Larionov:2008&2009

the present work

- How good is the spin symmetry in the single $\bar{\Lambda}$ spectrum?

Framework I

For nuclei system contains $\bar{\Lambda}$, the Lagrangian density,

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{\bar{\Lambda}}, \quad (1)$$

The Lagrangian density for $\bar{\Lambda}$, $\mathcal{L}_{\bar{\Lambda}}$ can be written as,

$$\mathcal{L}_{\bar{\Lambda}} = \bar{\psi}_{\bar{\Lambda}} \left(i\gamma^\mu \partial_\mu - M_{\bar{\Lambda}} - g_{\sigma\bar{\Lambda}}\sigma - g_{\omega\bar{\Lambda}}\gamma^\mu\omega_\mu \right) \psi_{\bar{\Lambda}}. \quad (2)$$

as $\bar{\Lambda}$ is charge neutral and isoscalar, it couples only to the σ and ω mesons.

From the Euler-lagrange equation, the Dirac equation for $\bar{\Lambda}$ hyperon can be obtained,

Dirac equation for $\bar{\Lambda}$

$$\left\{ \boldsymbol{\alpha} \cdot \mathbf{p} + V_{\bar{\Lambda}}(\mathbf{r}) + \beta [M_{\bar{\Lambda}} + S_{\bar{\Lambda}}(\mathbf{r})] \right\} \psi_{\bar{\Lambda}}(\mathbf{r}) = \epsilon_{\bar{\Lambda}} \psi_{\bar{\Lambda}}(\mathbf{r}), \quad (3)$$

where $M_{\bar{\Lambda}} = 1115.7$ MeV, $\epsilon_{\bar{\Lambda}}$ is the single-particle energy.

Framework II

The scalar and vector potentials, $S_{\bar{\Lambda}}(\mathbf{r})$ and $V_{\bar{\Lambda}}(\mathbf{r})$ can be written as,

$$S_{\bar{\Lambda}}(\mathbf{r}) = g_{\sigma\bar{\Lambda}}\sigma(\mathbf{r}), \tag{4}$$

$$V_{\bar{\Lambda}}(\mathbf{r}) = g_{\omega\bar{\Lambda}}\omega(\mathbf{r}), \tag{5}$$

According to the charge conjugation transformation,

the coupling constants

$$g_{\sigma\bar{\Lambda}} = g_{\sigma\Lambda}, \tag{6}$$

$$g_{\omega\bar{\Lambda}} = -g_{\omega\Lambda}. \tag{7}$$

Framework III

For a spherical system, the Dirac spinor of $\bar{\Lambda}$ has the form

$$\psi_{\bar{\Lambda}}(\mathbf{r}) = \frac{1}{r}\begin{pmatrix} iG_{n\kappa}(r)Y^{l}_{jm}(\theta,\phi) \\ -F_{\tilde{n}\kappa}(r)Y^{\tilde{l}}_{jm}(\theta,\phi) \end{pmatrix}, \quad j = l \pm \frac{1}{2}, \tag{8}$$

The Schrödinger-like equations for the upper (dominant) component can be obtained from Eq.(3),

the Schrödinger-like equation

$$\left[-\frac{1}{2M_+}\left(\frac{d^2}{dr^2} + \frac{1}{2M_+}\frac{dV_-}{dr}\frac{d}{dr} - \frac{l(l+1)}{r^2}\right) - \frac{1}{4M_+^2}\frac{\kappa}{r}\frac{dV_-}{dr} + M_{\bar{\Lambda}} - V_+\right]G(r) = \epsilon_{\bar{\Lambda}}G(r). \tag{9}$$

where $M_+ = M_{\bar{\Lambda}} + \epsilon_{\bar{\Lambda}} - V_-$ and $V_\pm(r) = V_{\bar{\Lambda}}(r) \pm S_{\bar{\Lambda}}(r)$.

$\frac{1}{4M_+^2}\frac{\kappa}{r}\frac{dV_-}{dr} \sim$ the spin-orbit term, which determines the energy difference between the spin doublets.

❶ Potential and spectrum

Taking ^{16}O as an example , with PK1 parameters for the nucleon part, and $g_{\sigma\bar{\Lambda}} = \frac{2}{3} g_{\sigma N}$; $g_{\omega\bar{\Lambda}} = -\frac{2}{3} g_{\omega N}$, the spectrum of $\bar{\Lambda}$ have been calculated.

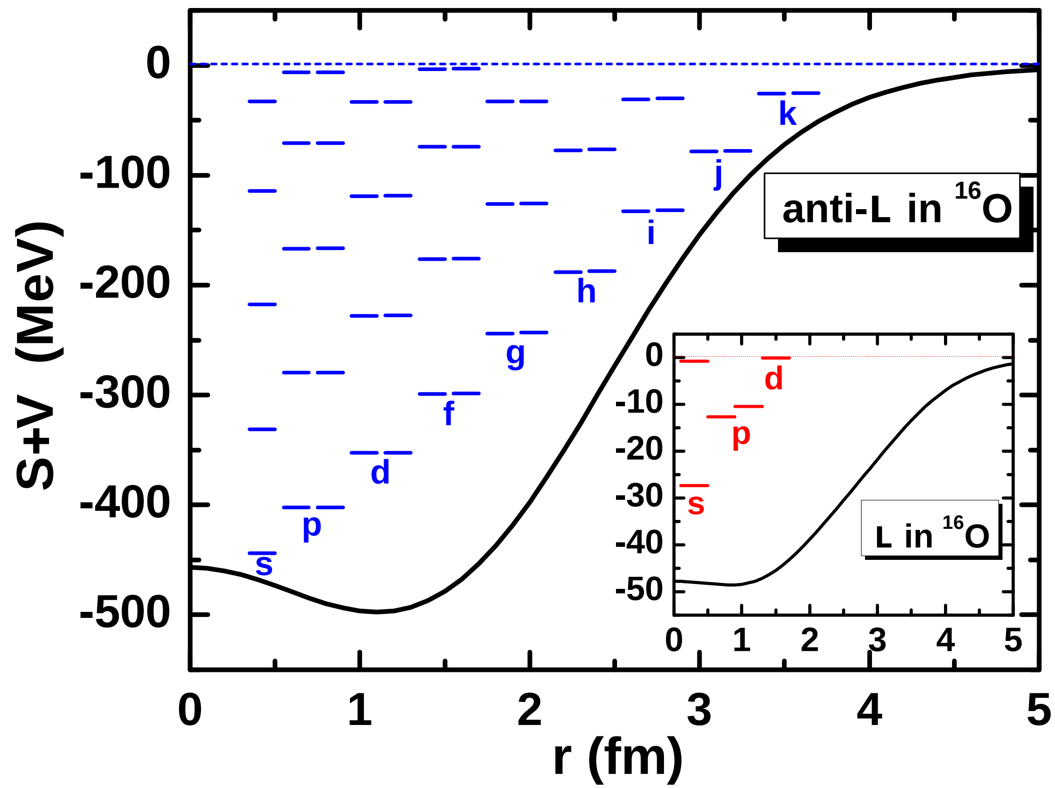

Figure: Potential and spectrum of $\bar{\Lambda}$ in ^{16}O. For each pair of the spin doublets, the left levels are with $\kappa < 0$ and the right one with $\kappa > 0$. The inset gives the potential and spectrum of Λ in ^{16}O.

❷ Spin-orbit splitting

The $\bar{\Lambda}$ spin-orbit splitting,

$$\Delta E_{s.o} = (\epsilon_{\bar{\Lambda}(nl_{j=l-1/2})} - \epsilon_{\bar{\Lambda}(nl_{j=l+1/2})})/(2l+1), \quad (10)$$

is plotted as a function of the the average energy,

$$E_{\rm av} = \frac{1}{2}(E_{\bar{\Lambda}(nl_{j=l-1/2})} + E_{\bar{\Lambda}(nl_{j=l+1/2})}) \quad (11)$$

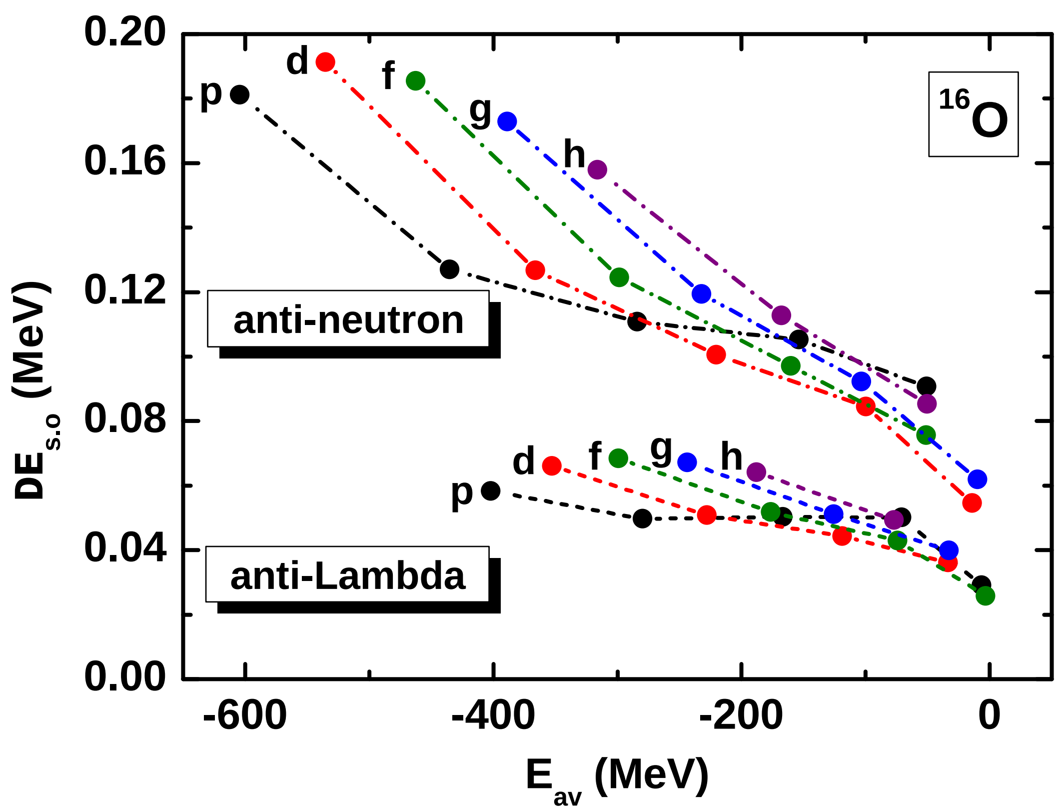

Figure: The spin-orbit splitting $\Delta E_{s.o}$ for $\bar{\Lambda}$ and antineutron in ^{16}O as a function of the average energy $E_{\rm av}$.

better spin symmetry in $\bar{\Lambda}$ spectrum

The spin-orbit term,

$$\frac{1}{4(M_+^{\bar{\Lambda}})^2}\frac{\kappa}{r}\frac{dV_-^{\bar{\Lambda}}}{dr} < \frac{2}{3}\cdot\frac{1}{4(M_+^{\bar{n}})^2}\frac{\kappa}{r}\frac{dV_-^{\bar{n}}}{dr},$$

due to:① $V_-^{\bar{\Lambda}}(r) = \frac{2}{3}V_-^{\bar{n}}(r)$;

② $M_+^{\bar{\Lambda}} > M_+^{\bar{n}}$.

with $M_+^{\bar{\Lambda}} = M_{\bar{\Lambda}} - (-\epsilon_{\bar{\Lambda}} + V_-^{\bar{\Lambda}})$,

and $M_+^{\bar{n}} = M_{\bar{n}} - (-\epsilon_{\bar{n}} + V_-^{\bar{n}})$

❸ Radial wave functions

The dominant component $G(r)$ of the wave functions of the spin doublets are expected to be almost identical,

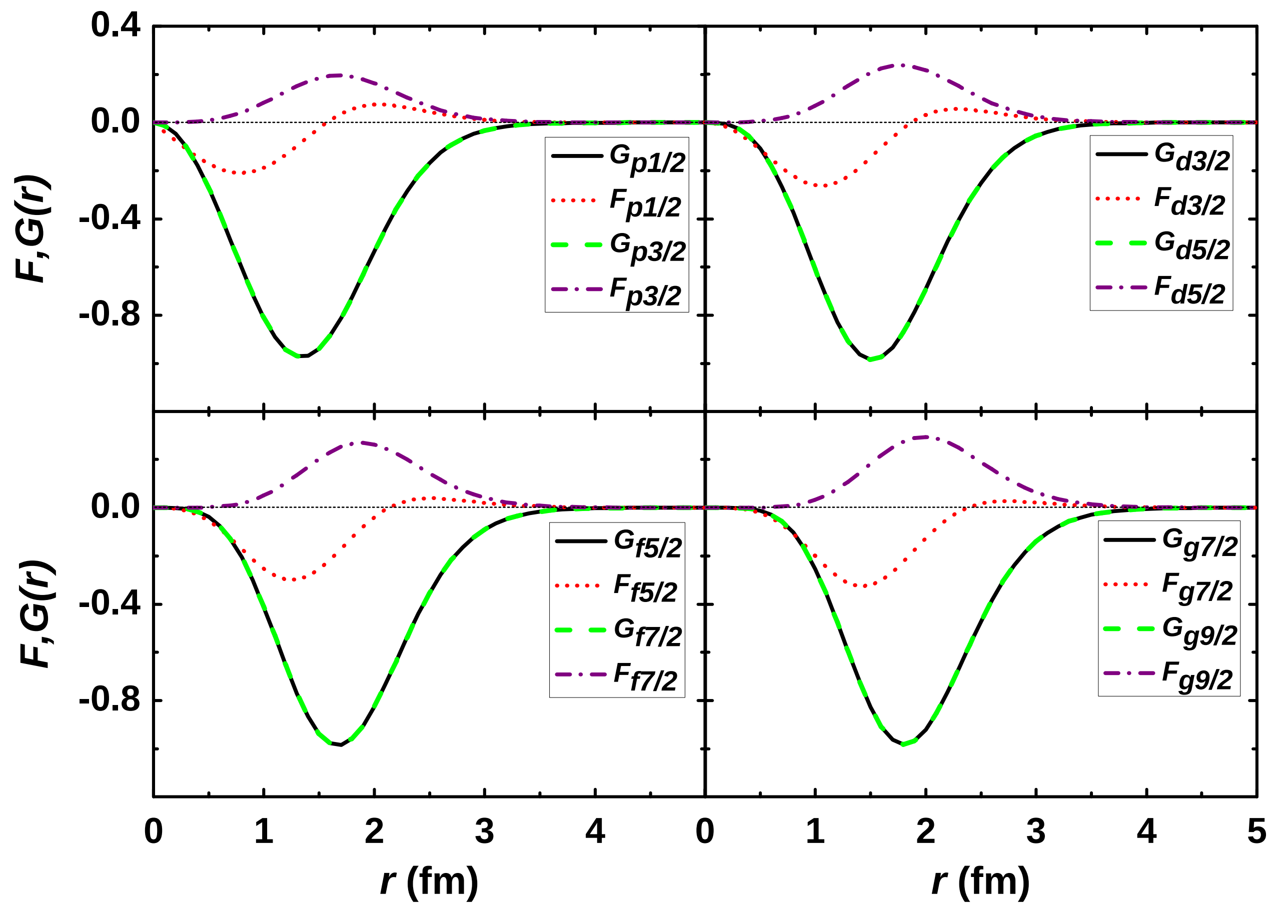

Figure: Radial wave functions of $\bar{\Lambda}$ spin doublets with different orbit quantum numbers in ^{16}O.

Summary and Perspective

Summary

- The spin symmetry in the single $\bar{\Lambda}$ spectrum in ^{16}O has been studied within the RMF theory.
- The spin-orbit splittings in the $\bar{\Lambda}$ spectrum have been found to be around 0.03-0.07 MeV, which are much smaller than those in antineutron spectrum 0.06-0.20 MeV.
- The dominant components of the Dirac spinor for the $\bar{\Lambda}$ spin doublets are found to be nearly identical.

Perspective

¿ What's the polarization effects due to the $\bar{\Lambda}$?

¿ How deep is the antinucleon potential in the nuclei?

¿ ...

Thank you!