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Beta Decay in ^{176}Yb *

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Abstract The beta-decay of ^{176}Yb $\rightarrow$ ^{176}Lu is calculated in the frame of projected shell model (PSM). The results are compared with experimental data.

Key words beta-decay, projected shell model, GT transition

1 Introduction

The fundamental question whether neutrinos have a non-vanishing rest mass is still one of the big open problems of current physics and astrophysics. The direct neutrino mass determination method relies on the detailed analysis of the end-point part of the beta decay spectrum of the some nuclei[1]. Recently a new concept for solar neutrino spectroscopy has been proposed based on " $\beta\beta$-solar-ν" target candidates, ^{176}Yb, ^{160}Gd and ^{82}Se [2]. This has been turned into a realistic detector design (LENS) which is using 20 t of Yb in form of a liquid scintillator[3]. A coincidence between the population of an excited state by neutrino capture and therefore emission of an electron) and the detection of the deexcitation photon serves as a signal. The implications of this experiment for double beta decay using two available isotopes, ^{168}Yb and ^{176}Yb, were investigated in Ref. [4]. However, β-decay data show surprisingly that $0^+ \rightarrow 1^+$ ν_e capture by nonspherical nuclei could be strong. In this paper, the potential of Yb-loaded liquid scintillator as proposed for solar neutrino spectroscopy are investigated with respect to beta decay in the frame of Projected shell model (PSM), which is an excellent model to deal with well-deformed heavy nuclei, based on shell model.

Studies of β-decay also provide an important element in our understanding of nuclear structure. β-decay rates are very sensitive to details of wavefunctions and therefore can provide a fine test of the nuclear model. we first calculate the energy levels, then test the wavefunctions by comparing the levels to the experimet data, and in the final step calculate the $\beta-$ decay rates. This final step is parameter free and provides a unique test of wavefunctions.

2 Projected shell model

The projected shell model (PSM) is a shell model constructed in a deformed muti-qp basis. Here PSM is briefly introduced. A more detailed description of the model can be found in the review article of Hara and Sun [5].

The Hamiltonian employed in the PSM is [5]

$$\hat{H} = \hat{H}_0 - \frac{1}{2}\chi \sum_{\mu} \hat{Q}^{\dagger}_{\mu}\hat{Q}_{\mu} - G_M \hat{P}^{\dagger}\hat{P} - G_Q \sum_{\mu} \hat{P}^{\dagger}_{\mu}\hat{P}_{\mu}, \quad (1)$$

where $\hat{H}_0$ is the spherical single-particle Hamiltonian, which contains a proper spin–orbit force [6]. The other terms in Eq. (1)

$$\hat{Q}_{\mu} = \sum_{\alpha\beta} c^{\dagger}_{\alpha} Q_{\mu\alpha\beta} c_{\beta},$$

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$$\hat{P}^{\dagger} = \frac{1}{2}\sum_{\alpha} c_{\alpha}^{\dagger} c_{\bar{\alpha}}^{\dagger},$$

$$\hat{P}_{\mu}^{\dagger} = \frac{1}{2}\sum_{\alpha\beta} c_{\alpha}^{\dagger} Q_{\mu\alpha\beta} c_{\bar{\beta}}^{\dagger}. \tag{2}$$

are quadrupole-quadrupole, monopole-, and quadrupole-pairing interactions, respectively. The strength of the quadrupole-quadrupole force χ is determined in such a way that has a self-consistent relation with the employed quadrupole deformation ε_2 [5]. The monopole-pairing force constants G_M used in the calculations are

$$G_M^n = \left[G_1 \mp G_2 \frac{N-Z}{A}\right] A^{-1}, \tag{3}$$

with "$-$" for neutrons and "$+$" for protons, which approximately reproduces the observed odd-even mass differences in the mass region, where G_1 and G_2 are justified to yield the known odd-even mass difference. Finally, the strength parameter G_Q for the quadrupole pairing was simply taken to be proportional to G_M. For the present calculation a value of 0.16 was chosen which is consistent with the value used in this mass region [5].

The ansatz for the angular momentum projected wave function is given by

$$\Psi_{IM}^{\sigma} = \sum_{\kappa} f_{\kappa}^{\sigma} \hat{P}_{MK_{\kappa}}^{I} |\varphi_{\kappa}\rangle, \tag{4}$$

where the index σ labels the states with the same angular momentum and κ the basis states. $\hat{P}_{MK}^{I}$ is the angular momentum projector [7] which projects good angular momentum from an intrinsic state $|\varphi_{\kappa}\rangle$. In this way, angular momentum conservation, which is violated in the deformed mean-field calculation, is restored. The basis states $|\varphi_{\kappa}\rangle$ have a good K quantum number, since we start from an axially symmetric potential. In the present calculations for even-even nuclei, the quasiparticle configurations are

$$|0\rangle,\quad \alpha_{\nu_1}^{\dagger}\alpha_{\nu_2}^{\dagger}|0\rangle,\quad \alpha_{\pi_1}^{\dagger}\alpha_{\pi_2}^{\dagger}|0\rangle,\quad \alpha_{\nu_1}^{\dagger}\alpha_{\nu_2}^{\dagger}\alpha_{\pi_1}^{\dagger}\alpha_{\pi_2}^{\dagger}|0\rangle, \tag{5}$$

and for odd-odd nuclei, $\alpha_{\nu}^{\dagger}\alpha_{\pi}^{\dagger}|0\rangle$. where $\alpha(\alpha^{\dagger})$ are the annihilator (creator) qp operators on this vacuum. The index n_i (p_i) runs over selected neutron (proton) states. The index κ in Eq. (4) runs over the states of Eq. (5). The vacuum $|\phi\rangle$ is determined by diagonalization of a deformed Nilsson Hamiltonian and a subsequent BCS calculation. Hereby the standard Nilsson scheme[6] is used for the deformed single-particle calculation. The configuration space includes three major shells, $N=4$, 5 and 6 for neutrons, and $N=3$, 4 and 5 for protons.

3 Formulism

The matrix elements of Gamow-Teller β-decay are

$$B(GT) = \frac{1}{2I+1} \mid \sum_{M'} \langle \Psi_{I'M'} \mid O^{GT} \mid \Psi_{IM} \rangle \mid^2, \tag{6}$$

where

$$O^{GT} = \sum_{\mu} t_{-}\sigma_{1\mu}. \tag{7}$$

For Fermi transition, one can get the matrix elements B(F) by using the operator $O^F = t_-$ instead of O^{GT}.

Supposing mother and daughter nucleus have the same deformation, then we do the calculation in the mother nucleus. In PSM[5],

$$\mid \Psi_{IM} \rangle = \sum_{K} F_{\kappa K}^{I} P_{KM}^{I} \mid \phi_K \rangle. \tag{8}$$

Because

$$\langle \Psi_{I'M'} \mid t_{-}\sigma_{1\mu} \mid \Psi_{IM} \rangle = \langle IM, 1\mu \mid I'M' \rangle \langle \Psi_{I'} \mid\mid \sigma_1 \mid\mid \Psi_I \rangle, \tag{9}$$

where

$$\langle \Psi_{I'} \mid\mid \sigma_1 \mid\mid \Psi_I \rangle = \sum_{K'K}\sum_{\nu} \langle IK'- \nu, 1\nu \mid I'K' \rangle \langle \phi_{K'} \mid \sigma_{1\nu} P_{K'-\nu K}^{I} \mid \phi_K \rangle F_{\kappa' K'}^{I'} F_{\kappa K}^{I}, \tag{10}$$

then

$$B(GT) = \frac{2I'+1}{2I+1} \mid \langle \Psi_{I'} \mid\mid \sigma_1 \mid\mid \Psi_I \rangle \mid^2. \tag{11}$$

The ft value is calculated by

$$ft = \frac{6163}{B(F) + (G_A/G_V)^2 B(GT)} \tag{12}$$

in units of second where $(G_A/G_V)^2 = 1.59$.

4 Calculation and conclusion

In the calculation, we suppose that ^{176}Yb and ^{176}Lu have the same deformation and therefore we use the neutron wavefunction in ^{176}Yb instead of that of the last occupied proton which has the same orbit in ^{176}Lu. We take $\varepsilon_2=0.243$, $\varepsilon_4=0.004$, $G1=20.12$, $G2=13.13$, and $\gamma=0.16$, respectively. We calculated the matrix elements for two β^- transitions. One is $0^+(^{176}\mathrm{Yb}) \rightarrow 1^+(^{176}\mathrm{Lu}, \mathrm{p}_{7/2}[404]-\mathrm{n}_{9/2}[624])$ (Channel A) and the other $0^+(^{176}\mathrm{Yb}) \rightarrow 1^+(^{176}\mathrm{Lu}, \mathrm{p}_{9/2}[514]-\mathrm{n}_{7/2}[514])$ (Channel B). The results are shown in the table 1. From the table, we notice that the calculated ft values have little difference with the experimental data, while for the matrix elements, the difference is big, especially for the transition of Channel B. This difference may come from our approximation which makes the overlap of the two wavefuctions is small. Our calculations are consistent with those in Ref. [2], where R. Raghavan pointed out Channel B feeds ^{176}Lu (339keV) with the ideal configuration $p_{9/2}[514]-n_{7/2}[514]$ for which the systematics suggest $\log_{10} ft=3.7-4.2$ among the strongest transitions. The $\nu_e(\mathrm{pp})-$sensitive channel A to ^{176}Lu(195KeV), not ideal with n,p assigned nominally in different major shells, may have $\log_{10} ft \geqslant 5$. Standard solar signal rates assuming $\log_{10} ft(ch.\mathrm{A})=5$ and $\log_{10} ft(ch.\mathrm{B})=3.7$ and therefore our calculations for ft values are also in agreement with these. Since these calculations are very sensitive to the wavefunctions, projected shell model can well describe the nuclear structure in this region.

Table 1. Comparisons between calculations and experiments.

	(p,n) (1998.1)	(p,n) (1998.5)	(^{3}He, t) (1998.7)	This work
$B(GT)_\mathrm{A}$	0.47	0.33	0.18	0.002
$\log ft_{1/2}$	4.26	4.57	5.10	6.37
$B(GT)_\mathrm{B}$		0.16	0.11	0.51
$\log ft_{1/2}$		5.20	5.52	3.98

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^{176}Yb的β衰变*

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摘要 采用投影壳模型对^{176}Yb的β衰变进行了计算, 并与实验结果进行了比较.

关键词 β衰变 投影壳模型 GT跃迁

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