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THE BLOCKING EFFECT ON THE β-DECAY PROPERTIES OF THE NEUTRON-RICH Ni ISOTOPES*

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The Q_β-window has been studied within the Skyrme HF–BCS calculations including the blocking effect of unpaired neutron and proton in cases of the even–odd and odd–odd nuclei. Using the energy-density functional T45 containing the tensor terms, we analyze this effect on the β-transition rates of the neutron-rich nuclei $^{72-80}$Ni.

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The correct description of the Q_β-values is the important ingredient for the reliable prediction of the half-life of the β-decay. To calculate the binding energy of the odd–odd and even–odd nuclei, we take into account the effect of the unpaired neutron and proton on the superfluid properties of nuclei, the well-known blocking effect [1, 2]. As an example, the β-decay properties of neutron-rich nuclei ^{72,74,76,80}Ni and the most neutron-rich ($(N-Z)/A = 0.28$) doubly-magic nucleus ^{78}Ni are studied. The β-decay properties of r-process "waiting-point nucleus" ^{78}Ni have attracted a lot of experimental efforts, see *e.g.* [3].

We use the EDF T45 which takes into account the tensor force [4]. The T45 set is one of 36 parametrizations, covering a wide range of the parameter space of the isoscalar and isovector tensor term added with refitting the parameters of the central interaction, where a fit protocol is very similar to that of the successful SLy parametrizations. This choice of the Skyrme EDF has been selected to reproduce the experimental Q_β value of ^{78}Ni (see Fig. 1) and enough positive value of the spin–isospin Landau parameter ($G'_0 = 0.10$ for T45). The pairing correlations are generated by a zero-range volume force with a strength of -270 MeV$\times$fm^3 and a smooth cut-off at 10 MeV above the Fermi energies [5, 6].

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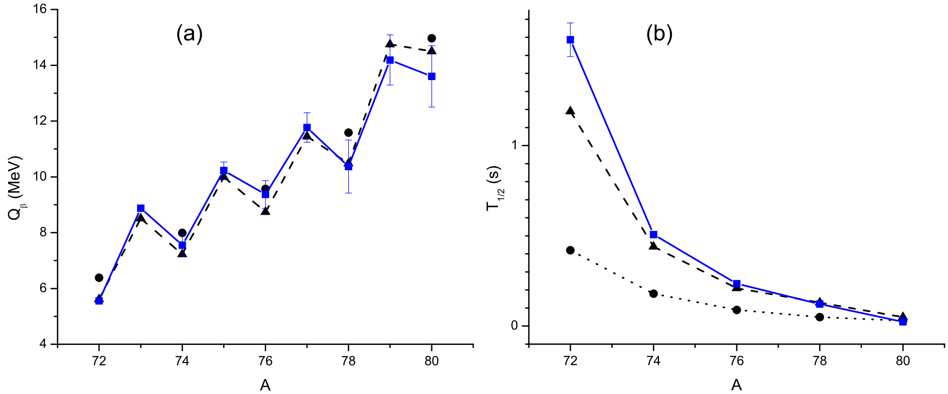

Fig. 1. (Color online) (a) The quasiparticle blocking effect on Q_β-values of $^{72-80}$Ni isotopes. (b) The half-lives of the β-decay of ^{72,74,76,78,80}Ni. Q_β-values are calculated with the blocking effect (triangles) and without the blocking effect (circles). Experimental data (squares) are from Ref. [10].

Assuming the spherical symmetry for the nuclei considered here, the starting point of the method is the self-consistent HF–BCS calculation [7] for the ground state properties of the even–even parent nucleus (N, Z). In the particle-hole channel, we use the Skyrme interaction with the tensor components and their inclusion leads to the modification of the spin-orbit potential [4].

The ground state of the odd–odd daughter nucleus $(N-1, Z+1)$ can be obtained as the neutron-quasiparticle proton-quasiparticle state. The neutron and proton quasiparticles can be simultaneously blocked [8]. Using the blocking effect for unpaired nucleons [1, 2, 7], we get the following secular equations:

$$\Delta_j = \frac{1}{2}\sum_{j' \neq j_2} V_{jj'} \frac{(2j'+1)\,\Delta_{j'}}{\sqrt{\Delta_{j'}^2 + \left(E_{j'} - \lambda\right)^2}} + \frac{1}{2} V_{jj_2} \frac{(2j_2 - 1)\,\Delta_{j_2}}{\sqrt{\Delta_{j_2}^2 + (E_{j_2} - \lambda)^2}}\,, \qquad (1)$$

where the indexes j denote the quantum numbers nlj, the values λ are the neutron and proton chemical potentials. The indexes j_2 emphasize the blocked neutron subshell and the blocked proton subshell near the Fermi energies. For ^{72,74,76,78}Cu, the neutron quasiparticle blocking is based on filling the $1g_{9/2}$ subshell and the $2d_{5/2}$ subshell should be blocked for ^{80}Cu. The proton $2p_{3/2}$ and $1f_{5/2}$ subshells are chosen to be blocked in the cases of ^{72,74,76}Cu and ^{78,80}Cu, respectively. It is worth pointing out that there is the closeness of the proton single-particle energies $2p_{3/2}$, $1f_{5/2}$ for ^{76}Cu.

The Q_β value can be obtained by the binding-energy difference between the daughter and parent nuclei

$$Q_\beta = \Delta M_{n-H} + B(Z+1, N-1) - B(Z,N)\,. \tag{2}$$

$\Delta M_{n-H} = 0.782$ MeV is the mass difference between the neutron and the hydrogen atom. As proposed in Ref. [9], the Q_β value of the even–even nucleus can be calculated without the blocking effect

$$Q_\beta \approx \Delta M_{n-H} + \lambda_n - \lambda_p - E_{2\mathrm{qp,lowest}}\,, \tag{3}$$

where $E_{2\mathrm{qp,lowest}}$ corresponds the lowest two-quasiparticle energy. The calculated Q_β values in the neutron-rich Ni isotopes are compared with the experimental data [10] in Fig. 1 (a). There is a remarkable odd–even staggering. For even–even nuclei, the Q_β analysis within approximation (3) can help to clarify the blocking effect. We find that the blocking effect induces a reduction of the Q_β values and it results in a improvement of the Q_β description, see Fig. 1(a).

To build the QRPA equations on the basis of HF–BCS quasiparticle states of the parent nucleus is the standard procedure [11]. Using the FRSA model, the QRPA eigenvalues (E_k) are obtained as the roots of the relatively simple secular equation [12–14], and we carry out QRPA calculations in very large two-quasiparticle spaces.

In the allowed GT approximation, the β^--decay half-life is expressed by summing the probabilities (in units of $G_A^2/4\pi$) of the energetically allowed transitions ($E_k^{\mathrm{GT}} \leq Q_\beta$) weighted with the integrated Fermi function

$$T_{1/2}^{-1} = D^{-1}\left(\frac{G_A}{G_V}\right)^2 \sum_k f_0\left(Z+1, A, E_k^{\mathrm{GT}}\right) B(\mathrm{GT})_k\,, \tag{4}$$

$$E_k^{\mathrm{GT}} = Q_\beta - E_{1_k^+}\,, \tag{5}$$

where $G_A/G_V = 1.25$ and $D = 6147\,\mathrm{s}$ [15]. $E_{1_k^+}$ denotes the excitation energy of the 1_k^+ state of the daughter nucleus. As proposed in Ref. [9], this energy can be estimated by the following expression:

$$E_{1_k^+} \approx E_k - E_{2\mathrm{qp,lowest}}\,. \tag{6}$$

It is worth mentioning that the spin-parity of the lowest two-quasiparticle state is, in general, different from 1^+.

The properties of the low-lying 1^+ states in the daughter nuclei ^{72,74,76,78,80}Cu are studied. There is the gradual reduction of β-decay half-lives with increasing neutron number [10], see Fig. 1 (b). One can see that our results calculated with the blocking effect reproduce this behavior. As expected, the largest contribution ($> 60\%$) in the calculated half-life comes from the 1_1^+ state. QRPA results indicate that the dominant configuration of the 1_1^+ wave function is $\{\pi 2p\frac{3}{2}\nu 2p\frac{1}{2}\}$ whose contribution is about 99% in all five nuclei. The inclusion of the blocking effect for the Q_β calculation reduces the transition energies (5) and this energy shift produces a sizable impact on the β-decay half-life. The calculated half-lives are in reasonable agreement with the experimental data [10] but they are much larger than the half-lives calculated with SGII+tensor interaction [6]. A possible reason might be the underestimated symmetry energy of 26.8 MeV for the SGII set and too strong tensor correlations in the case of the SGII+tensor interaction.

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