THE BLOCKING EFFECT ON THE $\beta$-DECAY PROPERTIES OF THE NEUTRON-RICH Ni ISOTOPES

E.O. SUSHENOK, A.P. SEVERYUKHIN

Bogoliubov Laboratory of Theoretical Physics
Joint Institute for Nuclear Research, Dubna, Russia
and
Dubna State University, Dubna, Russia

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The $Q_\beta$-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 $\beta$-transition rates of the neutron-rich nuclei $^{72–80}$Ni.

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The correct description of the $Q_\beta$-values is the important ingredient for the reliable prediction of the half-life of the $\beta$-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 $\beta$-decay properties of neutron-rich nuclei $^{72,74,76,80}$Ni and the most neutron-rich ($\langle N - Z \rangle/A = 0.28$) doubly-magic nucleus $^{78}$Ni are studied. The $\beta$-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 $Q_\beta$ 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 $-270 \text{ MeV} \times \text{fm}^3$ and a smooth cut-off at 10 MeV above the Fermi energies [5, 6].

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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:

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

where the indexes \(j\) denote the quantum numbers \(nlj\), the values \(\lambda\) 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.

Fig. 1. (Color online) (a) The quasiparticle blocking effect on \(Q_\beta\)-values of \(^{72−80}\)Ni isotopes. (b) The half-lives of the \(\beta\)-decay of \(^{72,74,76,78,80}\)Ni. \(Q_\beta\)-values are calculated with the blocking effect (triangles) and without the blocking effect (circles). Experimental data (squares) are from Ref. \[10\].
The $Q_\beta$ value can be obtained by the binding-energy difference between the daughter and parent nuclei

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

(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 $Q_\beta$ value of the even–even nucleus can be calculated without the blocking effect

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

(3)

where $E_{2qp,\text{lowest}}$ corresponds the lowest two-quasiparticle energy. The calculated $Q_\beta$ 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 $Q_\beta$ analysis within approximation (3) can help to clarify the blocking effect. We find that the blocking effect induces a reduction of the $Q_\beta$ values and it results in a improvement of the $Q_\beta$ 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 $\beta^-$-decay half-life is expressed by summing the probabilities (in units of $G_A^2/4\pi$) of the energetically allowed transitions ($E_k^{GT} \leq Q_\beta$) weighted with the integrated Fermi function

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

(4)

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

(5)

where $G_A/G_V = 1.25$ and $D = 6147$ 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:

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

(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 $\beta$-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 $\{\pi 2p_2^3\nu 2p_1^1\}$ whose contribution is about 99% in all five nuclei. The inclusion of the blocking effect for the $Q_\beta$ calculation reduces the transition energies (5) and this energy shift produces a sizable impact on the $\beta$-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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