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The impact of the tensor interaction on the β-delayed neutron emission of the neutron-rich Ni isotopes

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Abstract. The neutron emission of the β-decay of ^{74,76,78,80}Ni are studied within the quasiparticle random phase approximation with the Skyrme interaction. The coupling between one- and two-phonon terms in the wave functions of the low-energy 1^+ states of the daughter nuclei is taken into account. It is shown that the strength decrease of the neutron-proton tensor interaction leads to the increase of the half-life and the neutron-emission probability.

Study of the β-decay properties of the nuclei near the doubly magic isotope ^{78}Ni plays the crucial role in the modeling of the astrophysical r-process [1]. The multi-neutron emission is a multistep process consisting of the β-decay of the parent nucleus (N, Z) which results in feeding the excited states of the daughter nucleus (N - 1, Z + 1) followed by the multi-neutron emissions to the ground state or γ-deexcitation to the ground state of the product nucleus (N - 1 - X, Z + 1) [2]. The microscopic study of the β-decay half-lives and the β-delayed neutron-emission probabilities of the nuclei with high N/Z ratio asymmetry makes it possible to reconstruct the β-strength function [2, 3]. Taking into account the tensor interaction has a substantial effect on the Gamow–Teller (GT) transitions within the β-decay window [4]. A redistribution of the GT strength has been found due to the impact of the tensor correlations and $2p$-$2h$ fragmentation of the GT transitions [5].

One of the successful tools for studying charge-exchange nuclear modes is the quasiparticle random phase approximation (QRPA) with the self-consistent mean-field derived from a Skyrme energy-density functional (EDF), see e.g., [6–9]. These QRPA calculations enable one to describe the properties of the ground state and excited charge-exchange states using the same EDF. As proposed in Ref. [10], the study of the multineutron emission, following the β-decay, requires taken into account the phonon-phonon coupling (PPC). The finite rank separable approximation (FRSA) [11–13] for the residual interaction allows one to perform the calculations in large configurational spaces.

In this paper, we investigate the impact of the tensor correlations on the probability of the neutron emission. As the parameter set in the particle-hole channel, we use the Skyrme EDFs TIJ [14], which take into account the tensor terms. Indices I and J refer to the proton-neutron (β) and like-particle (α) coupling constants that define the contribution to the spin-orbit potential from the $\mathbf{J}^2$ terms:

$$U_{SO}^{(q)} = \frac{W_0}{2r}\left(2\frac{d\rho_q}{dr} + \frac{d\rho_{q'}}{dr}\right) + \left(\alpha\frac{J_q}{r} + \beta\frac{J_{q'}}{r}\right), \quad (1)$$

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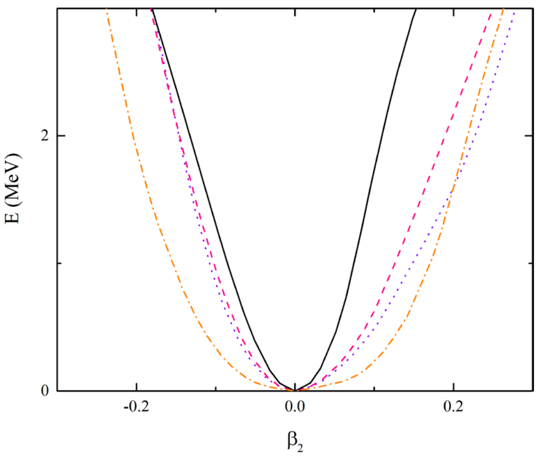

Figure 1. (Color online) Deformation energy curve as a function of the mass quadrupole deformation. The curves of ^{74}Ni, ^{76}Ni, ^{78}Ni and ^{80}Ni are denoted by the dotted, dashed, solid, and dash-dotted lines respectively.

$$\alpha = 60(J-2) \quad \text{MeV fm}^5 \tag{2}$$

$$\beta = 60(I-2) \quad \text{MeV fm}^5 \tag{3}$$

where ρ_q, J_q $(q = n, p)$ are the nucleon density and the spin-orbit current respectively. The parameter W_0 describes the strength of the spin-orbit force.

The starting point is the HF-BCS calculation of the ground state properties of the even-even parent nucleus (N,Z) within a spherical symmetry assumption. The continuous part of the single-particle spectrum is discretized by diagonalizing the HF hamiltonian on a harmonic oscillator basis. The pairing correlations are generated by a zero-range force with a strength $V_0 = -270$ MeV fm^3. This value of the pairing strength has been fitted to reproduce the odd-even mass difference in the studied region of nuclei [15, 16].

$$V^{(\mathrm{pp})}_{T=1}(\vec{r}_1,\vec{r}_2) = V_0\left(\frac{1-P_\sigma}{2}\right)\left(1-\eta\frac{\rho(r_1)}{\rho_0}\right)\delta(\vec{r}_1-\vec{r}_2),$$
$$V^{(\mathrm{pp})}_{T=0}(\vec{r}_1,\vec{r}_2) = fV_0\left(\frac{1+P_\sigma}{2}\right)\left(1-\eta\frac{\rho(r_1)}{\rho_0}\right)\delta(\vec{r}_1-\vec{r}_2), \tag{4}$$

where P_σ is the spin-exchange operator and ρ_0 is the nuclear matter density. We use $f = 1$ i.e. the realization of the SU(4) symmetry [17]. In this work, we use volume pairing forces ($\eta = 0$). The binding energies of the daughter $B(N-1, Z+1)$ and final nuclei $B(N-1-X, Z+1)$ are calculated with the blocking effect for unpaired nucleons [18].

Keeping spherical symmetry might not be that bad for ^{74,76,78,80}Ni. In fig. 1, we show the HF-BCS energy curve obtained with a constraint on the mass quadrupole moment Q_2 as a function of the dimensionless quadrupole deformation β_2:

$$\beta_2 = \sqrt{\frac{5}{16\pi}}\frac{4\pi Q_2}{3R^2A}, \tag{5}$$

where the radius constant is given by $R = 1.2A^{1/3}$ fm. The deformation energies are obtained using the EV8 code [19] that solves the HF-BCS equations for the same EDF via a discretization of the quasiparticle wave function on a three-dimensional Cartesian mesh.

The correct description of the Q_β values for the parent nuclei and the neutron separation energies (S_n, S_{2n}) for the daughter nuclei is the important ingredient for the reliable prediction of the neutron-emission probability. The Q_β-value and the neutron separation energies are given by

$$Q_\beta = \Delta M_{n-H} + B(N-1, Z+1) - B(N, Z), \tag{6}$$

$$S_{xn} = B(N-1, Z+1) - B(N-1-X, Z+1). \tag{7}$$

$\Delta M_{n-H} = 0.782$ MeV is the mass difference between the neutron and the hydrogen atom. Skyrme EDFs T43 and T45 has been selected to reproduce the experimental Q_β and S_n values (see fig. 2), and enough positive value of the spin-isospin Landau parameter ($G_0^{'} \geq 0.1$) [20]. The parameter set T43 corresponds to the relatively strong ($\beta/\alpha = 2.0$) neutron-proton tensor correlations and set T45 corresponds to the weak ($\beta/\alpha = 0.7$) neutron-proton tensor correlations with respect to the like-particle tensor part. The results of the HF-BCS calculations with the EDFs T43 and T45 are in a reasonable agreement with the experimental data [21, 22] (see Ref. [23] for more details).

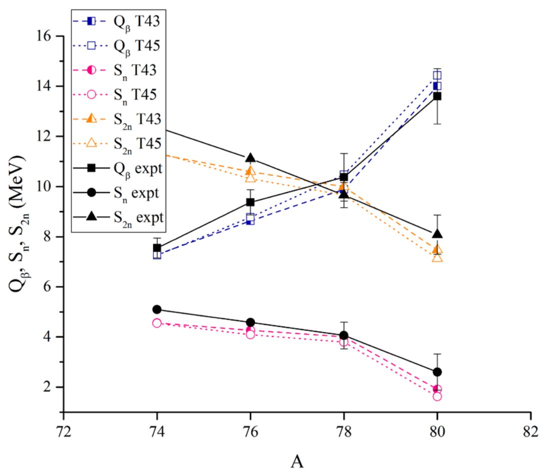

Figure 2. (Color online) The β-decay energy Q_β of ^{74,76,78,80}Ni and one- and two-neutron separation energies of Cu isotopes with the same mass number, calculated with Skyrme forces T43 and T45. Experimental data are taken from the Ref. [21, 22].

To build the QRPA equations on the basis of HF-BCS quasiparticle states of the parent nucleus is the standard procedure [24]. Using the FRSA model, the QRPA eigenvalues (E_k) are obtained as the roots of the secular equation [11–13], and we carry out QRPA calculations in very large two-quasiparticle spaces. To take into account the PPC effects we construct the wave functions from a linear combination of one-phonon and two-phonon configurations [5]

$$\Psi_\nu(JM) = \left(\sum_i R_i(J\nu) Q^+_{JMi} + \sum_{\lambda_1 i_1 \lambda_2 i_2} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) \left[Q^+_{\lambda_1\mu_1 i_1} \bar{Q}^+_{\lambda_2\mu_2 i_2} \right]_{JM} \right) |0\rangle\,, \tag{8}$$

where λ denotes the total angular momentum and μ is its z-projection in the laboratory system. The ground state of the parent nucleus (N, Z) is the QRPA phonon vacuum $|0\rangle$. The wave functions $Q^+_{\lambda\mu i}|0\rangle$ of the one-phonon excited states of the daughter nucleus (N - 1, Z + 1) are described as linear combinations of 2qp configurations; $\bar{Q}^+_{\lambda\mu i}|0\rangle$ is a one-phonon excitation of the parent nucleus

Table 1. The half-lives and the neutron-emission probabilities for the β-decay ^{74,76,78,80}Ni calculated with Skyrme interactions T43 and T45. Experimental data are taken from the Ref. [21].

A	T43			T45			Experiment
	$T_{1/2}$, 10^{-3}s	P_{1n}, %	P_{2n}, %	$T_{1/2}$, 10^{-3}s	P_{1n}, %	P_{2n}, %	$T_{1/2}$, 10^{-3}s
74	40	1	0	281	3	0	507.7±4.6
76	19	9	0	162	11	0	234.6±2.7
78	10	12	0	115	100	0	122.2±5.1
80	4	80	19	40	0	94	$23.9^{+26.0}_{-17.2}$

(N, Z). All one- and two-phonon configurations with the excitation energy of the daughter nucleus up to 19 MeV are included. Simultaneous taking into account the effects from the tensor force and the phonon-phonon coupling allows us not to use any quenching factors [25].

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

$$T_{1/2}^{-1} = D^{-1}\left(\frac{G_A}{G_V}\right)^2 \sum_k f_0(Z+1, A, E_k^{\mathrm{GT}})B(GT)_k, \tag{9}$$

$$E_k^{\mathrm{GT}} = Q_\beta - E_{1_k^+}, \tag{10}$$

where G_A/G_V=1.25 and D=6147 s [26]. $E_{1_k^+}$ denotes the excitation energy of the 1_k^+ state of the daughter nucleus. As proposed in Ref. [6], this energy can be estimated by the following expression:

$$E_{1_k^+} \approx E_k - E_{2qp,lowest}. \tag{11}$$

The difference in the characteristic time scales of the β-decay and subsequent neutron emission processes justifies an assumption of their statistical independence. As proposed in Ref. [27], the P_{xn} probability of the βxn emission accompanying the β-decay to the excited states in the daughter nucleus can be expressed as

$$P_{xn} = T_{1/2}D^{-1}\left(\frac{G_A}{G_V}\right)^2 \sum_{k'} f_0(Z+1, A, E_{k'}^{\mathrm{GT}})B(GT)_{k'},$$

where the GT transition energy ($E_{k'}^{\mathrm{GT}}$) is located within the neutron emission window $Q_{\beta xn} \equiv Q_\beta - S_{xn}$.

The impact of the tensor interaction on the half-lives and the probabilities of β-delayed neutron emission is shown in the table. The half-life description of $^{74-80}$Ni, obtained with the T45 EDF, are in a reasonable agreement with the experimental data [21]. The strong neutron-proton tensor force in the case of T43 set leads to the reduction of the β-decay half-lives for all studied Ni isotopes. In case of the β-decay of ^{76}Ni the neutron-emission probabilities, calculated with T43 and T45 EDFs, are in a reasonable agreement with the experimental data, P_{tot} = 14.0 ± 3.6% [21]. The N = 50 shell-closure is reflected in the tensor-force effect, as is shown in the table.

The neutron emission of the β-decay of ^{74,76,78,80}Ni are studied within the quasiparticle random phase approximation with the Skyrme interaction taking into account the tensor terms. The coupling between one- and two-phonon terms in the wave functions of the low-energy 1^+ states of the daughter nuclei is taken into account. It is shown that the reduction of the neutron-proton tensor interaction leads to the increase of the half-life and the neutron-emission probability. The results of calculations with the Skyrme interaction T45 are in a reasonable agreement with available experimental data.

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