EFFECTS OF TENSOR INTERACTION AND NEUTRON–PROTON PAIRING ON BETA-DECAY CHARACTERISTICS OF ^{130,132}Cd*

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The effects of the residual interaction in the particle–particle channel on β-decay characteristics and the multi-neutron emission probabilities in the β-decay of ^{130,132}Cd 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 inclusion of the spin–isospin interaction in the particle–particle channel leads to the reduction of half-lives and redistribution of one- and two-neutron emission probabilities. The competition of tensor interaction and neutron–proton pairing contribution in β-decay characteristics of the neutron-rich Cd isotopes is discussed.

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1. Introduction

The β-decay properties of the neutron-rich Cd isotopes near the neutron closed-shell $N = 82$ have always been of interest for nuclear structure studies [1] and radioactive beam experiments [1, 2]. A puzzle of the first 1^+ state in the ^{130}Cd was actively discussed in connection with the so-called "shell-quenching" effect [1]. The half-life of the "waiting-point" nucleus ^{130}Cd is also known to be important for setting up the time-scale for the r-process. A spectacular breakthrough has been achieved in the second generation radioactive-ion beam facilities. In the recent RIKEN studies [3], the beta-decay half-lives up to the ^{134}Cd were measured. The low-energy parts

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of the decay schemes have been recently measured in ^{129}In [4] and ^{130}In [5]. It is certainly of interest to further study the microscopic structure of these states.

The most sensitive to underlying nuclear structure is the multi-neutron emission: 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 $(N-1-X, Z+1)$ [6]. The microscopic study of the β-decay half-lives and the β-delayed neutron-emission probabilities of the nuclei with high N/Z asymmetry makes it possible to reconstruct the β-decay strength function [6, 7].

One of the successful tools for studying the charge-exchange nuclear modes is the quasiparticle random phase approximation (QRPA) with the self-consistent mean-field derived from a Skyrme force, see *e.g.*, [8–11]. This enables one to describe the properties of the ground state and excited charge-exchange states using the same force. As argued in Ref. [12], the study of multi-neutron emission following the β-decay of the neutron-rich nuclei would be more reliable if taking into account the phonon–phonon coupling (PPC). The finite rank separable approximation (FRSA) (see Refs. [13–15] and references therein) for the residual interaction allows one to perform such calculations in large configurational spaces.

The role of the residual neutron–proton (*np*) pairing interaction in the description of the low-lying Gamow–Teller (GT) strength within the QRPA-framework was discussed in Ref. [8]. Recently, the β-decay characteristics of Cd isotopes was described [12] within the microscopic model based on the Skyrme interaction with tensor components included [16]. The inclusion of the spin–isospin interaction in the particle–particle (*pp*) channel can further improve the model [17]. In the present report, we demonstrate the effect of the competition for tensor interaction and dynamical neutron–proton pairing in the β-decay characteristics of ^{130,132}Cd isotopes.

2. Details of calculations and results

The method has been discussed in detail in Refs. [12, 17], however, we recall it for completeness. The ground state properties of the even–even parent nucleus (N, Z) are described in the Hartree–Fock-BCS (HF-BCS) model, where spherical symmetry is imposed on the quasiparticle wave functions. The continuous single-particle spectrum is discretized by diagonalizing the HF-Hamiltonian on a harmonic oscillator basis. The Hamiltonian includes the Skyrme forces T43 and T45 [16] in the particle–hole (*ph*) channel and the surface peaked density-dependent zero-range force in the *pp* channel

$$V^{(pp)}_{T=1}(\boldsymbol{r}_1,\boldsymbol{r}_2) = V_0\left(\frac{1-P_\sigma}{2}\right)\left(1-\frac{\rho(r_1)}{\rho_0}\right)\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\,; \tag{1}$$

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

Here, P_σ is the spin-exchange operator and $\rho_0 = 0.16\,\mathrm{fm}^{-3}$ is the nuclear matter density. The strength $V_0 = -870\,\mathrm{MeV}\times\mathrm{fm}^3$, fixed to reproduce the odd–even mass difference of the studied nuclei [12]. The value of f is determined as the ratio of the strength $T = 1$ and $T = 0$ pairing interactions in *pp* channel.

The residual central interaction V^{ph}_{res} in the *ph* channel and V^{pp}_{res} in the *pp* channel can be obtained as the second derivatives of the energy density functional with respect to the particle densities and the pair densities, respectively. Following the method introduced in Ref. [13], we simplify V^{ph}_{res} by approximating it by its Landau–Migdal form. We keep only the $l = 0$ terms in V^{ph}_{res}. The spin–isospin residual interaction can be written as

$$V^{(a)}_{\mathrm{res}} = N_0^{-1}G_0^{\prime(a)}(r_1)(\sigma_1\sigma_2)(\tau_1\tau_2)\delta(\boldsymbol{r}_1-\boldsymbol{r}_2)\,, \tag{3}$$

where a is the channel index $a = \{ph, pp\}$, τ_i is the isospin operator, and $N_0 = 2k_{\mathrm{F}}m^*/\pi^2\hbar^2$, with k_{F} and m^* standing for the Fermi momentum and nucleon effective mass. The expressions for the parameters $G_0^{\prime(ph)}$ as well as for $G_0^{\prime(pp)}(r)$ are

$$G_0^{\prime(ph)} = -N_0\left[\frac{1}{4}t_0 + \frac{1}{24}t_3\rho^\alpha + \frac{1}{8}k_{\mathrm{F}}^2(t_1-t_2)\right]\,; \tag{4}$$

$$G_0^{\prime(pp)}(r) = \frac{1}{4}N_0 fV_0\left(1-\frac{\rho(r)}{\rho_0}\right)\,. \tag{5}$$

The *np*-QRPA equations are built on the basis of HF-BCS quasiparticle states of the parent (even–even) nucleus (N, Z) [18]. The eigenvalues of the QRPA equations are found numerically as the roots of the FRSA secular equation [14]. It enables us to perform QRPA calculations in very large two-quasiparticle spaces. It is shown that the matrix dimensions never exceed $(8N+4)\times(8N+4)$ independently of the configuration space size. If we omit the residual interaction in the *pp* channel, then the matrix dimension is reduced to $(4N+4)\times(4N+4)$ [15]. The studies of Ref. [14] enable us to conclude that $N = 45$ is enough for the GT transitions to the daughter nucleus.

To take into account the PPC effects, we follow the basic quasiparticle–phonon model (QPM) ideas [19]. The Hamiltonian can be diagonalized in a space spanned by states composed of one- and two-QRPA phonons [20]

$$\Psi_\nu(JM) = \left(\sum_i R_i(J\nu) Q^+_{JMi} + \sum_{\lambda_1 i_1 \lambda_2 i_2} P^{\lambda_1 i_1}_{\lambda_2 i_2}(J\nu) \left[Q^+_{\lambda_1\mu_1 i_1} \bar{Q}^+_{\lambda_2\mu_2 i_2} \right]_{JM} \right) |0\rangle \,, \tag{6}$$

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 $(N-1, Z+1)$; $\bar{Q}^+_{\lambda\mu i}|0\rangle$ is a one-phonon electric excitation of the parent nucleus (N, Z).

For constructing the wave functions (6) of the low-energy 1^+ states, the $[1^+_i \otimes 2^+_{i'}]_{\rm QRPA}$ terms are included which describe an impact of the quadrupole–phonon coupling. As it is pointed out in Refs. [12, 20], the $[1^+_1 \otimes 2^+_1]_{\rm QRPA}$ configuration is the most important for the half-life description since the $[2^+_1]_{\rm QRPA}$ state is the lowest collective excitation which leads to the minimal two-phonon energy and the maximal Hamiltonian matrix elements for coupling of the one- and two-phonon configurations.

As the first step in the present analysis, we examine the effect of the residual interaction in the *pp* channel on β-decay half-life of ^{130}Cd. Figure 1 displays the ratio of calculated-to-experimental half-life of ^{130}Cd (see the caption for details) and demonstrates the strong dependence of the β-decay

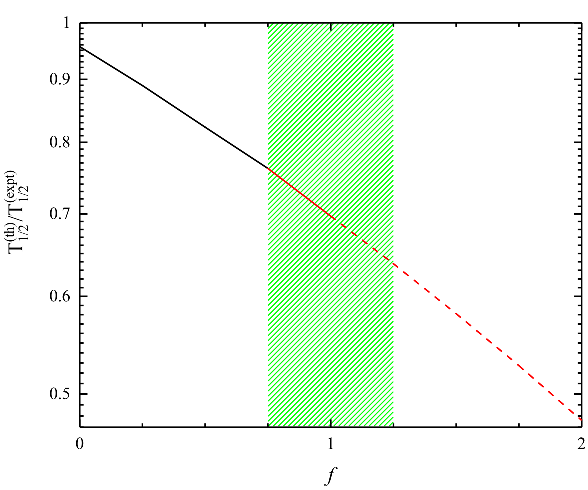

Fig. 1. The impact of dynamical neutron–proton pairing on the β-decay half-life of ^{130}Cd. Calculations performed with Skyrme force T43. Calculated half-life is normalized to the experimental value of $T^{(\rm expt)}_{1/2} = 127 \pm 2$ ms [3]. The shaded area roughly relates to the soft SU(4)-limit [21]; dashed line corresponds to the range of the parameter, which had not been used in the presented calculations.

half-life on the inclusion of spin–isospin interaction in the *pp* channel in the case of opened-shell nuclei; see in Refs. [12, 17]. Its increase leads to the redistribution of the high-energy GT transition strengths and, as a result, the acceleration of β decay. The enhancement of the effective neutron–proton interaction in the particle–particle channel up to $f = 1.5$ [22] reduces the half-life to the $T_{1/2}^{(\mathrm{th})} = 74$ ms. These calculations are performed with the Skyrme interaction T43. In the case of the Skyrme force T45, the weakening of the neutron–proton tensor interaction does not change this behavior, but only shifts the GT strength to the high-energy region and increases the half-life.

Let us study the impact of residual interaction in the *pp* channel on the β-decay rates of ^{132}Cd. The calculated half-life ($T_{1/2}$) and neutron-emission probabilities (P_{1n},P_{2n}) values are displayed in Fig. 2. The calculations are performed within FRSA model with the Skyrme forces T43 and T45. The PPC effects are also included. As expected, the account for the dynamical neutron–proton pairing leads to a noticeable reduction of half-life. Additional constraints on the β-strength function are given by the total and multi-neutron emission probabilities. The experimental $P_{n,\mathrm{tot}} = 60{\pm}15\%$ [2], while the calculated $P_{n,\mathrm{tot}}$ value of 100% may indicate the need for including the $T = 0$ pairing interaction. It is worth mentioning that our calculations

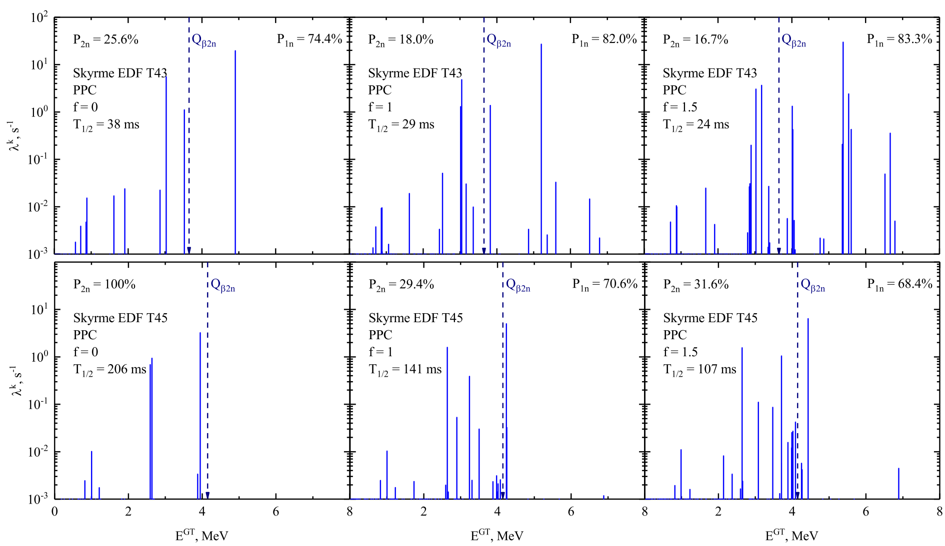

Fig. 2. The β-decay rates (λ^k), half-life ($T_{1/2}^{-1} = \sum_k \lambda^k$) and neutron-emission probabilities (P_{1n}, P_{2n}) values of ^{132}Cd calculated with Skyrme forces T43 (upper panels) and T45 (lower panels). The strength of parameter of f is varied from 0 to 1.5. The neutron-emission window $Q_{\beta 2n}$ is denoted by dashed line.

predict high probability of the two-neutron ($P_{2n} = 25.6\%$) emission in the case of the Skyrme force T43 [12]. The neutron–proton pairing significantly redistributes the β-decay rates of ^{132}Cd and results in the reduction of P_{2n} value. This reduction can be explained by the redistribution of the strength of GT transitions (Fig. 2). Indeed, increasing the strength of dynamical neutron–proton pairing (2) shifts the GT strength to the low-energy region. This effect is well-illustrated in our calculations performed with relatively weak neutron–proton tensor interaction with respect to neutron–neutron and proton–proton tensor terms (Skyrme force T45). The results, obtained without taking into account the residual neutron–proton pairing force ($f = 0$), predict a zero-probability of one-neutron emission for ^{132}Cd.

In summary, increasing the strength of the residual $T = 0$ pairing interaction leads to the significant redistribution of GT strength and results in the non-zero P_n value and reduction of the half-life of ^{132}Cd. It is shown that the competition of the tensor interaction and neutron–proton pairing has a substantial effect on the distribution of the Gamow–Teller transition strength. Decreasing the strength of neutron–proton tensor interaction amplifies the impact of neutron–proton pairing on the beta-decay rates.

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REFERENCES

[1] I. Dillmann *et al.*, *Phys. Rev. Lett.* **91**, 162503 (2003).

[2] M. Hannawald *et al.*, *Nucl. Phys. A* **688**, 578c (2001).

[3] G. Lorusso *et al.*, *Phys. Rev. Lett.* **114**, 192501 (2015).

[4] R. Dunlop *et al.*, *Phys. Rev. C* **93**, 062801(R) (2016).

[5] A. Jungclaus *et al.*, *Phys. Rev. C* **94**, 024303 (2016).

[6] I.N. Borzov, *Phys. Rev. C* **71**, 065801 (2005).

[7] I.N. Borzov, *Eur. Phys. J. Web Conf.* **107**, 06002 (2016).

[8] J. Engel *et al.*, *Phys. Rev. C* **60**, 014302 (1999).

[9] M. Bender *et al.*, *Phys. Rev. C* **65**, 054322 (2002).

[10] S. Fracasso, G. Colò, *Phys. Rev. C* **76**, 044307 (2007).

[11] C.L. Bai *et al.*, *Phys. Lett. B* **675**, 28 (2009).

[12] A.P. Severyukhin *et al.*, *Phys. Rev. C* **95**, 034314 (2017).

[13] Nguyen Van Giai, Ch. Stoyanov, V.V. Voronov, *Phys. Rev. C* **57**, 1204 (1998).

[14] A.P. Severyukhin, V.V. Voronov, Nguyen Van Giai, *Prog. Theor. Phys.* **128**, 489 (2012).

[15] A.P. Severyukhin, H. Sagawa, *Prog. Theor. Exp. Phys.* **2013**, 103D03 (2013).

[16] T. Lesinski *et al.*, *Phys. Rev. C* **76**, 014312 (2007).

[17] E.O. Sushenok *et al.*, *Phys. At. Nucl.* **82**, 120 (2019).

[18] J. Terasaki *et al.*, *Phys. Rev. C* **71**, 034310 (2005).

[19] V.G. Soloviev, *Theory of Atomic Nuclei: Quasiparticles and Phonons*, Institute of Physics, Bristol and Philadelphia 1992.

[20] A.P. Severyukhin *et al.*, *Phys. Rev. C* **90**, 044320 (2014).

[21] Yu.V. Gaponov, Yu.S. Lyutostanskii, *Sov. J. Part. Nucl.* **12**, 528 (1981).

[22] H. Sagawa, Y. Tanimura, K. Hagino, *Phys. Rev. C* **87**, 034310 (2013).