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Delayed neutron emission near the shell-closures

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Abstract. The self-consistent Density Functional + Continuum QRPA approach (DF+CQRPA) provides a good description of the recent experimental beta-decay half-lives and delayed neutron emission branchings for the nuclei approaching to (and beyond) the neutron closed shells $N = 28, 50, 82$. Predictions of beta-decay properties are more reliable than the ones of standard global approaches traditionally used for the *r*-process modelling. An impact of the quasi-particle phonon coupling on the delayed multi-neutron emission rates P_{2n}, $P_{3n,...}$ near the closed shells is also discussed.

1 Introduction

The β-decay half-lives and β-delayed neutron emission probabilities of very neutron-rich nuclei are of great value for nuclear structure theory. Reliable masses and beta-rates of extremely neutron-rich nuclei are indispensable for the *r*-process modeling. Accurate beta-decay data on the fission products are important for safety studies of advanced nuclear reactors.

A purely integral quantities, β-decay half-lives and β-delayed neutron emission probabilities, give an insight to isospin response of nuclei far from the stability. A combined analysis of total β-decay half-lives and multi-neutron emission rates (P_{xn}-values) enables one to reconstruct the beta-strength functions carrying back information on the nuclear density functional at high isospin-asymmetry regime. The beta-decay studies show that not only the neutron-halo nuclei near the drip-line reveal the features of weakly bound open quantum systems. Similar effects arise in neutron-rich nuclei because of "shell-erosion" induced by proton-neutron tensor interaction.

A substantial amount of more precise β-decay data on the fission and fragmentation products are expected to come from the acting radioactive beam facilities: ISOLDE-CERN, ALTO, RIKEN, TRIUMF, NSCL, as well as constructed FAIR, Spiral-2, HIE-CERN facilities. An importance of this field has been stated in the IAEA Project of creating new data base of the beta-decay and delayed neutron emission rates [1]. It will acquire accurate experimental data and theoretical predictions for nuclides beyond the reach of existing or planned facilities. In this respect, the fully microscopic models are of a special importance, as they ensure more reliable extrapolation of nuclear data to extreme N/Z ratios.

Based on the self-consistent description of the ground state properties within the local energy-density functional theory [2], the approach to the large-scale continuum quasi-particle random phase approximation (QRPA) calculations of the allowed Gamow-Teller (GT) and first-forbidden (FF) beta decays has been developed in [3]. In the report, the ground state properties and half-lives as well as delayed neutron-emission rates of (near) spherical nuclides near the neutron closed shells $N = 28, 50, 82$ is presented and compared with the recent experimental data [4–7]. Comparison with the standard global Finite Range Droplet Model (FRDM) [8] used for the astrophysical modeling is also be done. An emphasis is made on the constraints imposed by the half-lives as well as delayed neutron-emission rates on the beta-decay strength functions. A possible impact of the quasi-particle phonon coupling [9, 10] on the delayed multi-neutron emission rates P_{2n}, $P_{3n,...}$ near the closed shells is discussed as well.

2 Theoretical background

The self-consistent model for the GT and first-forbidden decays has been developed in [3] in which a detailed description and comparison with existing semi-microscopic global models can be found. The DF+CQRPA model treats the ground state and β-decay properties of (quasi)spherical nuclei.

1. The ground state properties are derived self-consistently in the energy-density functional theory. The present framework also exploits a new functional DF3a [11] and has a provision to fix (before variation) the ground state spin-parity of the parent (daughter) isobaric companion [4].

2. For excited states we follow an approximate treatment [3] in which the scalar and spin-isospin components of the DF can be approximately decoupled. This allows for independent nucleon-nucleon (NN) interactions in the scalar and spin-isospin channels. The strength parameters are considered as universal (A-independent) constants.

3. The β-strength functions are calculated within the continuum QRPA of the finite Fermi system theory. For

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the spin-isospin effective NN-interaction in the p-h channel a finite-range $\delta + \pi + \rho$ form is assumed. The nuclear medium modified one-π and one-ρ exchange terms, are important for the spin-isospin responses [3].

4. The correlations beyond the QRPA are included by re-scaling the spin-dependent multipole operators by the same energy-independent quenching factor $Q^{1/2} = (g_A/G_A)$. The one-pion component of the residual interaction is quenched by the same factor Q.

5. For the calculation of the β-decay half-lives we have considered allowed and first-forbidden transitions treated in terms of the reduced multipole operators depending on the space and spin variables [3].

6. The DF+CQRPA framework was successfully used for calculations of the beta-decay half-lives [3] and magnetic moments [12].

7. For a simple estimate of an impact of the $np-nh$ configurations on the β-strength functions, we use a spreading width of excitations $\Gamma\!\downarrow\approx\alpha\omega$ as in [13]. Also we studied an influence of quasiparticle-phonon coupling included via finite rank separable approximation (FRSA) [9, 10].

3 Results

Below the performance of the DF+CQRPA approach is exemplified. The main features of the β-decay and multi-neutron emission rates are described for the isotopes near the magic shell-closures in the neutron-rich sector.

3.1 ^{48}Ca region

The region of $Z\sim0$, $N>28$ is of great interest in the view of new experimental possibilities opened at FLNR, JINR for exploiting the Ca beams. In Fig. 1, the integral beta-decay characteristics calculated from the DF3+CQRPA beta-strength functions are compared with the recent data for the potassium isotopes. The experimental β-decay half-lives and total P_n values are reasonably well described by our model.The experimentally observed drop of the P_n value at $A = 50$ is related to occurrence of the additional first-forbidden transitions mediated by the odd-particles in the course of filling of the $N = 32$ and 34 subshells. Further steady increase of the P_n value is due to the impact of strong GT decays built on the $\nu 1f_{7/2}$-$\pi 1f_{7/2}$ transitions.

3.2 Nuclei below $Z = 28$ shell

The Co isotopes with $N \leqslant 50$ are a clean case for which the beta-decay characteristics are defined by the Gamow-Teller strength function. In Fig. 2, we show the GT strength distribution for ^{74}Co (in terms of log(ft) values). Importantly, the resulting $T_{1/2}$ and P_n values are very sensitive to the GT strength near the one-neutron separation energy.

As seen from Fig. 3, our calculations underestimate the half-lives and overestimate a bit the P_n values. In general, a very regular A-dependence of the calculated beta-decay observables agrees with the data and confirms a predominantly Gamow-Teller character of the beta-decay in this isotopic chain.

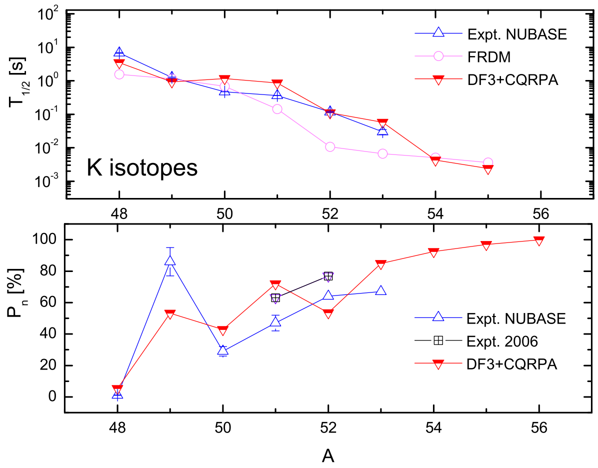

Figure 1. (Color online) Beta-decay half-lives and total P_n values for the K (potassium) isotopic chain. The experimental data have been obtained from the NUBASE evaluation [14]. The data of Ref. [15] are also shown.

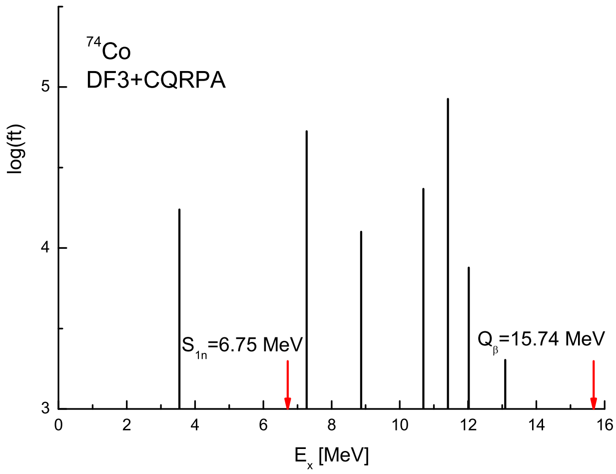

Figure 2. (Color online) The Gamow-Teller strength function for the decay of the ^{74}Co parent nucleus.

3.3 ^{78}Ni region

The most neutron-rich region of the nuclear chart in vicinity of ^{78}Ni may serve as a laboratory for exploring nuclear structure under extreme conditions. The $Z\sim28$ isotopes beyond N=50 may be affected by weakened neutron binding due to the ground-state spin inversion and possible existence of new neutron shell closures $N = 56 - 58$. An existence of neutron-halo structures is not excluded revealing unusual features of weakly bound open quantum system. These structural changes naturally impact the beta-strength function.

An evidence for new spherical subshell closure at N=58 was experimentally obtained recently for $^{83-86}$Ga isotopes [4, 5]. This subshell formed of two nearly degenerated orbitals may originate from migration of the neutron $2d_{5/2}$ and $3s_{1/2}$ orbitals causing a reduction of N=50 shell gap and some weakening of the ^{78}Ni doubly-magic core. Another peculiarity of this region is that the neutron-

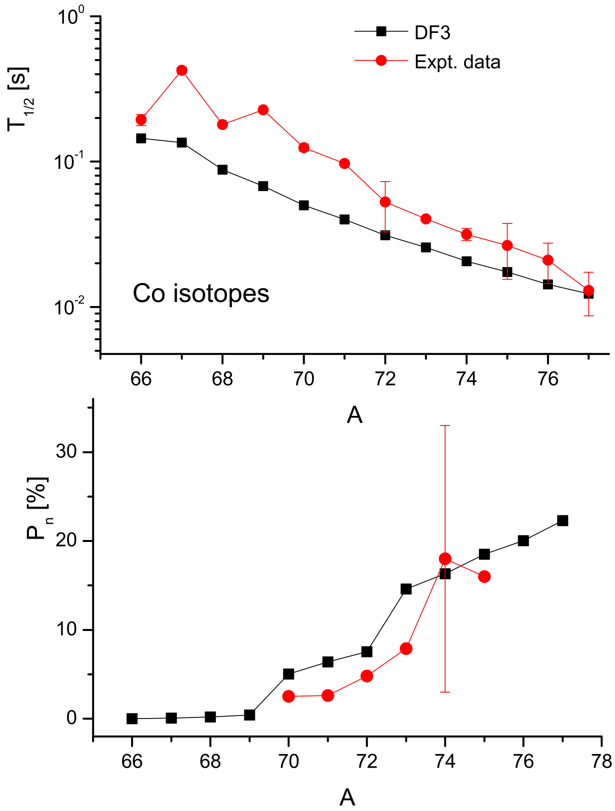

Figure 3. (Color online) The β-decay half-lives and total P_n values for the Co isotopic chain. Experimental data are taken from Refs. [6, 14].

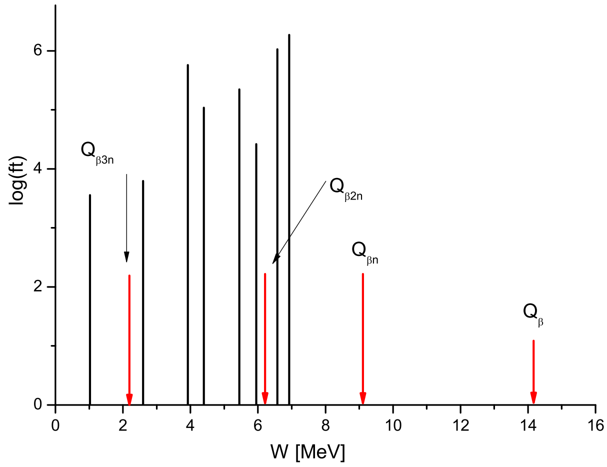

Figure 4. (Color online) The Gamow-Teller β-decay strength functions for ^{86}Ga plotted as a function of transition energy.

proton tensor interaction triggers a crossing of the proton $2p_{3/2}$ and $1f_{5/2}$ levels for nuclei beyond $Z = 28$. Resulting ground-state spin inversion has well been confirmed in magnetic moment measurements for Cu isotopes (see Ref. [12]).

Studying the β-decay of very neutron-rich nuclides with $N > 50$ in vicinity of the ^{78}Ni one meets with another difficulty. After crossing the closed neutron shells the neutrons fill positive parity orbitals while protons occupy negative parity orbitals and the first-forbidden transitions become possible. The share of the FF decays to the total half-life increases substantially for isotopes beyond the $N = 50$ shell. Clearly, in the scheme including both the GT and FF decays, the total half-lives for Ga chain at $N > 50$ depend on the ordering of the orbitals in the neutron ($N = 58$) as well as proton subshells. Additional measurements of the delayed multi-neutron probabilities would have provided us with important information on the beta-strength distributions within the sub-spaces corresponding to emission of $n = 0, 1, 2$ etc neutrons.

Below we discuss the case of ^{86}Ga: the most "powerful" $2n$ emitter in medium heavy nuclei region ($P_{2n} = 20 \pm 10\%$ [16]). The "DF3a+CQRPA" model is extended to account for spin inversion in the ^{78}Ni region. The approach is consistent with the systematics of the spin-parity of the ground states of Cu isotopes (understood as driven by the neutron-proton interaction when filling the $\nu 1g_{9/2}$ shell [17]). The calculation fixing the ground state to $\pi 1f_{5/2}$ single-particle state reproduces both $^{81-84}$Ga and new ^{86}Ga half-lives. No local adjustment was made.

Description of the P_{xn} values in ^{86}Ga is more difficult. They are mostly determined by the GT strength function, since the FF strengths ($\Delta J = 0, 1, 2$) being concentrated at the excitation energies below S_{1n} (transition energies higher the $Q_{\beta n}$). As seen from Fig. 4, our CQRPA calculation shows some deficiency of the GT strength within one-neutron emission sub-space. This is due to neglect of the GT strength fragmentation which may be caused by the effects beyond the simple $1p - 1h$ description and by deformation (both are not included in the DF3a+CQRPA model).

For the Ga isotope chain we estimated an impact of the $np - nh$ configurations beyond the CQRPA via spreading width $\Gamma\!\downarrow\, \approx \alpha\omega$, as suggested in Ref. [13]. Including the spreading (Figs. 5-7) makes the half-lives shorter and closer to the data [5], total P_n values increase, and the P_{xn} values are now $P_{1n} = 28\% > P_{2n} = 22\%$ [16]. This is a strong argument in favour of accounting for a quasiparticle-phonon coupling.

3.4 ^{132}Sn region

In ^{132}Sn region the GT and FF decays contribute differently to the beta-decay rates for the $Z < 50$ and $Z > 50$ isotopes. The intensive GT decays in the $Z < 50$ nuclei mostly correspond to the ($\nu 1g_{7/2}$, $\pi 1g_{9/2}$) configuration. The high-energy GT decays contribute strongly to the total half-lives of the nuclei with $Z < 50$, $N < 82$. Then at $N > 82$, the high-energy first-forbidden decays become opened which are mainly related to the ($\nu 1h_{11/2}$, $\pi 1g_{9/2}$) configuration. In Fig. 8, we exemplify the above said for the Pd isotopic chain. Importantly, the $1p - 1h$ DF3+CQRPA calculations [18] slightly overestimate the recent RIKEN data [7]. At the same time our FRSA calculation [10] including both the tensor interaction and $2p-2h$ configuration effects shows a very good agreement for ^{128}Pd.

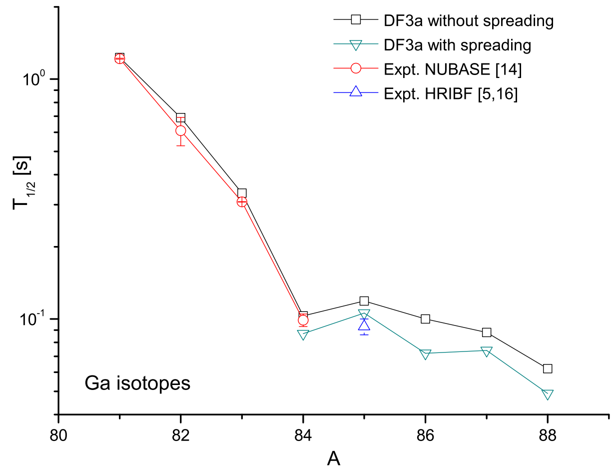

Figure 5. (Color online) The β-decay half-lives for the Ga isotopic chain calculated without and with inclusion of the spreading width. The experimental data are taken from Refs. [5, 14, 16].

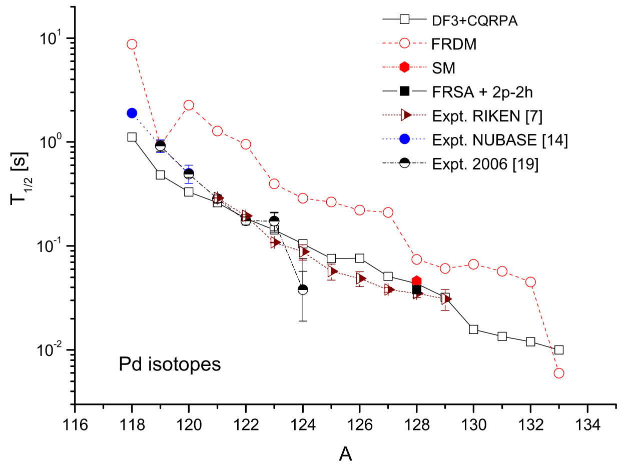

Figure 8. (Color online) Beta-decay half-lives for the Pd isotopic chain. These results are compared to the data [7, 14, 19] and half-lives based on the FRDM [8], the FRSA model including both the tensor interaction and $2p-2h$ configuration effects [10], the shell model (SM) [20].

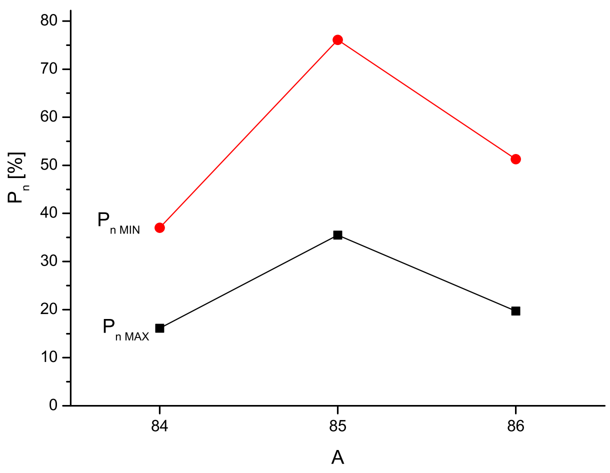

Figure 6. (Color online) The total delayed neutron emission probabilities for the Ga isotopic chain calculated without ($P_{\rm nMIN}$) and with inclusion of the spreading width ($P_{\rm nMAX}$).

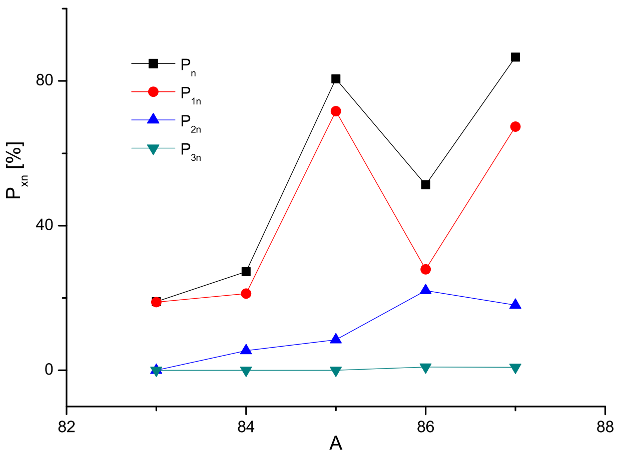

Figure 7. (Color online) The $P_{\rm 1n,2n,3n}$ and total $P_{\rm n}$ emission probabilities for the Ga isotopic chain calculated with inclusion of the spreading width.

As for nuclei beyond $Z = 50$ the $\pi 1g_{9/2}$ orbital is fully occupied, the GT transitions are related to low-energy $(\nu 1g_{7/2},\ \pi 1g_{7/2})$ configuration. Due to the phase space effect, the higher energy forbidden transitions which are opened at $N > 82$ and related to the $(\nu 2f_{7/2},\ \pi 1g_{7/2})$, $(\nu 1f_{7/2},\ \pi 2d_{5/2})$ configurations dominate the total half-lives. Though, for nuclei with $Z > 52$ and $N > 82$, $\pi 1g_{9/2}$ orbital is partially de-blocked due to pairing correlations, the GT transition strength is quenched by the occupancy factor of the proton level $(1 - v^2_{\pi 1g_{9/2}})$.

Probably, the most striking example of half-life reduction due to high-energy forbidden transitions is the kink at ^{134}Sb ($N > 82$) in Fig. 9. Notice, that our calculated half-lives are in rather good agreement with the data. For instance, in ^{136}Sb the $T_{1/2} = 0.80$ s which is rather close to the experimental value $T_{1/2} = 0.923 \pm 0.014$ s, as the FRDM [8] gives a factor 5 longer half-life.

In Fig. 10, we display the Q_β values for the Sb isotopes beta-decay and neutron emission thresholds in the daughter nuclei ($S_{\rm xn}$) calculated with the DF3 functional. One may conclude that two-neutron emission for $A > 135$ and three neutron emission for $A > 138$ are possible. However, compared to $Z < 50$ isotopes, the delayed neutron emission branching should be rather suppressed in the Sb isotopes due to the fact that the dominating FF transitions undergo outside the $Q_{\beta\rm n}$ window. Another complication is that the $P_{\rm xn}$ values are extremely sensitive to the $S_{\rm xn}$ values. Possible redistribution of the beta-strengths near the multi-neutron emission thresholds due to quasiparticle-phonon coupling is that counts. As seen from Fig. 11, in the ^{136}Sb isotope increasing the $Q_{\beta\rm n}$ value or decreasing the $Q_{\beta 2\rm n}$ thresholds by about 0.5 MeV would have changed the $P_{\rm 1n}$ and $P_{\rm 2n}$ values considerably. One has to mention that the accuracy of our calculation of the $Q_{\beta\rm xn}$ values is about 0.5-1 MeV. For instance, in ^{136}Sb our calculations with different versions of the density functional give the total $P_{\rm n}$ value from 5.4% to 15.6% and $P_{\rm 2n}$ value

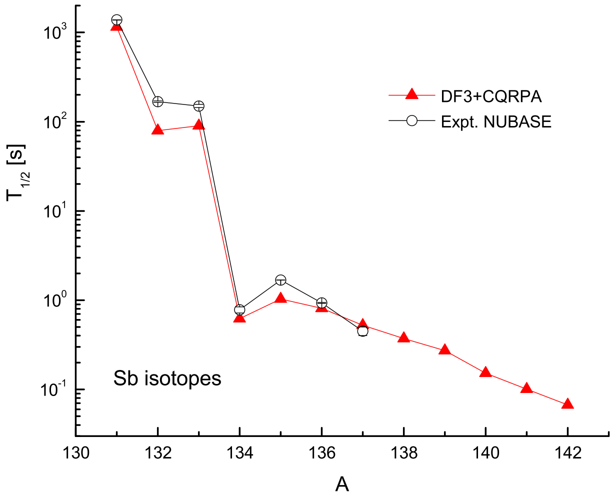

Figure 9. (Color online) Beta-decay half-lives for the Sb isotopic chain. The experimental half-lives were obtained from the NUBASE evaluation [14].

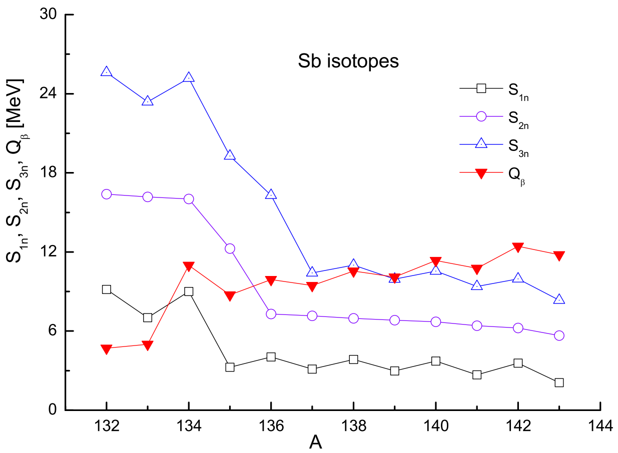

Figure 10. (Color online) Q_β values and the neutron emission thresholds in daughter nuclei for the Sb isotopes beta-decay.

from 3.1% to 5.2%. The experimental values [14] are: $P_n = 16.3 \pm 0.32\%$ and $P_{2n} = 0.26 \pm 0.02\%$. In the photo-fission measurements at JINR, Dubna [21] it was reported $P_{2n} = 2.0 \pm 0.2\%$.

4 Summary

With the universal set of the NN-interaction parameters the self-consistent approach to nuclear beta-decay [3] reliably describes both ground-state properties and small amplitude nuclear spin dynamics of (quasi)spherical nuclei in a wide region of the nuclear chart. Microscopic treatment of the GT and FF beta-decays within the single DF+CQRPA framework makes it possible to explain a number of peculiar effects observed in the beta-decay and delayed neutron emission of very neutron-rich nuclei beyond the closed neutron shells. Further extension of the self-consistent DF+CQRPA is related to description of deformed nuclei [22]. Due to a deficiency in extrapolating

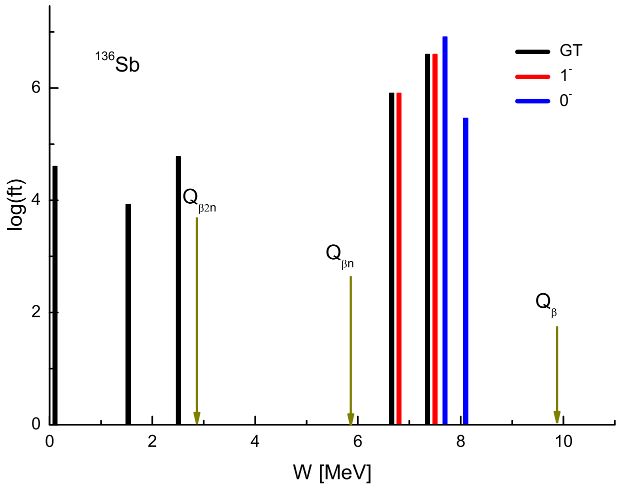

Figure 11. (Color online) The strength functions for the GT and FF decays in ^{136}Sb (plotted in terms of the transition energy)

the model parameters (defined near the line of stability), predictions of semi-empirical and schematic global models should always be taken with some reservation for unstable isotopes near the shell-closures.

The search for delayed multi-neutron emission at JINR, GSI, ALTO, HRIBF and RIKEN would be promising in the region beyond ^{48}Ca (K, Ca, Sc isotopes with $N > 30$). It is expected to be more favorable (though more difficult) for $Z < 50$ (Ag, Cd, In isotopes) than for $Z \geqslant 50$ (Sn, Sb, Te isotopes). The dedicated $(\beta - n)$ and $(\beta - n - \gamma)$ experiments at JINR, GSI, HRIBF, ALTO, RIKEN using fragmentation reactions and post-accelerated beams at FRIB facilities are indispensable for testing the nuclear structure models far off stability.

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