First-forbidden decays near the r-process paths

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The various supernova models fail so far in predicting the physical conditions necessary for a successful r-process nucleosynthesis. In addition to numerous problems in the quest of the astrophysical site for the r-process, nuclear physics uncertainties are still high. For the r-process calculations, self-consistent models are mandatory. The predictions of the β–decay rates based, on the same ground state description, as the one used to calculate the nuclear masses provide more reliable extrapolation far off stability.

In the previous microscopic large-scale calculations of the β–rates, a validity of the allowed transition approximation has not been critically analyzed which needs a revision. Though the "thumb rule" is that the β^-–decay half-lives become longer as closed (sub)shells are approached, the $T_{1/2}$ are also sensitive to the specific shell sequence. This is exactly due to the interplay of the Gamow-Teller (GT) and high-energy first-forbidden (FF) transitions near the shell closures. This feature calls for systematic large-scale calculations of the FF decays in the r-process relevant nuclei near N=50, 82, 126 neutron closed shells. In the proposed microscopic model both the GT and FF transitions are treated on the same footing.

1 The theoretical framework

We have followed the EDF+CQRPA approach to the large-scale calculations of the allowed GT and forbidden decays developed in in [1, 2]. It is based on the ground state description given by the Skyrme-MSk7 force [3] or alternatively Fayans energy density functional [4]. The DF3 version of this EDF [5] contains the two-body spin-orbit and velocity dependent effective NN-interactions, as well as the isovector spin-orbit force important for correct description of the single-particle levels near the "magic-cross" at ^{132}Sn [6]. For the excited states, the continuum QRPA (CQRPA) is applied with exact treatment of the particle-hole (ph) continuum and density-dependent pairing. A finite-range effective NN-interactions in the particle-hole is chosen in $\delta + \pi + \rho$ form [1, 2]. The effective T=0 interaction in the particle-particle (pp) channel is assumed to be similar to a like-particle pairing.

The GT and FF decays depend on seven β-moments related to the nuclear matrix elements of the following operators $\vec{\sigma}$; $\gamma_5, [\vec{\sigma}\vec{r}]^{(J=0)}$; $\alpha, \vec{r}, [\vec{\sigma}\vec{r}]^{(J=1)}$; $[\vec{\sigma}\vec{r}]^{(J=2)}$. The β-rates of the $J = 0, 1$ transitions are determined by the mixing of mutually cancelling β-moments. Besides, for the non-unique decays, the relativistic vector operator α, and axial charge operator γ_5 should be included alongside with the space-like operators. Two serious complications arise at this point. First, as it was shown on the basis of the chiral symmetry and soft-pion limit, $< \gamma_5 >$ vertex is amplified in the nuclear medium due to the meson-exchange currents and the effective NN-interactions [7]. Second, in a non-relativistic limit α and γ_5 correspond to the velocity-dependent fields $\vec{P}/2M$ and $\vec{\sigma} \cdot \vec{P}/2M$. Thus, the consistent treatment of the medium induced fields requires to take into account the velocity-dependent and two-body spin-orbit effective NN-interactions. A convenient approximation to be used in global calculations of total half-lives is to replace α and γ_5 by the space-dependent fields. For the matrix element of the α, an exact non-relativistic relation can be applied which reflects the conservation of the nuclear vector current :

$$< \alpha >= \xi/\lambda_e \cdot \Lambda_1 < i\vec{r} > \tag{1}$$

where λ_e is the electron Compton wave-length, ξ is the Coulomb parameter. In a fully self-consistent approach a precise cancellation of all the terms takes place except the averaged Coulomb potential $\bar{u_C}$, thus Λ_1 reads:

$$\xi\Lambda_1 = \omega_{if} + \bar{u_C}. \tag{2}$$

where ω_{if} is a β–transition energy (in units of $m_e c^2$). For the operator γ_5, no analogous exact relation exist due to the partial conservation of the axial current. The self-consistent FFS sum rule approach [8] is used to approximate the operator γ_5 by the operator $\vec{\sigma}\cdot\vec{r}$ taking into account the medium corrections which are mainly due to the spin-orbit and velocity dependent interactions [2]. With the resulting set of the space-dependent external fields, the large-scale microscopic calculations of the β-decay half-lives are feasible.

2 Results

β–decay in the Z <50 and Z≥50, N=82 regions. Unlike Z=28, N≈50 region, where a lot of the 1p1h high-energy GT and FF transitions exist, the only high-energy GT transition in the Z<50, N≈82 region is built on the $\nu 1g_{7/2} \rightarrow \pi 1g_{9/2}$ configuration. The high-energy FF decays are mainly due to the $\nu 1h_{11/2} \rightarrow \pi 1g_{9/2}$ configuration. Our results show no impact of the FF decays in Z=28, N=50 region, and a moderate (up to a factor of two) impact in Z<50, N=82 region [2]. The $^{130}\mathrm{Cd}\rightarrow^{130}\mathrm{In}$ β–strength function calculated in [5, 2] shows the 1^+ levels at the transition energies 6.95, 2.35, 0.65 and 0.10 MeV; 1^- levels at 6.45, 5.95, 4.10, 0.10 MeV and 0^- levels at 6.75, 2.85, 0.75 MeV. The total half-lives for Cd isotopic chain calculated in [2] (denoted at Fig.1 as DF3+CQRPA) are in overall agreement with the experimental ones [9] except for the ^{129}Cd and ^{132}Cd [10].

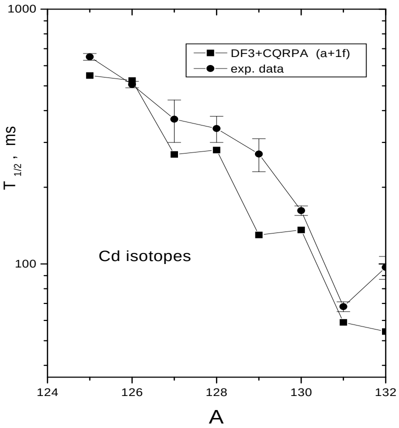

Fig. 1: The total half-lives
for Cd isotopes.

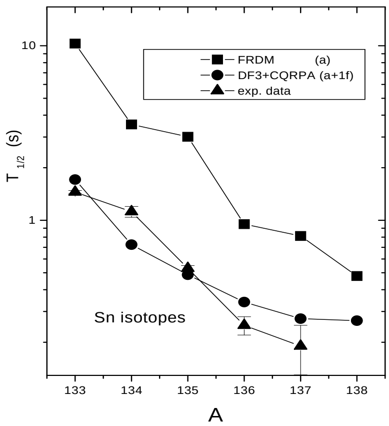

Fig. 2: The total half-lives
for Sn isotopes.

In contrary, for Z=50-51 and $N \approx 82$ nuclei in the ^{132}Sn region , the high-energy GT and FF transitions mentioned above are no longer possible, as the $1\pi g_{9/2}$–orbital is blocked. The higher energy FF transitions related to the $\nu 2f_{7/2} \rightarrow \pi 1g_{7/2}$, $\nu f_{7/2} \rightarrow \pi 2d_{5/2}$ configurations dominate in the total half-lifes of these nuclei, as well as for $Z \geq 52$ nuclei where the unblocking of the $1\pi g_{9/2}$–orbital starts due to pairing. This can be exemplified by the case of $^{133-137}$Sn nuclei (Fig.2) studied at RILIS, CERN [12]. In particular,the ^{135}Sn decay scheme [12] shows the low energy GT transitions at 4-5 MeV and high energy FF transitions at 7-9 MeV. The total half-life of 520(30) ms have been reported by [12] for ^{135}Sn. Our estimate [1, 2] is 2470 ms for the pure GT decay and 482 ms with first-forbidden decays included. As seen from Fig.2, the GT calculations by [11](denoted as FRDM+RPA, a) overestimate the experimental half-lives for $^{133-137}$Sn [12]. An agreement of our calculations [2] (denoted as DF3+CQRPA, a+f) with the experimental data shows that the FF decay of these nuclei is dominated by Coulomb mechanism.

β–decay v.s. (ν_e, e^-)–capture in N=126 region. In the important r-process region near Z≈60-80 and N=126, the role of the first-forbidden decays is decisive. These nuclei undergo high-energy first-forbidden decays related to the $\nu 1i_{13/2} \rightarrow \pi 1h_{11/2}$ configuration. Our CQRPA calculations predict a strong high-energy $J^\pi = 1^-$(S=1) transition near Z≈70 and N=126 with the β-decay energy of about 6 MeV, well above the GT transitions at 4 MeV corresponding to the $\nu 1h_{9/2} \rightarrow \pi 1h_{11/2}$ configuration. At the same time, the unperturbed β–decay energy of the main GT decay configuration $\nu 1i_{13/2} \rightarrow \pi 1i_{11/2}$ is low (about 1 MeV).

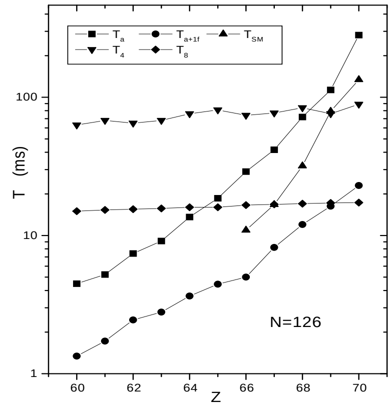

Fig. 3: The total half-lives for the N=126 chain.

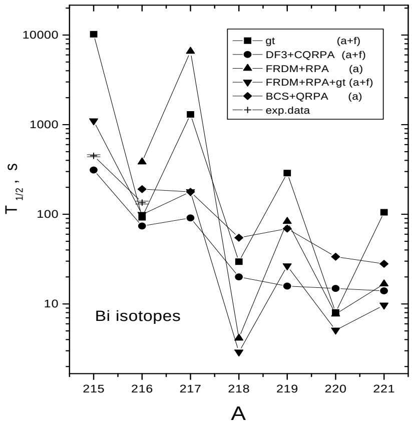

Fig. 4: The total half-lives for Bi isotopes.

The comparison with the shell–model (SM) calculations [13] performed in the GT approximation is displayed in Fig.3. We see that the inclusion of the FF transitions (denoted as DF3+CQRPA, a+f) made in [2] results in noticeably shorter half-lives in the N=126 region. The deviation with the GT approximation amounts to typically a factor 5 to 10, and is more pronounced for heavier nuclei approaching the closed proton shell at Z=82. Note that the shell–model half-lives [13] obtained for the GT decay with the quenching factor $(\frac{g_A}{G_A})^2$=0.55 would be shorter if the first-forbidden decays were included.

The shorter half-lives predicted for N=126 imply an acceleration of the matter flow through this "waiting point", both in r-process canonical scenario and in a neutrino wind model where the flow of matter to higher Z may speed up due to the combined effect of the β–decays and charged-current electron neutrino captures. Shown in Fig.3 are the calculated half-lives againist (ν_e, e^-)-capture at the neutrino temperature T_ν=4 MeV [14], and the ones by [16] at

T_ν=8 MeV (the neutrino luminosity is $L_\nu \approx 10^{52}$ erg s^{-1}, the distance from the center of the neutron star is R=100km).

We see from Fig.3 that even at T_ν=8 MeV with complete neutrino conversion $\nu_e \rightleftharpoons \nu_{\mu,\tau}$ in effect [16], the β–decays dominate over charged-current electron neutrino captures in this region of the r-process path (for the accepted values of L_ν, R and T). The shorter β–decay half-lives obtained in the N=126 region may change the estimate of the distance from the neutron star surface at which the neutrino-nucleus reactions occur and influence the picture of the r-process both in the canonical and in neutrino wind scenarios.

β–decay "east" of ^{208}Pb. At the time being, the predictions in Z=60–70, N=126 region can not be verified experimentally. The current experiments (see [19, 20]) concern mostly the nuclei "east" of ^{208}Pb. In the region around ^{208}Pb, 21 fast forbidden transitions are well known experimentally. The main problem theory may encounter is a possibility of cancellation of the leading matrix elements for J=0,1 transitions resulting in a decay retardation and deviation of the electron spectra from a statistical shape.

For heavy Bi isotopes (Fig.4) we compare the measured half-lives with the predictions from the existent global approaches [17, 11, 2, 18]. The total half-lives for the GT decay calculated within the FRDM+RPA model [11] overestimate the experimental ones by orders of magnitude. The scale of the odd-even effects predicted by [11] is generally too large because of the non-consistent treatment of the ground state properties and pairing correlations, and also due to the T=0 pn-effective interaction is not included in [11].

The results of statistical model (gt) [17] with a parametric description of the FF transitions, vary significantly from the odd-A to even nuclei (Fig.4). The results from the "micro-statistical" (FRDM-RPA-gt) model [18] (in which the "gross-theory" calculations of the FF decay is combined with FRDM+RPA description of the GT decay) are closer to the experimental data. However, obtained strong renormalization of the GT half-lives (for example in ^{216}Bi) is hard to explain. It may well come from the inconsistency in the microscopic and "gross-theory" inputs within this hybrid models.

In the calculations by [15] (BCS-QRPA) the strengths of the separable ph and pp NN-interactions are fitted to the experimentally known half-lives for each isotopic chain which is a purely empirical procedure. As the odd-even behavior of the half-lives calculated in [15] is reasonable (the T=0 paring has been included), such a procedure may give a sound local extrapolation. As the FF transitions has not been included, the calculations by [15] overestimate the experimental half-lives in the region of Bi isotopes.

Our results (DF3+CQRPA, a+f) [2] show a fairly regular behavior with some underestimation of the experimental total half-lives (Fig.4). The calculation may still be oversimplified in the specific region "east" of ^{208}Pb, especially if the ΔJ=0 transitions dominate in the decay schemes. This is mainly due to the neglect of the velocity-dependent terms in the effective NN-interaction and to the use of the Coulomb (ξ) approximation. However, the results are in a qualitative agreement with available experimental data on total half-lives.

In summary, within the microscopic model taking into account the GT and FF decays on the same footing, a strong impact of the high-energy FF transitions on the total β–decay half-lives in the regions of $Z \geq 50$, N=82 and $Z = 60 - 70$, N=126 is found. The calculations provide some guidance for the experiments in remote regions, in particular in the region "east" of ^{208}Pb.

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