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Neutrino-induced fission on nuclei near the r-process paths

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The calculations of the beta- and neutrino-induced rates are performed for the nuclei at Z=92-96 approaching the possible r-process paths in vicinity of the spherical neutron shells at N= 126, 184. The ground states of these experimentally unknown nuclei are treated self-consistently in the framework of the local energy-density functional theory. The beta-strength-functions of the Gamow-Teller and first-forbidden decays are calculated within the continuum QRPA approach. The beta-decay and beta-delayed neutron emission rates, neutron induced and beta-delayed fission rates, as well as the distributions of fission fragments and numbers of emitted neutrons are also analyzed within a single self-consistent framework.

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1. Introduction

Recent observations in low-metallicity, old galactic halo stars have revealed significant deviations of the abundances of the r-process elements from the solar r-process pattern near the fission products mass numbers A ≈90 [1]. This suggests revisiting the long-standing problems of fission cycling and r-process termination. It has been pointed out that enhancement at ≈90 may be related to the charge-current neutrino capture after freezout [2, 3]. As typical supernova neutrino energies are high enough to excite the pygmy and high-lying giant allowed (IAS, GT) and first-forbidden (FF) resonances (located at average energies of $E_x \approx$ 20 - 30 MeV in daughter nuclei well above the fission barriers), a subsequent process of fission is possible. The neutron separation energy decreasing with N-Z makes the neutron evaporation a major competeing particle decay channel. Hence, in the mass region near N=184 one needs to treat all the neutrino- and beta-induced weak reactions rates within a single self-consistent framework.

2. The theoretical framework

To calculate the beta-strength functions and neutrino-capture cross sections as a function of neutrino energy we have used the approach of [5, 6] to the large-scale calculations of the allowed Gamow-Teller (GT) and first forbidden (FF) decays. The ground states properties are treated self-consistently in the framework of the local energy-density functional (DF) theory. The Fayans phenomenological density-functional [7] consisting of a normal and a pairing part is adopted in its DF3 version [4]. For the excited states, the continuum quasiparticle random-phase approximation (CQRPA) equations of the finite Fermi system theory [8] are solved with exact treatment of the particle-hole (ph) continuum, pairing and effective NN-interaction in the ph and pp channels [9]. [1]

To describe the β- and ν-induced fission and neutron emission we use a statistical model ABLA [3]. Given the nuclear excitation energy, the decay of the nucleus all the way to the ground state of the daughter is treated within the Monte–Carlo approach. The probabilities of fission, neutron emission and the number of neutron emitted during decay path as a function of nuclear excitation energy is obtained. By folding this with the energy-dependent neutrino-capture cross section and summing over all available nuclear states at the given neutrino energy, the cross section for fission and neutron emission are calculated. By iterating the indicated two steps for a range of relevant neutrino energies one can then fold it with the spectrum in order to get the averaged neutrino cross section and decay probabilities.

3. The results

The beta-strength functions for the GT and FF-transitions are displayed in Fig.1. The predictions for nuclei with Z=92-96 near the N=184 neutron shell cannot be validated by the experimental data. The sum rule constraint on the total strengths of the GT and FF transitions has been controlled

[1] The "low energy" spin-isospin response ($\omega \leq \varepsilon_F$) is quenched due to the universal medium renormalization beyond the QRPA-type correlations: the np-nh configurations, delta-resonance admixtures etc.. These effects are taken into account via the quasiparticle local charge operators $\hat{e}_{qi} = e_q[V_0^{JLS}]$. The so-called spin-isospin "quenching factor" then is $Q = e_{qs}[\sigma\tau]^2$=$(g_A/G_A)^2$. For further details of the calculation see Ref.B03.

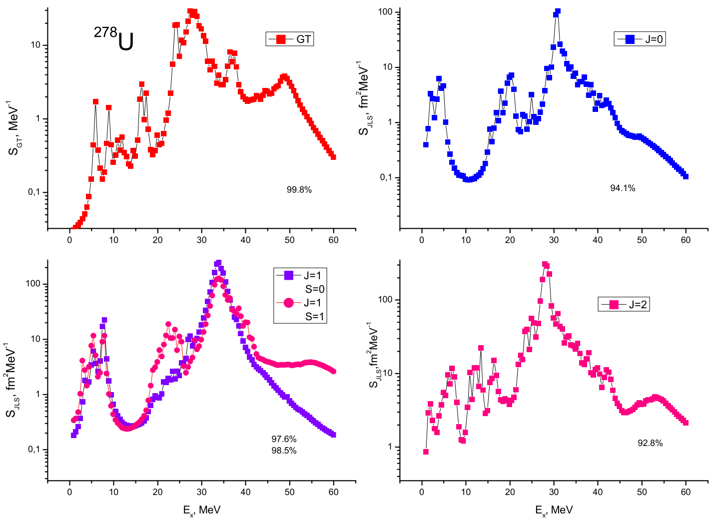

Figure 1: The GT and FF β–strength functions for ^{278}U calculated within the DF3+CQRPA (Q=0.81). The numbers show the exhaustion of the GT and FF sum rules.

instead. As shown in Fig.1, the GT sum rule in the U isotopic chain is fulfilled to 99.5% in the excitation energy interval of 80 MeV, while the FF sum rules are exhausted up to 93 - 99.8 %.

Unlike Z=28, N=50 and Z=50, N=82 regions [5], the competition of the high-energy GT and first-forbidden decays is important both below and above the N=184 closed shell. In the case of N$\leq$184 these are mainly due to the $\nu 1i_{11/2} \rightarrow \pi 1i_{13/2}$ GT-configuration and $\nu 1j_{15/2} \rightarrow \pi 1i_{13/2}$ FF-configuration. For N$\geq$184 the relevant FF transitions are from $\nu 1h_{11/2}$ to the $\nu 1i_{11/2}$ and $\nu 1i_{13/2}$ orbitals. The transition from $\nu 1h_{11/2}$ to the $\nu 1h_{9/2}$ partially occupied orbital is responsible for a strong decrease of the GT-half-life after crossing the N=184 shell.

In Fig.2 we compare our β–decay half-lives calculated in the GT+FF approximation with the ones calculated using the finite-range droplet model (FRDM) for the ground states description, the RPA for the GT decays and "gross theory" for FF decays [12]. The inclusion of the first-forbidden transitions within the DF3+CQRPA results in noticeably shorter half-lives in the N=184 region: the typical half-lives are 0.13s (GT) and 0.002s (GT+FF) at A=270 and 0.005 and 0.003s at A=285 correspondingly. Our calculations result in the total half-lives which are a factor of 2 - 5 shorter compared to [12]. For nuclei crossing the closed neutron shell at N=186,187 for the [12] predicts the longer half-lives than for N=184.

In Fig.3 we exemplify the total and partial folded neutrino cross sections and the average number of the neutrons emitted in β-induced and ν-induced evaporation for Np isotopes. The total neutrino-capture cross section show a smooth increase with mass number, as expected for the highly unstable nuclides [10]. Small fluctuations in this trend are caused by odd-even effects in the Q-values. Unlike Z=92-96 isotopes near N=126, the fission contribution near N=184 is small due to high fission barriers and low neutron separation energies. The very rare fission events result in about 10 neutrons on average, most of which come from the neutron-rich fragments. The beta-induced processes give off less neutrons than their neutrino-induced counterparts. As the mass

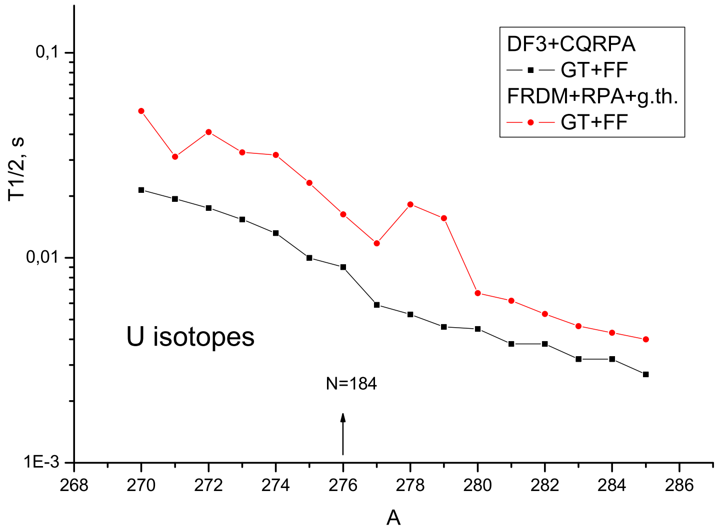

Figure 2: The calculated DF3+CQRPA total half-lives for the U isotopes (GT and first-forbidden decays included, Q=0.81). The half-lives labeled by FRDM+RPA+gr.th. are calculated with FRDM ground states description and using RPA for the GT decays + "gross theory" for FF decays [12].

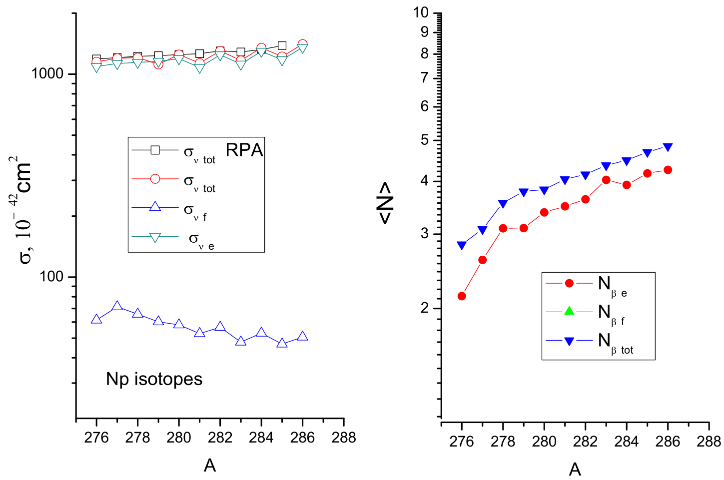

Figure 3: Left: The calculated total (squares - RPA [3], circles - DF+CQRPA), partial fission and neutron evaporation (up and down triangles) cross sections for neutrino-induced processes on the Np isotopes. Right: The calculated DF+CQRPA partial neutron numbers emitted in beta-induced (circles) and neutrino-induced (squares) evaporation processes on the Np isotopes.

number increases, the Q-values becomes larger than the average neutrino spectra energies and the mentioned difference diminishes. The RPA calculation by [3] which uses the masses from [11] as an input gives up to 20% higher cross sections with less pronounced structure for Z=92-96.

4. Conclusion

For specific nuclear density functionals and at certain astrophysical conditions, the r-process may continue even to very heavy nuclei with A≈300 and above. Then neutron-rich nuclei near the neutron magic number N=184 will be quite essential. The short β-decay half-lives are needed to reach these nuclei. A schematic estimate based on [11] indicates that this may take a few seconds. The half-lives predicted in the present work near the N=184 shell are much shorter than the ones from [11]. This implies that the neutrino-capture and beta decays can compete and should be taken into account in nucleosynthesis studies. The large amounts of neutrons emitted in both evaporation and fission events may cause additional neutron-induced events and presumably have to be included in the network.

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