β-Decay Rates of r-Process Nuclei in the Relativistic Quasiparticle Random Phase Approximation ◇

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The latest theoretical and computational advances in nuclear structure modeling have also had a strong impact on nuclear astrophysics. More and more often calculations of stellar nucleosynthesis, nuclear aspects of supernova collapse and explosion, and neutrino-induced reactions, are based on microscopic global predictions for the nuclear ingredients, rather than on oversimplified phenomenological approaches. The nuclear input for astrophysics calculations necessitates the properties of thousands of nuclei far from stability, including the characteristics of strong, electromagnetic and weak interaction processes. Most of these nuclei, especially on the neutron-rich side, are not accessible in experiments and, therefore, many nuclear astrophysics calculations crucially depend on accurate theoretical predictions for the nuclear masses, bulk properties, nuclear excitations, (n, γ) and (γ, n) rates, α- and β-decay half-lives, fission probabilities, electron and neutrino capture rates, etc.

The path of the r-process nucleosynthesis runs through regions of very neutron-rich nuclei. β-decays are particularly important because they generate elements with higher Z-values, and set the time scale of the r-process. Except for a few key nuclei, however, β-decays of r-process nuclei have to be determined from nuclear models. One of the crucial questions for structure models is, therefore, a consistent microscopic calculation of β-decay far from stability.

In this work we report the first application of the relativistic PN-QRPA in the calculation of β^--decay rates for neutron-rich nuclei. Self-consistent relativistic mean-field models have been very successfully applied to nuclear structure, not only in nuclei along the valley of β-stability, but also in exotic nuclei with extreme isospin values and close to the particle drip lines. The relativistic mean-field framework has recently been extended to include medium dependent meson-nucleon vertices. In Ref. [2] we have extended the relativistic Hartree-Bogoliubov (RHB) model [1] to include medium-dependent vertex functions. A phenomenological effective interaction, denoted DD-ME1, was adjusted to properties of nuclear matter and finite nuclei, and tested in the analysis of the equations of state for symmetric and asymmetric nuclear matter, of ground-state properties of the Sn and Pb isotopic chains [2], and deformed nuclei [3]. Our initial attempt to calculate β^- decay rates of r-process nuclei by simply employing the DD-ME1 interaction in the RHB plus PN-RQRPA framework was not successful. In general, the resulting half-lives were more than an order of magnitude longer than the empirical values. The reason is that DD-ME1, as well as most other successful relativistic mean-field interactions, has a relatively low effective nucleon mass, especially when compared to effective masses of Skyrme forces. This means that, because the density of states around the Fermi surface is low, in a self-consistent relativistic QRPA calculation of β-decay the transition energies are low, and this result in long lifetimes. In order to be able to calculate β-decay half-lives, in this work we adjust a new relativistic mean-field density-dependent interaction with a higher value of the effective nucleon mass, by including an isoscalar tensor-coupling term in the model Lagrangian.

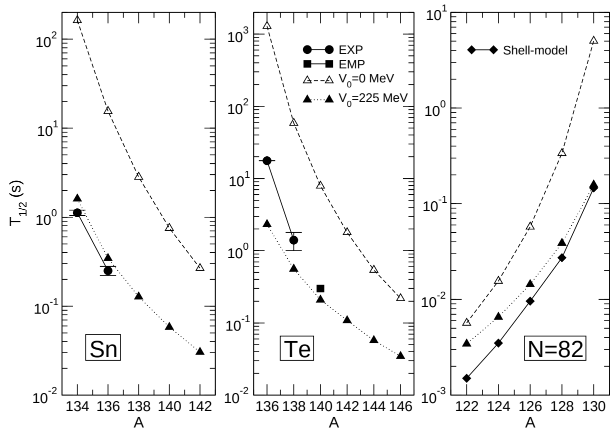

Fig. 1: Calculated half-lives of Sn (left panel) and Te (middle panel) isotopes for two values of the $T = 0$ pairing strength, in comparison with experimental data. In the right panel the results for the $N = 82$ isotones are compared with the shell-model results [4].

Fig. 1 we compare calculated half-lives of Sn and Tc isotopes and of isotones with N=82 with experimental values and with calculations within the shell model of Ref. [4]. It turns out that is is very important to take into account a T=0 pn-interaction in the pairing cannel.

In this work the newly developed relativistic PN-QRPA has been for the first time applied to Gamow-Teller β-decays of nuclei relevant for the r-process. The RHB+QRPA model employed in this work is fully self-consistent. For the interaction in the particle-hole channel effective Lagrangians with density-dependent meson-nucleon couplings are used, and pairing correlations are described by the pairing part of the finite range Gogny interaction. Both in the ph and pp channels, the same interactions are used in the RHB equations that determine the canonical quasiparticle basis, and in the matrix equations of the RQRPA.

The relativistic PN-QRPA presents a valuable tool for the investigation of weak interaction rates of neutron-rich nuclei. It can be used for microscopic calculations not only of Gamow-Teller, but also of first-forbidden decays, which seem to play an important role for β-decay rates in the N≈126 region.

References

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