Shell model half-lives for r-process nuclei*

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The astrophysical r-process produces about half of the heavy elements in the Universe by a sequence of the fast neutron-capture reactions interrupted by photodissociations and followed by beta decays, running through extremely neutron-rich nuclei. The beta decays of the waiting-points, associated with nuclei with the magic neutron numbers $N = 50, 82, 126$, play a crucial role for the r-process dynamics and elemental abundance distributions. Unfortunately only few data are known experimentally for the waiting point nuclei at $N = 50, 82$, while for $N = 126$ the astrophysical models rely fully on theoretical predictions. In addition to the Gamow-Teller (GT) transitions, the calculations of half-lives in this region have to account for first-forbidden (FF) contributions, as the neutron and proton Fermi levels of neutron-rich nuclei may be located in shells of different parities. A first attempt to estimate such forbidden contributions has been taken within the gross theory [1]. More recently, Borzov extended the QRPA studies based on the Fayans energy functional to a consistent treatment of allowed and first-forbidden contributions to r-process half-lives [2]. While these calculations find that forbidden contributions give only a small correction to the half-lives of the $N = 50$ and $N = 82$ waiting point nuclei, they result in a significant reduction of the $N = 126$ half-lives. This important finding has been our motivation to extend our shell model calculations of waiting point half-lives to include also FF transitions. We have thus developed the shell model code NATHAN [3, 4] to compute such transitions and studied their influence on the half-lives of r-process nuclei at $N = 50, 82$ and 126. Meanwhile similar shell model calculations became available for $N = 126$ isotones [5], however in a restricted valence space and applying different quenching factors for transition operators. The model spaces and interactions used in our shell model calculations are described in detail in Ref. [6]. Also the results for $N = 50$ and $N = 82$ nuclei are presented there, showing an overall good agreement with the half-lives known experimentally. The role of FF contributions in $N = 50, 82$ isotones appear to be minor in our SM calculations, as anticipated in [2]. For the $N = 126$ r-process nuclei, the calculations have been done in a large configuration space including ($d_{5/2,3/2}$, $s_{1/2}$, $g_{7/2}$, $h_{11/2}$) orbits for protons and ($h_{9/2}$, $f_{7/2,5/2}$, $i_{13/2}$, $p_{3/2,1/2}$) for neutrons and employing effective interaction from [7]. Seniority truncation scheme (up to 4 broken pairs) has been chosen to provide a realistic description of correlations within this valence space. In Fig. 1 we show the half-lives of $N = 126$ isotones obtained in our work and compared to other available theoretical models. The SM half-lives are noticeably faster than those predicted by global models, i.e. QRPA on top on the FRDM approach and do not exhibit any staggering. In spite of different model spaces and interactions employed, our results are very close to those from Ref. [5]. We confirm that the FF contributions to the total half-life are significant for all $N = 126$ isotones and start to dominate over the GT for nuclei with $Z \geq 70$.

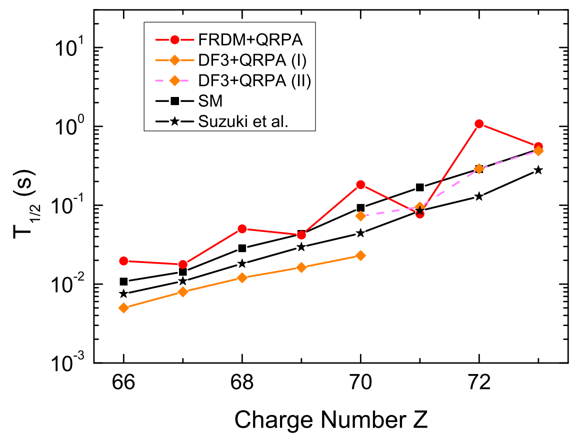

Figure 1: Half-lives of $N = 126$ r-process nuclei in different theoretical models. See text for more details.

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