Role of Astromers on Stellar Beta-decay rates in r-process Nucleosynthesis

Shrikant Thorat[1],* Sutanu Bhattacharya[1], A. K. Jain[1,2], B. Maheshwari[3], A. Goel[1], R. Palit[4]
[1] *Amity Institute of Nuclear Science & Technology, Amity University Uttar Pradesh, Noida - 201313*
[2] *Department of Physics, Indian Institute of Technology Roorkee, Roorkee-247667*
[3] *Department of Physics, University of Zagreb, HR-10000, Croatia*
[4] *Department of Nuclear and Atomic Physics, Tata Institute of Fundamental Research, Mumbai-400005, India*

Introduction

Hundreds of nuclear isomers have now been identified across the chart of nuclide [1]. The beta-decaying isomers, which mostly lie on the n-rich side of the stability line, are expected to play a crucial role in the nucleosynthesis of heavy mass nuclei [2]. Such nuclei have now been termed as astromers and represent a major focus of present researches in nuclear astrophysics [3]. So far, most of the astromers which have been studied in nuclear astrophysics belong to the low mass region like ^{26}Al, and ^{35}Cl [4, 5]. But their role has generally remained a missing component in the heavy mass region, especially in r-process nucleosynthesis. More specifically, the beta-decaying isomers should play an important role in the r-process nucleosynthesis. The stellar abundance of heavy elements depends on many factors like the reaction rates, beta decay rates, density and temperature of plasma etc. The nuclear structure information becomes very important in such calculations. In this paper we focus on the beta-decaying isomers, present in the neutron rich region of heavier mass nuclei, beyond the iron peak. We calculate the stellar plasma beta decay rates with the inclusion of isomeric state, and the isomeric stellar beta decay rates to understand the role of isomers on the formation of elements.

Methodology and calculations

In the stellar medium, isomeric states in the nucleus can be thermally populated and these metastable states may undergo beta-decay transition to the ground or the excited state of the daughter nucleus. The total beta decay rate in stellar medium is given by [6]

$$\lambda_\beta = \sum P_i \sum \lambda_{ij} \tag{1}$$

Here, Pi is the population probability of the ith state. The summation extends over all the included excited states. At thermodynamic equilibrium, the population probability of the excited state having excitation energy E$_\mu$ is given by [7],

$$P_\mu = \frac{N_\mu}{N} = \frac{(2J_\mu + 1)exp^{\frac{-E_\mu}{kT}}}{G} \tag{2}$$

where J$_\mu$ is the spin of the state μ, and T is the stellar plasma temperature. The number density in state μ is denoted by N$_\mu$ and the total number density by N. The nuclear partition function is given by G. In this paper, we have calculated the stellar beta decay rates for three n-rich nuclei: ^{85}Kr, ^{129}Sn, and ^{166}Ho. We have included the lowest lying ten excited states in the calculations for each nucleus. Additionally, we have also calculated the stellar beta decay rates for all the cases in which partition function has been obtained with respect to the isomeric state.

Results and Discussion

We have identified 93 beta decaying astromers in the n-rich region from our atlas, which may play an important role in the r-process [1, 2]. We have classified these isomers into three broad categories on the basis of their

*Electronic address: shrikantthoratsci@gmail.com

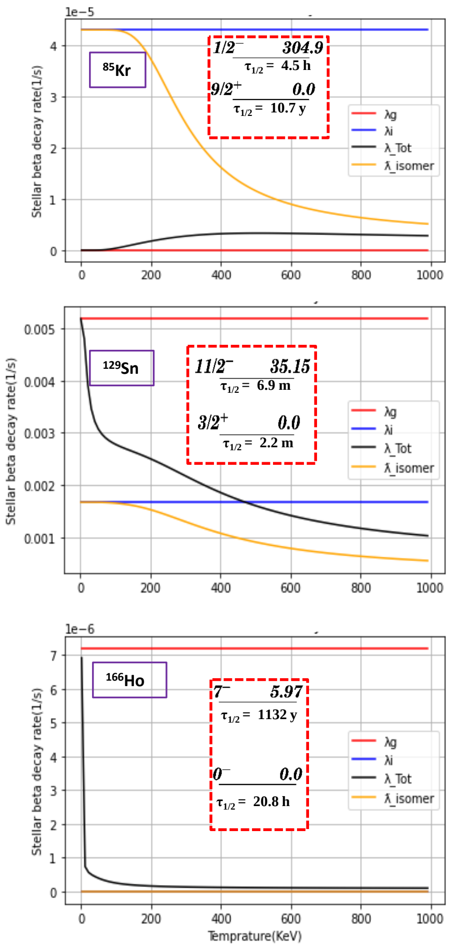

FIG. 1: Plots for total (λ_Tot), and isomeric stellar decay rates (λ_isomer). λ_i and λ_g are temperature independent constant values for isomer and ground state. Shown in the inset are the isomeric and ground level properties

half-lives. Here we show the results for three nuclei from each category. ^{85}Kr: The ground state half-life τ_g is very large compared to the isomeric half-life τ_i, i.e. $\tau_g \gg \tau_i$. In ^{129}Sn: $\tau_g \approx \tau_i$. And finally, ^{166}Ho: $\tau_g \ll \tau_i$. Results of our calculations are shown in Fig. 1. In ^{85}Kr, the ground state stellar decay rate (red line) controls the overall trend. However, the isomer does influence the total decay rate (black line) at higher temperatures. In ^{129}Sn, the total stellar beta decay rate is significantly influenced by the isomeric decay even at lower temperatures. In ^{166}Ho, the isomeric stellar beta decay rate seems to be in total control of the total stellar decay rate and this influence starts from the lower temperatures. We also notice a reversal of the trend in the decay rate in going from ^{85}Kr to ^{129}Sn or,^{166}Ho. Whereas the total decay rate rises in ^{85}Kr, it falls with temperature in other two cases. This is due to the large isomeric half-life in the latter two cases. We are yet to explore other complex situations like the effect of excitation energy, presence of more than one isomer on the total stellar decay rates.

From our calculations, we conclude that the astromers are going to play a very crucial role in deciding the total stellar decay rates in stellar environment. It is, therefore, imperative that all abundance calculations must incorporate astromers in the calculations. Further calculations for more complex situations are underway.

Acknowledgement

AKJ acknowledges the award of a SERB research grant CRG/2020/000770 to support the work. BM acknowledges the financial support from the Croatian Science Foundation and the École Polytechnique Fédérale de Lausanne under the project TTP-2018-07-3554.

References

[1] S. Garg, B. Maheshwari, B. Singh, Y. Sun, A. Goel, A. K. Jain, Atlas of nuclear isomers-Second edition, At. Data & Nucl. Data Tables **150** (2023) 101546.

[2] A.K. Jain, B. Maheshwari, A. Goel, Nuclear Isomers: A Primer, Springer Nature, 2021.

[3] G.W. Misch, S.K. Ghorui, P.Banerjee, Y. Sun, M.R. Mumpower, Astro. Phys. Journal. Supl. **252** (2020) 2.

[4] A. Coc, M. Porquet, and F. Nowacki, Phys. Rev. C **61** (1999) 015801.

[5] S. Gupta, B.S. Meyer, Phys. Rev. C **64** (2001) 025805.

[6] Christian Iliadis, Nuclear Physics of Stars, Wiley, 2007.

[7] R.A. Ward, W. A. Fowler, Astro-Phys. Journal **238** (1980) 266.