Impact of structural effects and coexisting shapes on decay characteristics relevant in astrophysical nuclear synthesis

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Introduction

Nuclei with A≈80, situated far from the β-stability line, hold a significant role in astrophysical nuclear synthesis via the rapid proton capture (rp) process route. Weak interaction mediated rates on isotopes of Mo have a meaningful contribution during the development of phases of stars before they go supernova. The relative abundance coupled with the stellar weak rates on Molybdenum (Mo) isotopes may change the lepton-to-baryon content of the core material. [1]. The isotopic anomalies documented in Mo and Ru hold significance not only for comprehending the formation of the solar system but also for understanding Earth's accretion [2]. These anomalies suggest nucleosynthesis mechanisms that go beyond the conventional p-, s-, and r-processes, generating interest in synthesizing stable isotopes within a mass range spanning from Z=30 to Z=48 [3]. Neutron-rich isotopes of Zr (Z=40), Mo (Z=42), and Ru (Z=44), that are also known for rapid shape phase transitions and shape instabilities, play a significant role in heavy element nucleosynthesis. Their decay characteristics, that may be influenced by the structural transitions, can provide meaningful inputs to the modelling of astrophysical r-process phenomena [1, 3, 4].

Moreover, use of Mo as constructive material for different types of nuclear reactors and recent development suggesting the application of isotopically modified Mo to develop fuel rods to improve safety of light-water and fast nuclear reactors has only increased interest in the study of Mo isotopic chain [5]. These nuclei are also captivating attention due to their predominant triaxial shapes and coexistence of different shapes [6] that may impact decay modes. Within the A≈100 mass region, anomalies in isotope shifts, swift shape transitions, shape instabilities, and coexistence are known, particularly in nuclei with neutrons close to the magic number N=50 [7]. This variety of nuclear shapes strongly support the essential influence of underlying shell structure and nuclear collectivity on nucleus stability and structure, knowledge of which may be relevant in nucleosynthesis processes.

Brief desrcrption of the work

This study is focused on investigating the ground state shapes and shape transitions in the astrophysically intriguing Mo isotopic chain. Energy minima are identified with respect to Nilsson deformation parameters (β_2, γ) in the quest of nuclei with coexisting shapes. This is achieved using of the Nilsson Strutinsky Method (NSM) [8] and the Relativistic Mean Field (RMF) Model using the NL3* parameter [9]. The entire isotopic range of Mo, from the proton drip line to the neutron drip line, is covered within these theoretical frameworks. The charge-changing transitions greatly effect the late evolutionary phases of massive stars. [1]. Hence, β_2 values derived from the RMF model are used as input for calculating the β decay half−lives, for those nuclei showcasing shape coexistence in both the NSM and the RMF Model.

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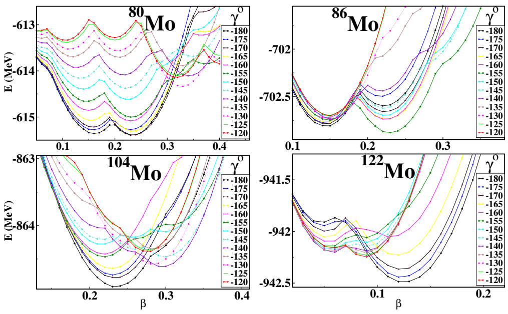

FIG. 1: Ground state energy minima trace for shape and deformation.

Results and Discussion

Figure 1 is representative plots of energy minima traced for the ground states of Mo isotopes as a function of β and γ for ^{80,86,104,122}Mo. The isotope chain starts with an oblate shape phase observed for first unbound nucleus (^{78}Mo) and progresses rapidly to predominantly competing oblate and triaxial minima. Ground state prolate shapes emerge only around magic neutron number 50 and for nuclei near mass number A≈140 which is neutron drip-line for even-even nuclei. Notably, nuclei exhibiting coexisting shapes are identified for isotopes ^{80,81,82,83,84,86,100,104,106,108,122}Mo; a phenomenon that appears distinct within the realm of finite many-body quantum systems [10].

Experimental values of quadrupole deformation [11] match better with those corresponding second minima observed for a few shape coexisting nuclei($^{104-108}$Mo), where the first minima did not match well with data. Similar trend is observed in proton separation energy for ^{4,86,104,106,108,112}Mo and in neutron separation energy for ^{86,100,106}Mo nuclei. This uncommon observation suggests the possibility that these nuclei may spend some time in a secondary minima state during measurements before it eventually decays or transitions to the ground state associated with the first minimum.

β decay half−lives are calculated for transitions where both parent and daughter nuclei are shape isomers. Few half−lives observed for transition from ground state of parent to ground state of daughter nuclei are far away from experimental values, when compared with transitions from secondary minimum state of parent to ground state of daughter or vice−versa, indicating the effect of shape coexistence on β decay half−lives which may be useful in astrophysical studies [1].

Conclusion

A comprehensive study to trace the shape coexistence in astrophysically interesting Mo nuclei has been conducted. These nuclei exhibit rapid shape phase transitions, shape instabilities and mixing and the γ softness with the predominance of triaxial shape phase just as observed for Ru [12]. This work sheds light on the complex interplay of shapes, deformations, and coexistence within the Mo isotope chain, contributing to a deeper understanding of their behavior in diverse astrophysical scenarios. Impact of shape coexistence on structural properties and lifetimes is evident from the study. Albeit not forbidden, validation of these observations needs further investigation.

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