Impact of Vibrational Level Density Enhancements on Neutron Emission and Cross-Section Reduction in ^{69}Ge Production

M.M. Musthafa[1], M.P. Sreelakshmi[2],* C.V. Midhun[1], T.T. Vafiya Thaslim[1], and K.P. Shabna[3]

[1] *Department of Physics, University of Calicut-673635, Malappuram, Kerala, India*
[2] *Government Victoria College, Palakkad-678001, Kerala, India and*
[3] *St.Aloysius College Eluthuruth-680611, Thrissur, Kerala, India*

Introduction

A precise theoretical understanding and accurate theoretical models is essential for predicting nuclear reactions of desired quality. In the case of the $^{\rm nat}Zn(\alpha, xn)^{69}Ge$ reaction, default theoretical calculations successfully reproduce excitation functions up to 30 MeV. However, they fail to account for the cross-sections at higher energies (30–40 MeV) [1, 2]. The theory of multi-nucleon emission in this energy range significantly deviates from default calculations, indicating the need for more advanced models to track complex cascades and better estimate production cross-sections at these energies.

The discrepancy is due to existenance of a shell closed core of ^{69}Ge. As a magic nucleus, it has a stable core with only the valence nucleons contributing to excitation. In such cases, the normal level density models, which assume excitation of the entire nucleus, are not applicable. Instead, the excitation is limited to the valence nucleons, which carry maximum energy and enhance the level density, increasing the likelihood of vibrational effects. This also suppresses further particle emission, complicating cross-section predictions.

Additionally, nucleon emission at high energies, driven by pre-equilibrium effects, may further inhibit cascaded neutron emissions. This study investigates how these two processes—vibrational enhancement and pre-equilibrium emission—impact the production cross-section of ^{69}Ge at higher energies.

*Electronic address: sreelakshmimp14@gmail.com

Exploration of Cascade Emission Systematics

The analysis of excitation functions for ^{68}Zn$(\alpha, 3n)^{69}$Ge shows a notable discrepancy in the 30–40 MeV energy range. The primary contribution to ^{69}Ge production in this range comes from the ^{68}Zn$(\alpha, 3n)$ reaction. The reduction in ^{69}Ge production compared to default theoretical calculations is likely due to the inhibition of multi-neutron emission from ^{72}Ge, which decreases the reaction rate through branching of higher-energy neutrons.

To explore this inhibition, the TALYS 1.96 nuclear reaction code was employed to investigate various mechanisms. These processes are mainly influenced by either pre-equilibrium effects or enhancements in level density. Four different pre-equilibrium modes available in the TALYS code were tested and compared with experimental data. Out of the four models, Exciton model with numerical transition rates with optical model for collision better agreed with experimental cross-sections only for lower energy range (10-30 MeV) and could not predict for higher energy range(30-40MeV) (figure 2).

Additionally, level density enhancements were introduced in the TALYS input files for ^{72}Ge, ^{71}Ge, and ^{70}Ge with the results also compared to experimental observations. This systematic approach helps to identify the factors responsible for the deviation in theoretical predictions especially for higher energy range (30-40 MeV) (figure 3).

Results and Discussion

The investigation into level density enhancement for ^{71}Ge and ^{70}Ge reveals a sig-

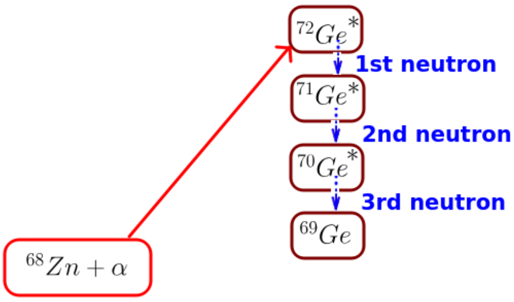

FIG. 1: Schematics of Cascaded neutron emission

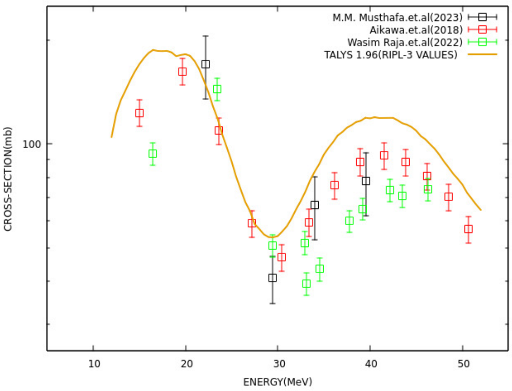

FIG. 2: Illustration of theoretical calculations with RIPL-3 recommended level densities incorporating pre-equilibrium effects

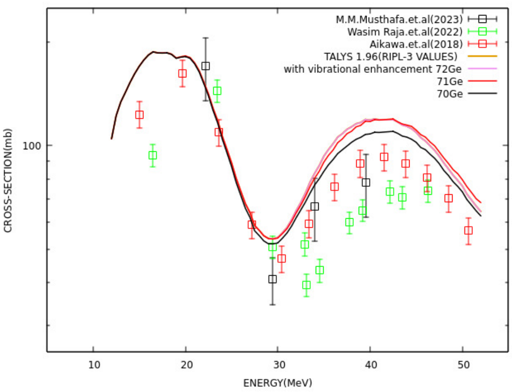

FIG. 3: Illustration of the theoretical calculations with enhancement in level densities

nificant effect on the production cross-section of ^{69}Ge in the 30–40 MeV energy range. In alpha-induced reactions on natural zinc, the compound nucleus ^{72}Ge is formed at high energies, which subsequently decays through cascaded neutron emission (figure 1).

The enhancement of level densities in the intermediate nuclei, ^{71}Ge and ^{70}Ge, plays a crucial role in inhibiting the secondary neutron emission. The higher level densities, especially those vibrationally enhanced, increase the probability of emitting high-energy neutrons during the primary emission stage. These high-energy neutrons, emerging from vibrationally enhanced states, carry away a substantial portion of the excitation energy, which in turn suppresses further neutron emission in subsequent stages.

As a result, the inhibition of cascaded neutron emissions leads to a reduced population of the final residue, ^{69}Ge. The suppression of secondary neutron emissions, coupled with the branching preference towards higher-energy neutrons, significantly alters the production cross-sections at these higher energy ranges. This behavior illustrates the importance of vibrational enhancements in the nuclear reaction modeling, where failure to account for such effects can lead to discrepancies in theoretical predictions.

These findings suggest that the inclusion of vibrational level density enhancements in nuclear reaction codes, such as TALYS, is critical for accurate modeling of neutron emissions, particularly in reactions involving nuclei near shell closure. The reduced residue population of ^{69}Ge, observed in the current study, reproduces in a better way, confirming that vibrational enhancement in intermediate nuclei is a key factor in explaining the observed cross-section reduction in the 30–40 MeV range.

References

[1] Raja et al Eur. Phys. J. A 58, 259 (2022).
[2] Musthafa et al., Proc. of DAE Symp. on Nucl. Phy. 67 p.719 (2023)