Investigating the effect of excess neutrons on fusion of mid-mass nuclei

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Introduction

The nuclear fusion of exotic nuclei plays an important role in synthesis of heavier elements via r-process nucleosynthesis and to understand various stellar phenomena. According to r-process, the production of heavier elements occurs in the neutron-rich environments [1]. The main possible site for the formation of heavier elements are the core collapse supernovae and merger of binary neutron stars [2].

Fusion of nuclei away from the line of stability also plays a key role to understand the origin of X-ray super-bursts. In this process an energy of ~ 10^{42} ergs (energy released by Sun in one decade) is emitted in few hours [3]. These X-ray super-bursts are proposed to be fueled by the burning of Carbon atom, which is ignited due to the localized heating of neutron star crust by the fusion of ^{24}O + ^{24}O or by the fusion of neutron-rich nuclei [4]. Hence, it is important to investigate the fusion of neutron-rich nuclei, to understand the origin of X-ray super-bursts.

The fusion of neutron rich nuclei is different from the β-stable nuclei as the valence neutrons in neutron-rich nuclei are loosely bound and can get easily polarized as it approaches the other nuclei during the fusion process. In the present work, the investigation of fusion enhancement due to increased number of neutrons has been investigated using the experimental fusion cross-sections existing in the literature.

Experimental fusion cross-sections

Fusion reactions cross sections of ^{16}O + ^{58,62}Ni; ^{16}O + ^{70,72,73,74,76}Ge; ^{40}Ca+^{40,44,48}Ca and ^{32,36}S + ^{48}Ca systems have been included in present investigation to explore the effect of neutron excess on fusion cross-sections. The fusion excitation function of ^{16}O+^{58,62}Ni reactions have been measured by Keeley *et al.* [5] using ^{16}O beam from 14UD tandem accelerator at the Australian National University, Canberra. Evaporation residues (ERs) were separated from scattered beam using compact velocity filter.

The fusion cross-sections of ^{16}O + ^{70,72,73,74,76}Ge systems was measured by Aguilera *et al.* [6] using ^{16}O beam from tandem FN Van de Graff accelerator at University of Notre Dame. The evaporation residue were identified using recoil velocity spectrometer. ^{40}Ca+^{40,44,48}Ca system has been measured by Aljuwair *et al.* [7] by bombarding ^{40}Ca beam from Tandem Van de Graaff, Brookhaven National Laboratory. ERs were detected using NIT-BNL velocity selector. ^{32,36}S + ^{48}Ca reactions were studied by Montagnoli *et al.* [8] using ^{32}S & ^{36}S beams from XTU Tandem accelerator of the Laboratori Nazionali di Legnaro of INFN. ERs were detected using Electrostatic deflectors and MWPCs.

Results and discussion

Fusion excitation functions for ^{16}O + ^{58,62}Ni is shown in Fig. 1(a) and it has been observed that the fusion cross-sections for both the systems is nearly same at well above the fusion barrier, whereas fusion cross-sections are enhanced for ^{62}Ni as compared to ^{58}Ni at near and below the fusion barrier. This can be interpreted as polarization due to the four extra neutrons in ^{62}Ni, which provided the easier path for the fusion. In Fig. 1(b), similar results have been observed with ^{44}Ca and ^{48}Ca showing higher fusion at near and below the barrier as compared to ^{40}Ca. The enhancement is much higher in moving from ^{40}Ca to ^{44}Ca as compared to ^{44}Ca to ^{48}Ca. The doubly magic configuration (shell effect) of ^{40}Ca target may hinder the fusion, resulting in lowered fusion cross-sections. On the same lines the lower fusion enhancement for ^{48}Ca can attributed to shell effect of ^{48}Ca (Proton number = 20 magic number and Neutron number = 28 semi-magic number).

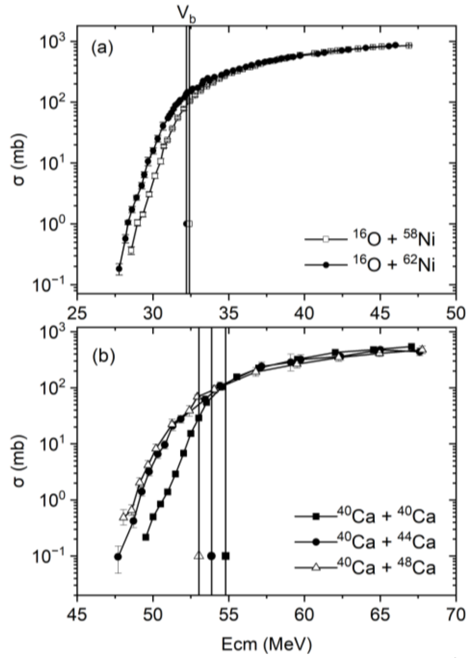

Fig. 1 Fusion excitation functions (a) for ^{16}O + ^{58,62}Ni [5] and (b) for ^{40}Ca+^{40,44,48}Ca [7].

Fig. 2(a) shows the fusion excitation functions of ^{16}O + ^{70,72,73,74,76}Ge, it is observed that fusion cross-sections for ^{74,76}Ge is higher than ^{70}Ge which can be due to the presence of extra neutrons. Interestingly, it has been found that fusion cross-section is maximum for ^{73}Ge among all the targets under investigation. It can be due to presence of unpaired neutron in ^{73}Ge as compared to other target nuclei, the similar aspect has been reported in a theoretical study too [9]. For ^{72}Ge the fusion cross-sections are lower than ^{70}Ge, which can be due to structural effect in ^{72}Ge.

In Fig. 2(b) the comparison of the fusion cross-sections for ^{32,36}S + ^{48}Ca has been reported. It is observed that fusion is lower for system with more neutron number. This may be because of some structural or dynamical effects present in these systems. Hence, a unified picture of fusion of nuclei with excess neutrons is still missing and no theoretical model is available to predict the fusion of such nuclei (which is an important input for the theoretical model to understand the astro-physical phenomena). More fusion measurements are required to better tune the fusion model for nuclei away from stability line.

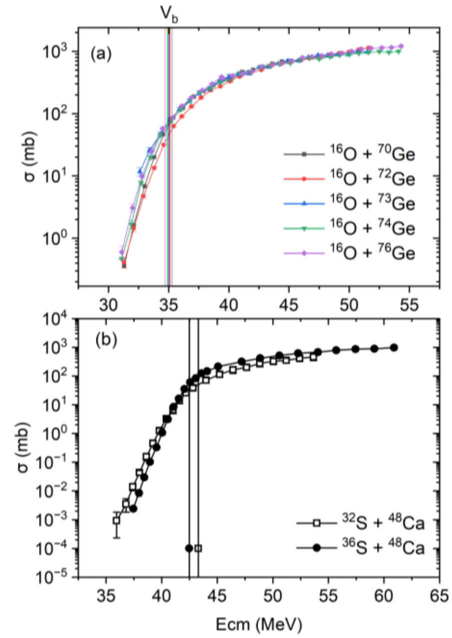

Fig. 1 Fusion excitation functions (a) for ^{16}O + ^{70,72,73,74,76}Ge [6] and (b) for ^{32,36}S + ^{48}Ca [8].

With this motivation in mind, we are planning to measure the fusion cross-sections of ^{28}Si +^{40,44}Ca to unfold the effect of extra neutron and shell effects on fusion cross-sections.

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