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Neutron capture cross-sections relevant to explosive burning scenarios

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Introduction

The Rapid Neutron Capture or *r-process* is a nucleosynthesis process, which is responsible for synthesis of half of the heavy nuclei in the universe. There are two well-established astrophysical sites, where the r-process can occur and they are *Core-collapse Supernovae* and *Neutron Stars*[1].

Neutron stars are the densest objects observed in the universe. When a massive star ($M > 8M_{\odot}$) exhausts its nuclear fuel and *dies*, then the compact remnant is usually a neutron star. The neutron star is characterized by extremely strong magnetic and gravitational fields, and neutron rich matter. It is the only object in the cosmos whose average density is comparable to the density of nucleus (nuclear density $\sim 10^{17} kgm^{-3}$).*Binary mergers* of neutron stars has been recently experimentally identified as one of the active sites for r-process nucleosynthesis.

Although, the properties and behaviour of neutron stars have been studied extensively, yet many aspects of the subject are still unanswered and multi-disciplinary fields of study are necessary to solve them. Theoretical simulations of neutron star and its dynamics are of special importance in this aspect. In recent literature [2], simulation has been performed using SKYNET nuclear reaction code. In the code, Neutron Star Mergers (hereafter *NSM*) and its characteristic environments have been considered, and the r-process nucleosynthesis during merger phenomena has been simulated theoretically. Considering the neutrino-driven wind model, it has been reported in [2] that the neutron capture reaction rates of neutron-rich nuclei around closed-shell structure ($\sim N = 28$) play an important role in determining the final r-process abundance pattern. (E.g. n-rich isotopes of *calcium, gallium, chromium, vanadium*, etc.). Hence, both experimental and theoretical measurements regarding neutron capture cross-sections of such neutron-rich nuclei are required to predict the correct abundance pattern as observed in the universe. According to the simulation (Ref. [2]), one of the important capture reactions, to which the final isotopic abundance pattern is highly sensitive, is: $^{52}Ca + n \rightarrow {}^{53}Ca + \gamma$. The neutron rich reactant nuclei, like ^{52}Ca are unstable isotopes with very short half-lives. Hence, experimental determination of these reaction cross-sections or rates are difficult. So, usually the statistical Hauser-Feshbach model [Ref. Rauscher et al. (2000) [3]] is widely used in theory and simulations, for calculating the reaction rates of such reactions. However, experimental evidence of doubly

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magic features in a short-lived calcium isotope, ^{52}Ca (N = 32), was obtained [4]. Hence, ^{52}Ca, should be a closed-shell structure and to describe the nucleus, the single particle approximation or *shell model* interaction would be more suitable. The aim here is to calculate the results from the single particle theory and compare it to the statistical model.

Method

The measurements of radiative capture reactions of highly unstable neutron-rich nuclei (e.g. ^{52}Ca) is very challenging and the *Coulomb Dissociation* (CD) of radioactive ion beam at intermediate energies, is a powerful experimental tool [5,6,7,8]. But due to limited access of RIB, one can calculate the same using large scale shell model calculation. The cross-section of the capture reaction can be calculated using Eq. 1 [5,6,7] and that cross-section has been converted into photo absorption cross-section using Eq. 2. The neutron capture reaction cross-section of that neutron-rich nucleus, $\sigma_{cap}(n,\gamma)$ can be obtained through principle of detailed balance.

$$\frac{d\sigma}{dE^*} = \frac{16\pi^3}{9\hbar c} n_{E1}(E^*) \sum_{n,l,j} C^2S(I_C^\pi, n, l, j) \times \left(\sum_m \mid \langle q \mid \frac{Ze}{A} r Y_m^1 \mid \psi_{n,l,j}(r) \rangle \mid^2 \right) \tag{1}$$

C^2S is the spectroscopic factor of each $\psi_{n,l,j}$ state, which is calculated with VS-IMSRG [9]. The standard pf-shell has been taken as valence space, using 3 interactions to get an idea of interaction dependence.

$$\sigma_{photo} = \frac{d\sigma}{dE^*} \frac{1}{n_{E1}} E^* \tag{2}$$

From the cross-section, the reaction rate can be calculated using:

$$N_A \langle \sigma v \rangle = N_A \sqrt{\frac{8}{\pi\mu}} \frac{1}{(K_B T)^{\frac{3}{2}}} \int_0^\infty E \sigma_{cap} e^{-\frac{E}{K_B T}} dE \tag{3}$$

Where the symbols have their usual meanings.

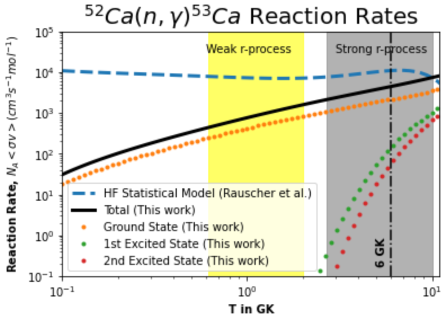

FIG. 1: Comparison of variation of reaction rate for $^{52}Ca(n,\gamma)^{53}Ca$ for different models

Results

The computed reaction rates of $^{52}Ca(n,\gamma)^{53}Ca$ at 6 GK temperature (typical of r-process) has been shown in Fig. 1 by solid black line and long dashed line represents HF [3] calculation. It is clear from figure that HF calculation is almost 59 % higher than the direct breakup model coupled with modern shell model calculation. We shall also present the calculation of other reactions, $^{54}Ca(n,\gamma)^{55}Ca$, $^{56}Ti(n,\gamma)^{57}Ti$, $^{53}Sc(n,\gamma)^{54}Sc$, $^{55}Sc(n,\gamma)^{56}Sc$ etc. and its impact on model calculation.

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