Exploring heavy-ion fusion mechanism at stellar energies

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Introduction

The exploration of nuclear fusion mechanism at deep sub barrier energies for heavy-ion reactions involving light nuclei is of utmost significance in understanding numerous astrophysical phenomena. As ^{12}C and ^{16}O are the main nucleosynthesis products of Helium burning process in the stars, the fusion reactions such as ^{12}C+^{12}C, ^{12}C+^{16}O and ^{16}O+^{16}O play an essential role in the later stages of evolution of heavy stars. The understanding of the fusion mechanism of these reactions at the stellar energies is of utmost significance in exploring the production of heavy elements in stars as well as the nucleosynthesis in various stellar explosions such as the type Ia and II supernovae [1, 2]. In addition to this, fusion reactions involving neutron rich nuclei are also important to explore the possibility of fusion induced burning in the white dwarfs and accreting neutron stars. Due to the β captures in the extreme astrophysical environments, the crust of neutron star comprises of highly neutron rich nuclei such as ^{22}O, ^{24}O, ^{28}Ne and ^{34}Ne etc. Consequently, there is the possibility of occurrence of fusion reactions such as ^{22}O+^{22}O, ^{24}O+^{24}O, ^{28}Ne+^{28}Ne and ^{34}Ne+^{34}Ne in the neutron star crust [2, 3].

The heavy-ion fusion in the exotic stellar environments occur at extreme sub-barrier energies. A considerable amount of efforts are being devoted to measure the fusion cross-section for reactions ^{12}C+^{12}C, ^{12}C+^{16}O and ^{16}O+^{16}O at sub-barrier energies. However, the experimental measurement of fusion cross-section at deep sub barrier energies and for reactions involving highly unstable neutron rich nuclei is a tedious task. Thus, it is crucial and interesting to explore the reliability of different theoretical approaches to understand the fusion mechanism of heavy-ion fusion reactions of astrophysical significance. Following this, we aim to study the fusion mechanism for ^{16}O+^{16}O and ^{22}O+^{22}O reactions at stellar energies using the Hill-Wheeler (HW) and Kemble transmission coefficients supplemented with the well-known relativistic mean field (RMF) formalism [1].

Theoretical Formalism

For astrophysical reactions, the cross-section is generally represented in terms of the astrophysical S-factor [1, 2] as,

$$S(E_{c.m.}) = E_{c.m.} \times \sigma(E_{c.m.}) exp(2\pi\eta). \quad (1)$$

Here, $\eta = \frac{Z_1 Z_2 e^2}{4\pi\hbar v}$ is the dimensionless Sommerfeld parameter and $v = \sqrt{2E_{c.m.}/\mu}$ denotes the relative velocity of the target-projectile system. The cross-section (σ) is calculated using the $\ell-$summed Wong model. Two different approaches namely the Hill-Wheeler (HW) and Kemble approximations are used to obtain the penetration probability through the fusion barrier formed due to strong interplay of Coulomb, centrifugal and nuclear potentials [1]. The short range and attractive nuclear potential formed between two fusing heavy-ions is obtained within the double folding approach supplemented with RMF approach for the non-linear NL3* parameter set. The relativistic R3Y effective nucleon-nucleon potential obtained by solving the RMF equations for mesons can be written as,

$$V^{R3Y}_{eff}(r) = \frac{g^2_\omega}{4\pi}\frac{e^{-m_\omega r}}{r} + \frac{g^2_\rho}{4\pi}\frac{e^{-m_\rho r}}{r} - \frac{g^2_\sigma}{4\pi}\frac{e^{-m_\sigma r}}{r} + \frac{g^2_2}{4\pi} r e^{-2m_\sigma r} + \frac{g^2_3}{4\pi}\frac{e^{-3m_\sigma r}}{r} + J_{00}(E)\delta(r). (2)$$

More details of the theoretical formalism adopted can be found in Ref. [1].

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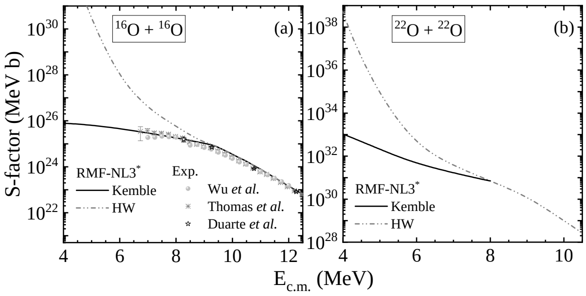

FIG. 1: The astrophysical S-factor (MeV b) for (a) $^{16}O+^{16}O$ and (b) $^{22}O+^{22}O$ reactions calculated using the HW (dash dotted line) and Kemble (solid line) transmission coefficients. The experimental data [4, 5, 6] are also given for comparison. See text for details.

Results and Discussion

First, the applicability of nuclear potential obtained using RMF-NL3* approach [1] is assessed for $^{16}O+^{16}O$ reaction at above and around the barrier energies, where experimental data is available [4, 5, 6]. The occurrence of nuclear fusion at energies below the Coulomb barrier can only be interpreted through the quantum mechanical tunneling of the fusion barrier. Here, we have used Hill-Wheeler (HW) and Kemble transmission coefficients to obtain the barrier penetration probability at the energies of astrophysical relevance. In HW approach, the analytic expression for barrier transmission coefficient is obtained under the parabolic barrier approximation. On the other hand, the Kemble approach is refined version of well-known Wentzel-Kramers-Brillouin (WKB) approach and uses the exact barrier shape, which is obtained here within the RMF formalism to determine the barrier penetration probability [1]. The astrophysical S-factor (MeV b) calculated using the nuclear potential obtained from RMF-NL3* formalism along with HW (dash dotted line) and Kemble (solid line) approximations are shown in Fig. 1(a) as a function center of mass energy $E_{c.m.}$ (MeV) for $^{16}O+^{16}O$ reaction. On comparing the results of HW and Kemble transmission coefficients with the experimental data from [4, 5, 6], it can be noted that the HW approximation gives a nice overlap with the experimental data at above barrier energies and it overestimates the S-factor at the below barrier energies. However, the Kemble approximation supplemented with nuclear potential from the RMF approach provides a satisfactory match with the experimental data at below barrier energies. These observations infers that the Kemble approximation furnished with RMF formalism can be used to provide predictions for the heavy-ion reactions at deep sub-barrier energies of astrophysical significance, whereas, the HW approximation is applicable at above barrier energies. Following this, the astrophysical S-factor (MeV b) for $^{22}O+^{22}O$ reaction calculated using the microscopic nuclear potential obtained within RMF-NL3* approach is shown in Fig. 1(b). It can be noticed from Fig. 1(b) that the S-factor for $^{22}O+^{22}O$ reactions is higher in magnitude by several orders as compared to the $^{16}O+^{16}O$ reaction. This is because on moving towards neutron rich nuclei, the nuclear potential becomes more attractive whereas the Coulomb potential remains the same. This results in lower fusion barrier and higher cross-section. However, these results are preliminary and more comprehensive analysis involving more reactions of astrophysical significance is under process.

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