Study of Fusion Cross Section of $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ and $^3\mathrm{He}(^3\mathrm{He},2p)^4\mathrm{He}$ Reactions at Astrophysical Energy Using Double Folding Model Potential

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Abstract: Nuclear fusion reactions at the sub-barrier energy regime (typically, 1 eV to a few keV) govern different fundamental aspects of the primordial nucleosynthesis in compact objects. One of the primary keys to understanding the relationship between stellar evolution and nuclear reaction dynamics is the energy dependence of astrophysical observables like fusion cross section $\sigma(E)$. We have studied ^{3}He(α,γ)^{7}Be and ^{3}He(^{3}He,2p)^{4}He reactions by considering the quantum mechanical tunneling phenomenon. As an improvement over our earlier work, in this context, we invoked the idea of folding model potential for numerical computation of $\sigma(E)$. The results of our calculation are compared with those found in the literature. The present results are in good agreement with the experimental results.

Keywords: Nuclear cross section, double folding model, tunneling.

I Introduction

Over the last twenty years thermonuclear explosions in accreting binary star systems have been an object of considerable attention. The basic concept of the thermonuclear runaway as the driving explosion mechanism seems reasonably well understood, but there are still considerable discrepancies between the predicted observables and the actual observations [1]. Nuclear physics plays a crucial role in many important phenomena occurring in the core to the crust of astrophysical objects, leading to the development of this ever-hot discipline of physics called nuclear astrophysics. Big Bang nucleosynthesis (BBN) offers the deepest reliable probe of the early universe, being based on well-understood Standard Model physics [2,3]. At the first time, Bethe (1939) described the evolution and formation of light elements like ^{2}H, ^{3}He, α, etc. during Big Bang nucleosynthesis [4]. Big Bang nucleosynthesis is the production of nuclei other than those of the lightest isotopes of hydrogen during the early phases of the universe [5]. Elements heavier than lithium are formed through stellar nucleosynthesis, evolution, and death of stars [6]. The formation of heavier elements up to the isotopes of Iron (Fe) can be successfully explained by Big Bang nucleosynthesis [7]. Beyond iron (Fe), elements can be created by fusion processes. Heavier elements than iron are formed by many other processes such as slow neutron capture (s-process), rapid neutron capture (r-process), neutrino-induced reactions, and explosive events in supernovae [8,9]. In the literature review, we had found a large amount of data on nuclear reactions involving charged particles such as protons, deuterons, and alphas and chargeless particles like neutrons. Cross sections for the production of light elements in capture, transfer, and fusion reactions are of great interest for their astrophysical importance. The measurement of this type of reaction allows one to study complicated nuclear dynamics of fusion reactions. Among the transfer and capture processes, the capture cross section is always greater than that of the transfer process. In the dense plasma of evolved stars, where the plasma screening effect is dominant, the standard classical thermonuclear reaction rate is not applicable [10]. Therefore, a standard theoretical model for thermonuclear reaction rate involves fusion cross section $\sigma(E)$, which is energy (E)-dependent, as an integral part of astrophysical S-factor, which is also merely energy-dependent and is highly needed. In hydrostatic equilibrium, the solar temperature lies in the range of K to K, which is far too low to trigger a nuclear reaction, which demands a temperature of a few K in the solar core. It was Gamow who explained the nuclear fusion near the Coulomb barrier through the tunneling process, which is a quantum mechanical phenomenon [11]. Tunneling through a narrow window takes place in a thermonuclear non-resonant reaction for charged particles, but at certain conditions, a resonant reaction occurs at relevant energies, which is not considered here [12].

A whole layer of information and observables would remain inaccessible without proper calculations of nucleosynthesis. The theoretical model gives insight into the nuclear reactions and nuclear fusion and the specific uncertainty associated with their reaction rates. Accurate predictions of the corresponding cross sections are very desirable to perform experiments for different types of fusion processes. In the present work, we have computed the fusion cross section of ^{3}He(α,γ)^{7}Be and ^{3}He(^{3}He,2p) ^{4}He reactions and compared it with the experimental data found in literature [13,14]. To explain the fusion cross section, the compound nucleus model [15] can be used, which is a two-step process, and later Li et al. introduce the selective resonant tunneling model (SRTM) [16], which dominates over the compound nucleus model. Using SRTM, Li et al. (2002) successfully computed the fusion cross section for D + T using a complex square well and compared the findings with experimental data. In 2004, Li et al. computed the cross section for D + D and D + ^{3}He using SRTM [17]. In the present work, for the computation of fusion cross section, we adopt the double folding model [18] for ^{3}He(α,γ)^{7}Be and ^{3}He(^{3}He,2p)^{4}He reactions.

In section II, we present the concept of a theoretical model for the fusion cross-section calculation. This included the astrophysical S-factor and double folding potential. The computed results and comparison with the experimental result are made in section III. We close with a summary and conclusion in section IV.

II Theoretical Framework

A good knowledge and understanding of the cross section $\sigma(E)$ of the nuclear reactions are essential for the broad picture of the nucleosynthesis network [19]. In astrophysical aspects, Coulomb barriers play a crucial role for the fusion reaction, and sub-barrier tunneling has occurred in the stellar energy regime [20]. Though the temperature is not sufficient for triggering the fusion reaction, by tunneling, the fusion reaction has been accomplished. For the calculation of the Gamow factor [21], three types of potential have been adopted here, which are Coulomb, nuclear (DFP), and centrifugal potential. The astrophysical S-factor, $S(E)$ [22], which is an integral part of the fusion cross section $\sigma(E)$, has been used to remove the energy dependence and is a vital astrophysical parameter. The fusion cross section, far below the Coulomb barrier [10], is given in equation - 1.

$$\sigma(E) = \frac{S(E)}{E} \exp\left(- \int_{r_1}^{r_2} \sqrt{\frac{2\mu(V_{\text{eff}} - E)}{\hbar^2}}\, dr \right) \tag{1}$$

where μ is the reduced mass of the system and $\hbar$ is the reduced Planck's constant and E is the projectile energy. The astrophysical S-factor is introduced to remove the strong energy dependence of nuclear reaction cross sections caused by the Coulomb barrier. The parametric equation for the astrophysical $S(E)$, from ref. [23], is given in equation -2.

$$S(E) = S_0 + S_1 E + S_2 E^2 \tag{2}$$

Where S_0, S_1, S_2 are the constants. The remaining term in equation-1 i.e. V_{eff} is given in equation-3 [24].

$$V_{\text{eff}}(r) = V_C(r) + V_N(r) + V_{\text{Centi}}(r) \tag{3}$$

The first term of the equation-3 denotes the Coulomb potential. This potential is charge dependent of projectile and target of colliding system [25]. The Coulomb potential is given in equation-4.

$$V_C(r) = \begin{cases} 1.44\dfrac{Z_1 Z_2}{r} & \text{for } r > R \\ 1.44\dfrac{Z_1 Z_2}{2R}\left(3 - \dfrac{r^2}{R^2}\right) & \text{for } r \le R \end{cases} \quad \text{[MeV]} \tag{4}$$

Where Z_1 and Z_2 are the charges of projectile and target particles, R is the radius of the sphere of the nuclei. The third term of the equation-3 denotes the centrifugal barrier of the colliding system and is given in equation-5.

$$V_{\text{Centi}}(r) = \frac{\hbar^2 l(l+1)}{2\mu r^2} \tag{5}$$

Where l is the angular momentum and r is the radius. The final term of the total potential is the complex potential $V_n(r)$, described as the double folding potential $V_{\text{DF}}(r)$. The double folding model potential is dependent on the matter distribution of the nucleus and is independent of nuclear charge and nuclear spin also. The double folding potential can describe the mean field interaction between the colliding nuclei. The double folding potential model provides valuable information about the projectile and target nucleus. The basic inputs in the double folding model potential calculation are the nuclear densities of the colliding nuclei and the effective nucleon-nucleon interaction between the projectile nucleons and the target.

As double folding model potential is density dependent, we need to know the density distribution of the nucleus. The matter density distributions of the target and projectile have many natures, such as Fermi distribution, Gaussian distribution, and Variational Monte Carlo (VMC) [23]. In the double folding model calculation, we have used a Gaussian matter distribution, which is exponential in nature. Fermi matter distribution is also exponentially decreasing in nature. From various kinds of effective interaction, we use DDM3Y-type interaction for the calculation of double folding model potential. The DDM3Y-type interaction is acting on a short range of the nuclear density and contains no explicit density dependence.

We consider the double folding potential between the nucleus of ^{3}He (with atomic number 2 and atomic mass number 3) and the nucleus of ^{4}He (with atomic number 2 and atomic mass number 4). The density distribution used in the double folding potential calculations is very important in examining nuclear reactions. We use the double folding potential to calculate the real parts of nucleus-nucleus scattering for several systems, which is introduced in the optical model [26]. The double-folding model, with realistic nucleon-nucleon interaction based upon a G-matrix constructed from the Reid potential, is used to calculate the real part of the optical potential for heavy-ion scattering [27]. In the direct channel, the double-folding potential [28] is calculated by integrating the nucleon-nucleon interaction over the ^{3}He and ^{4}He density distributions $\rho_1(\mathbf{r}_1)$ and $\rho_2(\mathbf{r}_2)$ of the colliding nuclei and represented by equation-6.

$$V_{\text{DF}}(\mathbf{r}) = \int\int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)V_{\text{NN}}(\mathbf{s})\, d^3r_1\, d^3r_2 \tag{6}$$

Where $\mathbf{r}$ is the distance between the nuclei of projectile and target and $\mathbf{r}_1$ and $\mathbf{r}_2$ are the distances from the centre of nuclei respectively. The equation-6 involves a six-dimensional integral. The angle between $\mathbf{r}_2$ and $\mathbf{r}$ is θ_1 and that of $\mathbf{r}_2$ and $\mathbf{r}$ is θ_2.

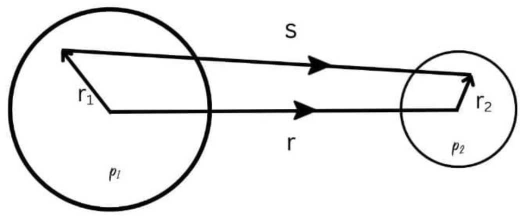


Figure 1: Coordinates used in double-folding potential calculations. For the nuclei of projectile and target.

The nucleon-nucleon distance $\mathbf{s}$ can be written in terms of $\mathbf{r}$, $\mathbf{r}_1$, $\mathbf{r}_2$ and represented by the equation-7.

$$\overrightarrow{s} = \overrightarrow{r} - \overrightarrow{r_1} + \overrightarrow{r_2} \tag{7}$$

The term in equation-6 denotes the nucleons-nucleons interaction. The Fermi and Gauss distribution of nuclear is given by equation-8 and equation-9.

$$\rho(r) = \frac{\rho_0}{1 + \exp((r - c)/a)} \tag{8}$$

$$\rho(r) = c \exp\left(-(r/\alpha)^2\right) \tag{9}$$

Where $\rho_0 = 2.607$ fm^{-3}, $c = 2.0$ fm, $a = 0.486$ fm for the Fermi distribution, and $c = 2.0$ fm^{-3}, $\alpha = 2.08207$ fm for the Gaussian distribution.

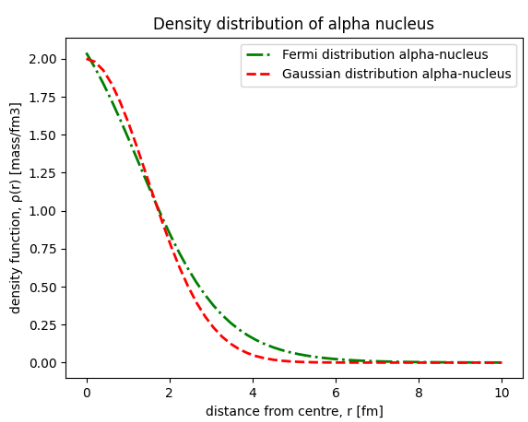


Figure 2: Nuclear matter distribution of reaction projectile+target.

There are two versions of DDM3Y-type nucleon-nucleon interactions [29]: the DDM3Y-Reid nucleon-nucleon interaction and the DDM3Y-Paris effective nucleon-nucleon interaction. The spin- and isospin-independent central terms of the two DDM3Y interactions can be represented by equation-10 and equation-11.

$$\text{DDM3Y-Reid:} \quad v(r) = 7999\frac{e^{-4r}}{4r} - 2134\frac{e^{-2.5r}}{2.5r} \tag{10}$$

$$\text{DDM3Y-Paris:} \quad v(r) = 11062\frac{e^{-4r}}{4r} - 2538\frac{e^{-2.5r}}{2.5r} \tag{11}$$

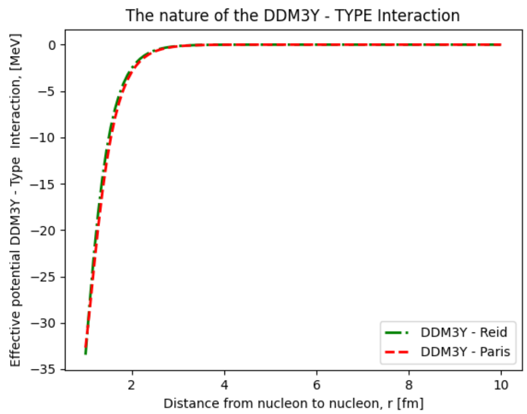


Figure 3: The shape of the DDM3Y-Type interaction for the reaction projectile + target.

The Schrodinger equation for the nuclear, Coulomb and angular momentum term potential is given in equation-12.

$$\left(\nabla^2 + \frac{2\mu V_{\text{eff}}}{\hbar^2} - k^2\right)\psi(\mathbf{r}) = 0 \tag{12}$$

Where $k^2 = \frac{2\mu E}{\hbar^2}$ and $\psi(\mathbf{r})$ represents the sum of the nuclear and Coulomb wave function and has been given in equation-13.

$$\psi(\mathbf{r}) = \psi_N(\mathbf{r}) + \psi_C(\mathbf{r}) \tag{13}$$

In the equation-13, the second term i.e. the Coulomb wave function hold only incoming wave although in asymptotic range the nuclear wave function appear for the outgoing wave. Equation—13 has been reduced in one-dimension r dependent only and has been given in equation-14.

$$\left(-\frac{d^2}{dr^2} + \frac{l(l+1)}{r^2} + \frac{2\mu}{\hbar^2}V_{\text{eff}} - k^2\right)\psi(r) = 0 \tag{14}$$

Where l is the angular momentum quantum number. Now, when an alpha nucleus is injected into another alpha nucleus for the ^{3}He + ^{4}He nuclear reaction, the relative motion of that alpha-alpha system can be described in terms of the wave function $\psi(r)$ of that system, and the general solution $\Psi(r,t)$ of Schrodinger equation-15 for the interacting nuclei has been given in equation-15.

$$\Psi(r,t) = \frac{1}{\sqrt{4\pi r}}\psi(r)\exp\left(-\frac{iEt}{\hbar}\right) \tag{15}$$

III Results and Discussions

In practice the thermonuclear fusion reaction occurs by quantum mechanical tunneling of the interacting particles through mutual Coulomb barriers. Here we computed the fusion cross section in the sub-barrier regime of energy in the astrophysical aspects [30]. In the computation of the fusion cross section, in the present study we incorporate the astrophysical S-factor, which has three parameters and is given in table1. A star gains its power from the nuclear fusion reaction. The proton-proton chain reaction is the main process of energy production of a lower-mass star [31]. At the initial stage, two protons fused together to form a deuterium nucleus and simultaneously produced one positron and one neutrino. Then, the produced deuterium captures a proton and forms a Helium nucleus along with a gamma photon, and it gives one Helium-4 nucleus. At the later stage, one Helium-3 nucleus and one Helium-4 nucleus merged together and formed one beryllium-7 nucleus along with a gamma photon [32].

$$^{1}\mathrm{H} + ^{1}\mathrm{H} \rightarrow ^{2}\mathrm{H} + e^{+} + \nu \tag{16}$$

$$^{1}\mathrm{H} + ^{1}\mathrm{H} \rightarrow ^{1}\mathrm{He} + \gamma \tag{17}$$

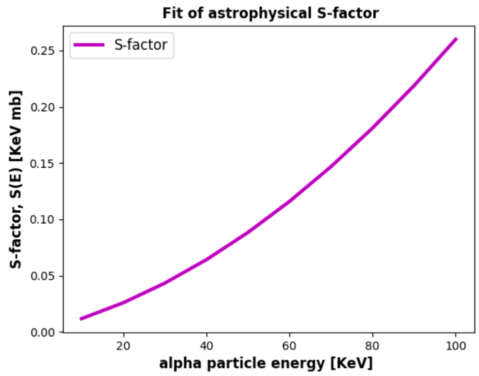
$$^{3}\mathrm{He} + ^{3}\mathrm{H} \rightarrow ^{4}\mathrm{He} + ^{1}\mathrm{H} + ^{1}\mathrm{H} \tag{18}$$

$$^{3}\mathrm{He} + ^{4}\mathrm{He} \rightarrow ^{7}\mathrm{Be} + \gamma \tag{19}$$

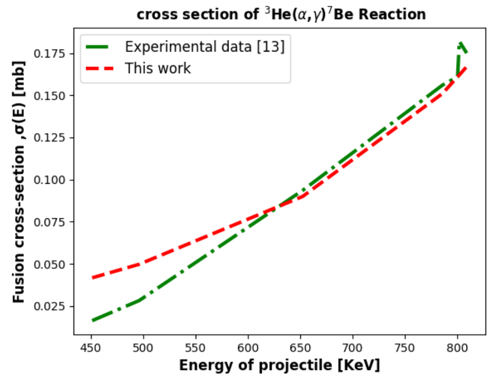
At a low astrophysical energy regime, the result for the reaction ^{3}He + ^{4}He has been given in figure 4. The computed result for the astrophysical S-factor of the reaction ^{3}He + ^{4}He has been depicted in Figure 4. To plot the astrophysical S-factor, the parameters of table-1 have been used. The cross section for the reaction ^{3}He + ^{4}He has been computed using Python-3 code and compared with the experimental data from ref. [13]. In the present study, our computation matched with the experimental data, which justifies the incorporation of double folding potential in equation 3.

Table 1: Parameters for the calculation of astrophysical S-factor

Reactions	$\mathbf{S_0}$ (keV mb)	$\mathbf{S_1}$ (mb)	$\mathbf{S_2}$ (mb/keV)
^{3}He(α,γ)^{7}Be	0.001	0.09×10^{-2}	0.169×10^{-4}
^{3}He(^{3}He,2p)^{4}He	0.001	0.02×10^{-2}	0.15×10^{-2}

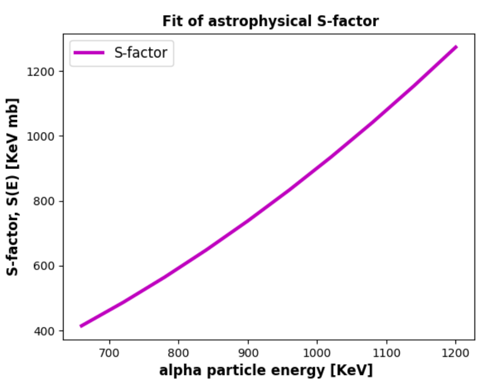


(a) (a) Fitting of astrophysical S-factor

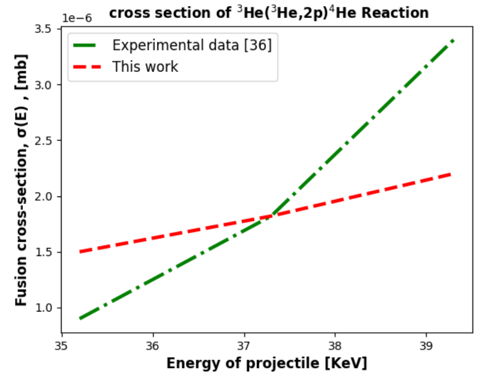


(b) (b) Comparison of cross sections for ^{3}He(α,γ)^{7}Be.

Figure 4: (a) Fitting of astrophysical S-factor by using equation 2 and table 1. Astrophysical S-factor in keV mb and energy in keV in lab system. (b) Comparison between experimental data points and computed data points for the ^{3}He(α,γ)^{7}Be reaction. The experimental data points are taken from ref. [13]. The cross section is in mb and energy in keV in the lab system.



(a) (a) Fitting of astrophysical S-factor



(b) (b) Comparison of cross sections for ^{3}He(^{3}He,2p)^{4}He.

Figure 5: (a) Fitting of astrophysical S-factor by using equation 2 and table 1. Astrophysical S-factor in keV mb and energy in keV in lab system. (b) Comparison between experimental data points and computed data points for the ^{3}He(^{3}He,2p)^{4}He reaction. The experimental data points are taken from ref. [14]. The cross section is in mb and energy in keV in the lab system.

Using the Selective Resonant Tunneling Model (SRTM), X.Z. Li [33] computed the fusion cross section for the D+T reaction using a complex square well and made a comparison with experimental data from Ref. [13]. In 2004, Li et al., again using the SRTM model, computed the D+D and D+^{3}He reactions' fusion cross section. All the computations provide a clear picture of the fusion cross sections of the light elements' nucleosynthesis. In 2019, Singh et al. [34] computed fusion cross section and astrophysical S-factor for some light nuclei such as D+D, D+T, and ^{3}He+D. Using SRTM, Khan et al. [1] in 2023 computed the same for the resonant cross section for D+D and p+^{11}B. The quantum tunneling model using double folding potential was used by V. Durant et al. [35] in 2018 for the computation of the fusion cross section of the ^{16}O + ^{16}O reaction. In the present work, a quantum tunneling model followed by a double folding potential has been used for the computation of the fusion cross section of ^{3}He + ^{4}He nuclear reactions. We made the comparison between our computational data and the experimental data from Ref. [13]. The figure-5 depicted our results and comparisons of fusion cross sections for the ^{3}He + ^{4}He nuclear reactions. The computed results are in good agreement with the recent experimental data [13]. No significant dissimilarity has been seen between the result computed with the double-folding model potential and the experimental results.

IV Summary and Conclusion

One of the goals of the present work was to determine the suitability of the double folding potential model to incorporate in the effective potential, which is introduced in the Gamow factor. The presently discussed fusion cross sections are based on ground states of the projectile (^{3}He) and target (^{4}He). Understanding the equation of states (EOS) nuclear reaction dynamics of asymmetric nuclear matter gives significant insight into nuclear ground state properties. The interaction potential for ^{3}He and target ^{4}He has been calculated by using Double-Folding Potential. The double folding model was defined using the integration of the nucleon density distribution of the two colliding nuclei and the nucleon-nucleon interaction potential. The matter density distribution of the target and projectile has been shown in figure 2, which is also a nature of Fermi and Gaussian distributions. The nature of the nucleon-nucleon interaction of the DDM3Y-Reid and DDM3Y-Paris interactions was plotted in figure 3. The NumPy library is what allows a user to convert text to numbers and conduct numerical analysis. Matplotlib is the primary graphing library for Python 3, and every graph from this research was created using Matplotlib. SciPy allows for modifications to graphs and data. We use the Python-3 code to analyze the double-folding potential.

^{3}He + ^{4}He The nuclear reaction is the main process in both Big Bang nucleosynthesis (primordial nucleosynthesis) and the p-p chain of the hydrogen-burning stars. The ^{3}He + ^{4}He nuclear reaction has been analyzed at low energies on the basis of the double folding potential mechanism. It has been thought that our computation will give new questions and furnish a moral testimonial for future cross-section studies and nuclear model calculations.

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