IMPACT OF PLASMA PARAMETERS ON NUCLEAR FUSION

Ayan Kumar Makar

Centre of Plasma Physics, Institute for Plasma Research, Sonapur, Assam, India.
email: icerstark07@gmail.com

ABSTRACT

Prior experiments on nuclear fusion have revealed that the rate of nuclear fusion essentially depends upon plasma density. pressure and temperature. To probe this dependency relation in particular an approach has been taken to achieving nuclear fusion by mediating metal electrons as screening agents to bring light fusion elements "closer". as in deuterated materials. and such lattice Confinement were utilised to measure the degree of nuclear fusion. Based on this a computational analysis has been performed with justifiable assumptions. using TALYS code to estimate the nuclear reaction cross - sections and modern software tools based on the Monte Carlo technique for particle transport simulations. Furthermore plasma beta (β) defined by the ratio between the plasma pressure to the magnetic pressure has been calculated with altering profiles of plasma density and temperature. It can be interpreted from the results that altering profiles of plasma parameters affect the absolute reaction cross sections of the interacting nuclei and thus have an impact on overall plasma fusion dynamics.

ABSTRAK

Eksperimen terdahulu mengenai pelakuran nuklear telah mendedahkan bahawa kadar pelakuran nuklear pada asasnya bergantung kepada ketumpatan plasma. tekanan dan suhu. Untuk menyiasat hubungan pergantungan ini khususnya pendekatan telah diambil untuk mencapai pelakuran nuklear dengan mengantarkan elektron logam sebagai agen penapisan untuk membawa elemen pelakuran ringan "lebih dekat". seperti dalam bahan yang dideuter. dan Pengkurungan kekisi tersebut digunakan untuk mengukur tahap pelakuran nuklear..Berdasarkan ini analisis pengiraan telah dilakukan dengan andaian yang wajar. menggunakan kod TALYS untuk menganggarkan keratan rentas tindak balas nuklear dan alat perisian moden berdasarkan teknik Monte Carlo untuk simulasi pengangkutan zarah. Tambahan pula plasma beta (β) yang ditakrifkan oleh nisbah antara tekanan plasma kepada tekanan magnet telah dikira dengan mengubah profil ketumpatan dan suhu plasma. Ia boleh ditafsirkan daripada keputusan bahawa mengubah profil parameter plasma mempengaruhi keratan rentas tindak balas mutlak nukleus yang berinteraksi dan dengan itu mempunyai kesan ke atas keseluruhan. dinamik gabungan plasma.

Keywords: Nuclear fusion. computational analysis. fusion dynamics. plasma parameters. confinement. cross sections

INTRODUCTION

Several critics believe that the formation of beautiful night sky is an exemplar of success of the nuclear fusion reaction. In technical terms Nuclear Fusion means the combination of two or more lighter nuclei to form a heavier nucleus with release of colossal amounts of energy. Thus, it is a type of exothermic nuclear reaction. This is the process that power the stars and currently ongoing research are focussed on harnessing the fusion energy which has the potential to provide us inexhaustible amounts of clean and green energy. One of the main difficulties involved in reproducing the conditions favourable to controlled thermonuclear fusion reaction is that the temperature requirement is extremely high and one of the approaches to solve this problem. In fact, it to be solved to a great extent. is to first convert the fusion fuel into the plasma state. The parameters -density. temperature and pressure of plasma physics in addition to time play an important role in determining the rate of nuclear fusion. and help in self-sustaining fusion reaction to take place thus these parameters are also called critical fusion parameters. It has been found that optimum maintenance of these parameters supports in self-sustaining nuclear fusion to take place [1-2]. Few conditions that are required for nuclear fusions are high temperatures. high density and prolonged stability. The case of hot temperature demand put us within the regime of plasmas. Plasma act as a medium in which the nuclear fusion reaction can take place [3]. Among some of the well-known features involving collisions among the plasma species including medium and heavy ions. when the energy is slightly above the coulomb barrier is complete fusion (CF) and incomplete fusion (ICF) [4-5]. In case of CF reaction. the fusion of the interacting nuclei takes place completely resulting into the formation of an excited compound nucleus (CN) whereas in the ICF reaction process. only a part or a specific fragment of the interacting nuclei fuses with each other, resulting into the formation of a composite system [6-7]. The coulomb barrier explicitly refers the energy barrier owing to electrostatic interaction that both the interacting nuclei ought to surpass so that they can get close enough to bear a nuclear fusion reaction. 'Coulomb barrier' unremarkably refers to the barrier shaped by the repulsive 'Coulomb' and therefore enticing 'nuclear' (nucleus-nucleus) interactions in an exceedingly central (s-wave) collision [8]. This barrier is usually referred to as fusion barrier (for light-weight and medium mass heavy-ion systems) or capture barrier (heavy systems). In general. a significant amount of centrifugal part is also present to such a barrier (non-central collisions). Major aspects of the Coulomb barrier (barrier energy. radius and curvature) are measured by the first and second derivative of the overall interaction potential (nuclear+Coulomb+centrifugal) relative to the internuclear distance. Additionally, the reduced mass of the radial motion influences the efficacy of the barrier curvature [9]. It has been found that the plasma as a medium must possesses optimal value of its critical parameters like density. temperature and pressure for self -sustaining nuclear fusion reaction to take place [10-11]. Thus, the optimum maintenance of these parameters serves an important aspect in power generation using controlled thermonuclear reactions [12].

Theoretical Formalism

Nuclear fusion reaction counts on the dynamics of the highly energetic nuclei for collisionality. with successive re-arrangement of nucleons and the discharge of energy in the form of kinetic energy of the product particles and their excitation energy. The nuclei are assumed to be mutually interacting electrostatically with each other.According the dynamical model of Swiatecki [13]. dynamical evolution of the reaction consists of three milestones: (i) attainment of contact. (ii) Conquering conditional saddlepoint and (iii) Conquering unconditional saddle point.In case of light ions conquering the first barrier (attainment of contact) also promishingly assures overcoming the second barrier (overcoming conditional saddlepoint). However, for heavier ions at the touching point of two interacting nuclei the attractive nuclear forces cease to be minimum leading insufficient condition for the nuclear fusion reaction to occur thus an additional energy. so called "extra push." is required for sending the system above the conditional saddle point for feasible complete fusion reaction resulting into formation of the compound nucleus. the third barrier must also be overcome i.e. the system must overcome the unconditional saddle point as well. The additional energy. so called "extra push." can trigger the reaction intensely to a greater or lesser extent. Based on this model a relation has been established depending on the parameters that ascertain the ‘’extra push ‘’ value for a given system and is given by

$$\left(\frac{Z^2}{A}\right)_{effective} = \frac{4Z_P}{A_P^{\frac{1}{3}}} Z_t A_t^{\frac{1}{3}} \left(A_P^{\frac{1}{3}} + A_t^{\frac{1}{3}}\right) \tag{1}$$

the above relation depends only upon the atomic (Z) and mass (A) numbers of the incident ions (p) and the target nuclei (t) [13]. It is also noteworthy that the system which has conquered the first two barriers may or may not assist in automatic conquering of the third barrier (unconditional saddle point) which results into the formation of compound nucleus. In that case when the system is unsuccessful in overcoming the third barrier.an extra-extra thrust is required to create a compound nucleus. Thus, more energy is needed for the complete fusion reaction to take place. It can also be estimated that the temperature. pressure and density of the fusion plasma play a key role in determining the ‘’ extra -push or thrust ‘’ value. Thus, maintenance of these parameters at optimum level ensure that the nuclear fusion reactions do actually occur. The existence of these energy barrier leads to categorization of nuclear reactions into four broad categories as shown in the (Figure 1) and (Figure 2).

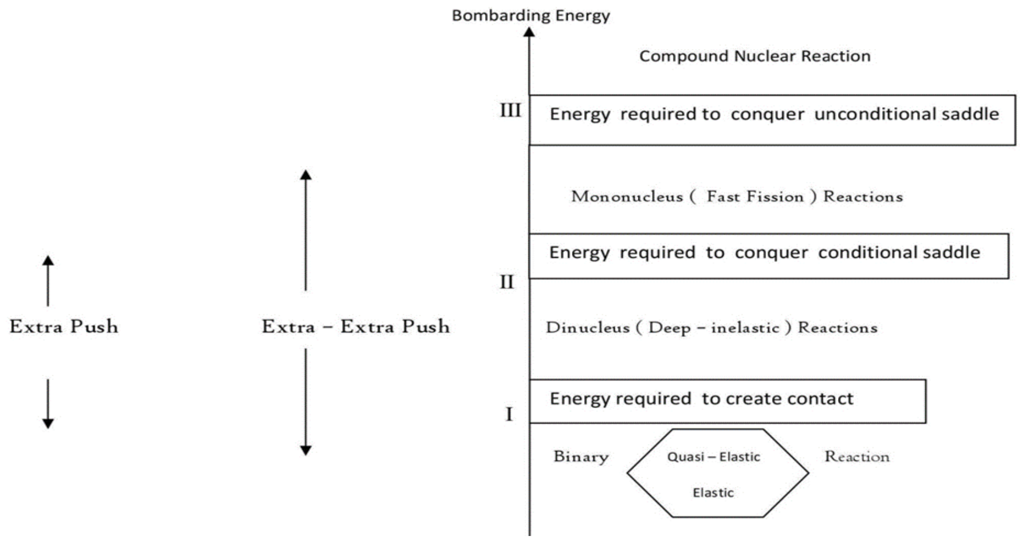

Figure 1. Demonstration of the correlation between three energy obstacles. Kinds of nuclear reactions and classifications of extra thrust

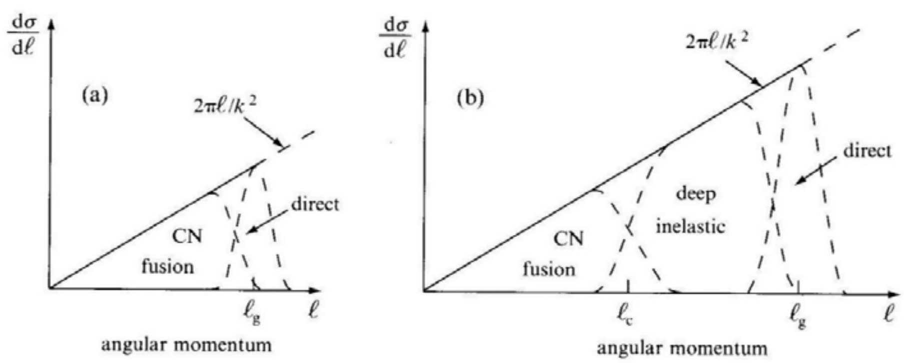

Figure 2. Schematic representation of decomposition of total fusion cross section under partial wave analysis (a) the grazing angular momentum ($\boldsymbol{\ell_g}$) is less than critical angular momentum ($\boldsymbol{\ell_c}$) (b) the grazing angular momentum ($\boldsymbol{\ell_g}$) is greater than critical angular momentum ($\boldsymbol{\ell_c}$). the area enclosed under the dashed line indicates the region where heavy ion reaction mechanism is feasible.

To formulate the nuclear fusion reaction rate induced by plasma density. temperature and pressure. a binary reaction has been assumed here. in which there are ρ_1 nuclei per unit volume of one species interacting with ρ_2 nuclei per unit volume of another species. To determine the rate at which two nuclear systems interact it may be supposed that nuclei of the first system form a stationary system within which the nuclei of the second system move with a velocity of v cm/sec. which is the relative velocity of the nuclei. Let ʘ be the cross section for the given reaction. Then ρ_1ʘ gives the number of nuclei of the first system which will react with each nucleus of the second system while traversing a distance of 1cm. Thus, the total distance travelled by all the nuclei of the second system in one second will be $\rho_2 \odot$. Therefore, the rate of nuclear fusion reaction per unit volume can be formulated as

$$R\ (Fusions/m^3) = \rho_1 . \rho_2 \{ \odot \mathrm{v} \}_{12} \tag{2}$$

where

ρ_1 and ρ_2 are the densities of nuclei 1 and 2 respectively. and

$$\{ \odot \mathrm{v} \}_{12} = \iint d^3\, \mathrm{v}_1\, d^3\, \mathrm{v}_2\, f1\, (\mathrm{v}_1) f2\, (\mathrm{v}_2) | \mathrm{v}_1 - \mathrm{v}_2 | \odot_f (| \mathrm{v}_1 - \mathrm{v}_2 |) \tag{3}$$

is the reactivity of the nuclear fusion reaction.

where

v is the velocity. f is the distribution function of the velocity and $\odot_f$ is the cross section of the nuclear fusion.

Moreover, the fusion collisional cross section of the two nuclei can be approximated in the form of Equation (4). as

$$\odot(E) = \frac{Constant}{E^{\frac{3}{2}}} . exp \left[\frac{-2^{\frac{3}{2}}}{h} \frac{\Pi^2 M^{\frac{1}{2}} Z_1\ Z_2\ e^2}{E^{\frac{1}{2}}} \right] \tag{4}$$

where

h can be considered as the Planck's constant. M can be considered as the reduced mass of two discrete nuclei interacting with each other.

It can be contended that the nuclear fusion reaction possesses a definable cross section which is assumed as the sum total cross sections of the complete and incomplete fusion reactions. Although the relative energy of the interacting nuclei is very less [14]. The collisional cross section increases with the relative particle energy because of the dominating exponential term in the above equation. However, they peak at a maximum value beyond which they do not increase further [15] (Figure 3).

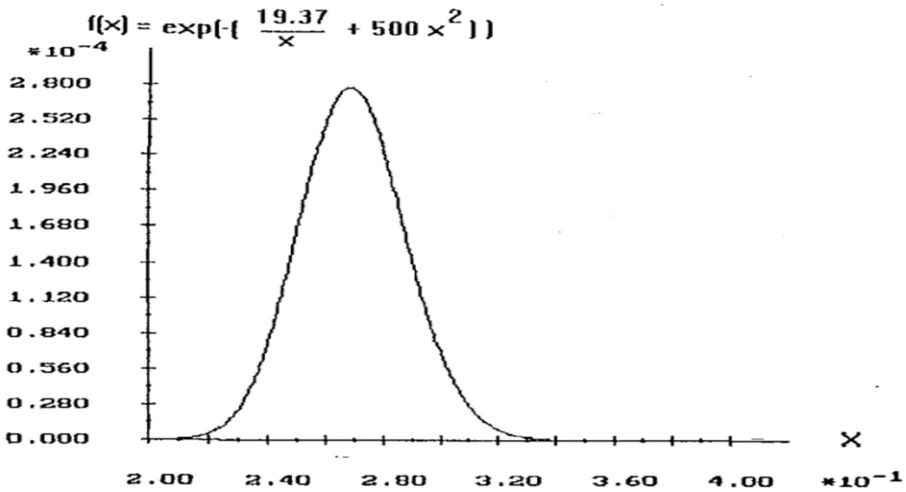

Figure 3. A schematic diagram representing the function : $\boldsymbol{exp} \left[\frac{-2^{\frac{3}{2}}}{h} \frac{\Pi^2 M^{\frac{1}{2}} Z_1\ Z_2\ e^2}{E^{\frac{1}{2}}} \right]$. the constant numbers so used in the expression are values of the parameters for the reaction in the equation (4). where $\boldsymbol{x}$ is a non-dimensional velocity. $\boldsymbol{x} = \frac{u}{v_0}$. here $\boldsymbol{v_0} = \boldsymbol{6.62 \times 10^7}$ cm/s

The nuclear reaction rate is determined by two major factors: Coulomb scattering of projectile nuclei on target nuclei and nuclei tunnelling across the Coulomb barrier. When charged projectiles are elastically scattered on a target nucleus. such as a deuteron. some of the projectile particle's energy is transmitted to the target nucleus. heating it. The target deuteron may grow energetic enough to permit further nuclear fusion processes through tunnelling across the Coulomb barrier depending on the projectile particle energy and the efficiency of kinetic energy transfer during the scattering event (Figure 4).

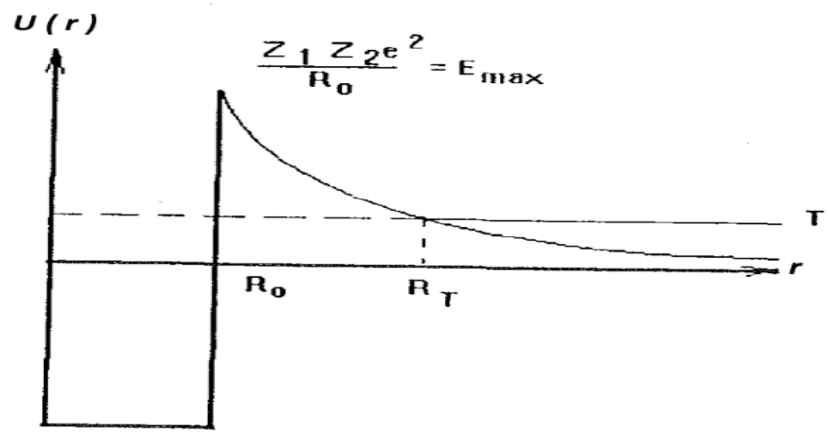

Figure 4. The variation of coulomb potential energy $\boldsymbol{U\,(r)}$ with internuclear distance $(\boldsymbol{r})$

In this paper. the electron screening impact on Coulomb scattering and the tunnelling process including charged projectiles has been studied and the higher effectiveness of transfer of kinetic energy by energetic neutrons on target deuteron nuclei has been established. ensuing in successive nuclear reactions. Electron screening of target nuclei is often modelled by a negative uniform shift $-U_e$ of the Coulomb barrier $U_c(r)$. where U_e is the potential energy due to electronic screening effect and can be written as

$$U_e = \frac{z_1 z_2 e^2}{\lambda_{sc}} \tag{5}$$

Here z_1. z_2 are the atomic numbers of projectile and target. e and λ_{sc} are the electronic charge and screening length respectively. Similarly. the standard columb barrier $U_c(r)$ can also be written as

$$U_c\left(r\right) = \frac{z_1 z_2 e^2}{r} \tag{6}$$

Here. r being the radial distance between projectile and target. the concept of electronic screening potential can be theoretically justified when the classical turning point r_{ctp} is very small compared to screening length λ_{sc}. i.e. $r_{ctp} \ll \lambda_{sc}$ or $E \gg U_e$. where E is the total energy of the centre of mass (CM) reference frame. Thus. the experimentally measured tunnelling probability in Centre of mass frame can be written as

$$\sigma_{\exp}\left(E\right) = \sigma_{screen}\left(E\right) = \sigma_{bare}\left(E + U_e\right) \tag{7}$$

here the collisions of bare ions are considered to be at higher energy. $E + U_e$.

The equation (7) can be rewritten as

$$\sigma_{\exp}\left(E\right) = \sigma_{bare}\left(E\right)\mathrm{F}\ \left(E\right) \tag{8}$$

Here $\mathcal{F}(\,E\,)$ is the enhancement factor. It has been found that the enhancement factor $\mathcal{F}(\,E\,)$ increases significantly when deuterium interacts with host metals. particularly at low deuteron energy. Also, it has been revealed that the enhancement factor $\mathcal{F}(\,E\,)$ increases significantly with increasing atomic number and with decreasing projectile energy [16]. In deuterated materials subjected to ionising radiation (quanta or intense electron e-beam). dense plasma streams are formed inside an irradiated sample consisting of nonequilibrium double temperatures' plasma with movable hot electrons and cold deuteron ions. Inside the plasma a bound state between deutron ions and the energetic electrons cannot be formed since the coulomb interaction $\left(\widetilde{U}_{ie} \sim \frac{q_i q_e}{\bar{r}}\right)$ between them is much smaller than the average kinetic energy of the electrons$\left(\bar{k}_e \sim Tk_e\right)$. which is not ideal for bound state formation. Therefore.

$$\overline{K_e} \gg |\overline{U_{\iota e}}| \tag{9}$$

The existence of plasma can be justified by inequality of equation (9) which can be rewritten as

$$KT_e \gg e^2 n^{1/3} \tag{10}$$

where

the mean distance between ions. $\bar{r} \sim n^{-\frac{1}{3}}$ (11)

Now considering the Debye length. $\lambda_{De} = \left(\frac{Tk_e}{4\pi e^2 n}\right)^{\frac{1}{2}}$ (12)

The equation (12) can be rewritten with the help of equation (11) as:

$$\lambda_{De}{}^2 \gg \frac{\bar{r}^2}{4\pi} \rightarrow \lambda_{De} > \frac{\bar{r}}{\sqrt{4\pi}} \cong 0.28\bar{r} \tag{13}$$

The equation (13) essentially represents that inside the plasma. $\lambda_{De} \gg \bar{r}$. It can also be revealed from equations (11) and (13) that the number of electrons in Debye sphere. $N_{De} >> 1$.

Thus.

$$N_{De} \sim n\left(\frac{4\pi}{3}\lambda_{De}{}^3\right) \gg 1 \tag{14}$$

Hence the statements of equation (13). equation (14) follows from equation (9). the necessary requirement of plasma existence.

COMPUTATIONAL ANALYSIS AND DISCUSSION

The plasma as a medium has a significant role in regulating the fusion fractions over a reaction channel. In nuclear fusion. the Monte Carlo method is the predominant computational tool for particle transport simulations and thus it has been employed in the present research. It has enabled a flexible and straightforward geometry representation and described the current process in complete 3D geometry without the need for real-world approximations. The nuclear interaction cross-sections have been employed in the nuclear data files for continuous energy representations. Thus. only the statistical uncertainty of the computation and the inconsistencies of the underlying nuclear cross section data impact the precision of the calculations. Most Nuclear calculations predict the rates of reaction as evaluated by Hauser–Feshbach (HF) model [17]. It is based on the postulate (Bohr's hypothesis) that the capture process takes place as a result of intermediary production of a compound system that can attain a state of thermodynamic equilibrium. Consequently. the compound system is then classically referred to as the compound nucleus. The overall cross-sections of interacting ions (as proposed in section 2) were therefore analysed with TALYS -1.4 nuclear model code which provided an estimation of the absolute variation of collisional cross sections (Figure 5).

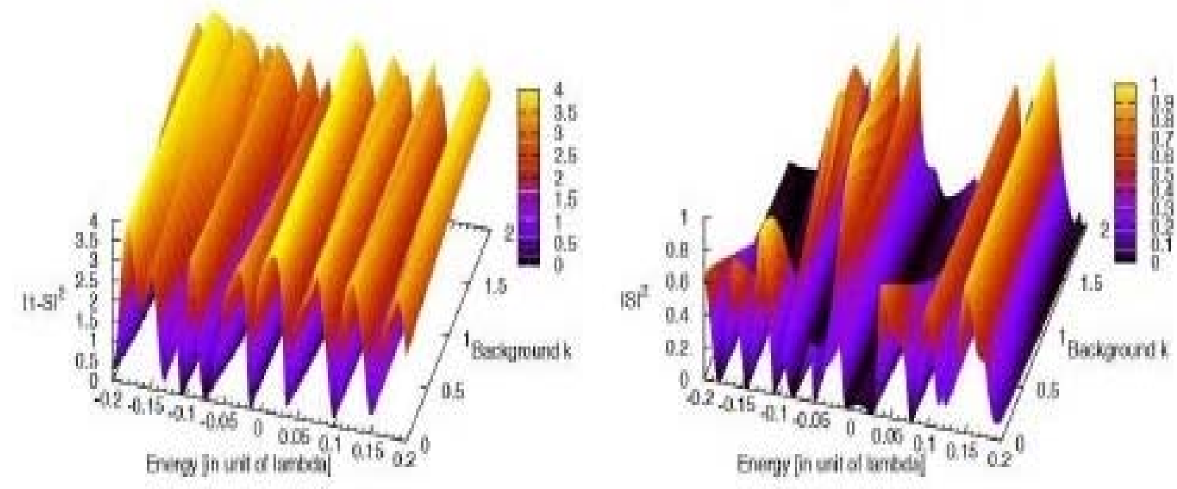

Figure 5. Computed elastic and inelastic cross -sections with background component ***K***

In binary reaction (as proposed in section 2). TALYS estimates the corresponding cross sections of the compound nucleus by jls scheme.

$$\sigma^{\mu}_{\alpha\alpha'} = D^{comp}\pi\lambda^2 \sum_{j=mod(I^{\mu}+S.1)}^{\ell_{max}+I^{\mu}+S} \sum_{\Vert=-1}^{1} \frac{2j+1}{(2I^{\mu}+1)(2S+1)} \sum_{j=|J-I^{\mu}|}^{J+I^{\mu}} \sum_{\ell=|j-s|}^{j+s} \sum_{j'=|J-I'|}^{J+I'} \sum_{\ell'=|j'-s'|}^{j'+S'} \delta_{\pi}(\alpha)\delta_{\pi}(\alpha') \frac{\langle T^{J}_{\alpha\ell j}(E_a')\rangle\langle T^{J}_{\alpha'\ell'j'}(E_{a'})\rangle}{\sum_{\alpha''.\ell''.j''}\delta_{\pi}(\alpha'')\langle T^{J}_{\alpha''.\ell''.j''}\left(E_{a''}\right)\rangle}\,\omega^{J}_{\alpha\ell j\alpha'\ell'j'} \quad (15)$$

In the equation 15, E_a. S. $\pi_0.\ell.j$ represent the energy. spin. parity. orbital and total angular momentum respectively of the interacting nuclei. The symbols labelled with prime represent the corresponding properties of the ejectile emitted during the reaction. The symbols $|^{\mu}.\Vert^{\mu}.\left(|'.\Vert'\right)$ defines the spin and parity of the residual nucleus. whereas $J\ and\ \Vert$ represent the spin and parity of the compound system. The initial system of interaction can be defined as $\alpha = \left(a.s.E_a.E_x^{\mu}.|^{\mu}.\Vert^{\mu}\right)$. Here E_x^{μ} represent the excitation energy of the interacting nuclei. $\alpha' = \left(a'.s'.E_a{}'.E_x'.|'.\Vert'\right)$ is similar for the final system of ejectile and residual nucleus. $\boldsymbol{\delta_{\pi}(\alpha) = 1.}$ if $(-1)^{\ell}\pi_0\Vert^{\mu} = \Vert$ and 0 otherwise (the same condition is applicable to the final system $\boldsymbol{\alpha'}$). In the above equation $\lambda.T.\omega.D^{comp}$ represent the relative motion. wave length. transmission coefficient. width fluctuation correction factor and the depletion factor respectively. The depletion factor D^{comp} can be written as $D^{comp} = \frac{(\sigma_{reac}-\sigma^{disc.direct}-\sigma^{PE})}{\sigma_{reac}}$. Here σ_{reac} is the total reaction cross section. $\sigma^{disc.direct}$ is the total discrete direct cross section and σ^{PE} is the preequilibrium cross section. The impact of plasma in determining the probability of complete and incomplete fusion in a nuclear fusion reaction can be conceived on the basis of measured plasma parameters. for e.g. temperature. density and pressure and inspecting the variation of collisional cross - sections of the interacting nuclei as well (Table 1).

It can be interpreted that as the plasma temperature. density and pressure gradually increase beyond the ignition temperature. the collisional cross sections of interacting nuclei decrease that means the mutual effective area available for interaction or the probability of occurring the scattering phenomena decreases because of the collisional kinetic effects (Figure 6 - Figure 8).

Table 1. Variation of plasma parameters with absolute nuclear cross sections

S.No	Plasma density	$\boldsymbol{\beta}_{effective}$ -	Plasma Temperature	Absolute Cross Sections ($\boldsymbol{\sigma_R}$) in mb
1.	1.5×10^{20} m^{-3}	0.030	2×10^6 K	2700 ∓ 19
2.	2.5×10^{20} m^{-3}	0.031	6×10^6 K	2400 ∓ 06
3.	3.5×10^{20} m^{-3}	0.032	10×10^6 K	1900 ∓ 09
4.	4.5×10^{20} m^{-3}	0.033	16×10^6 K	1300 ∓ 05
5.	5.5×10^{20} m^{-3}	0.034	22×10^6 K	1000 ∓ 12
6.	6.5×10^{20} m^{-3}	0.036	26×10^6 K	900 ∓ 10

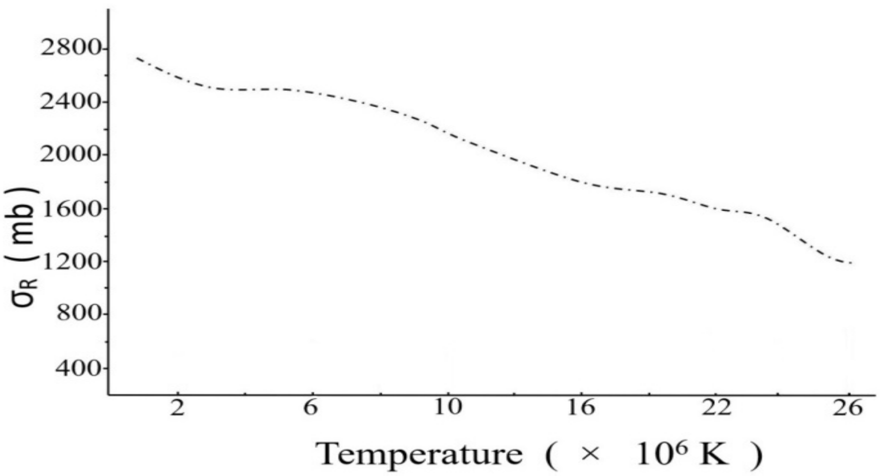

Figure 6. Variation of absolute collisional cross section with plasma temperature

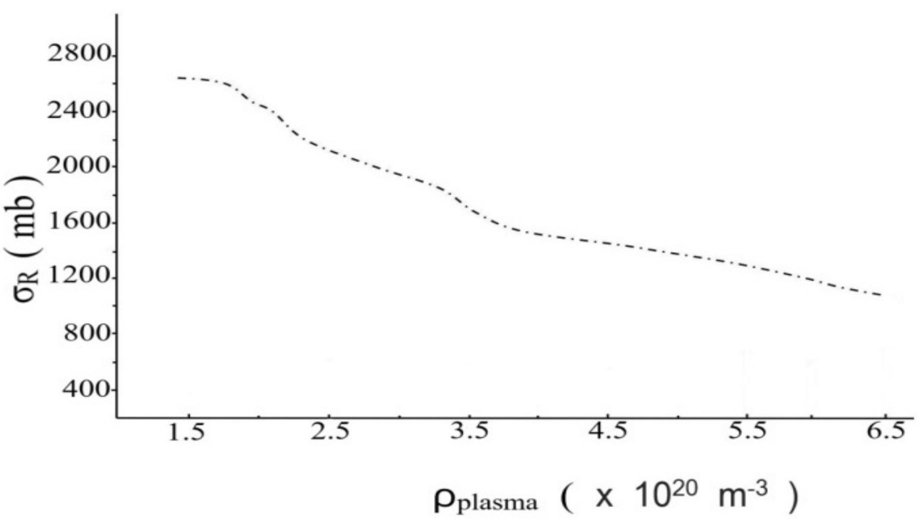

Figure 7. Variation of absolute collisional cross -section with plasma density.

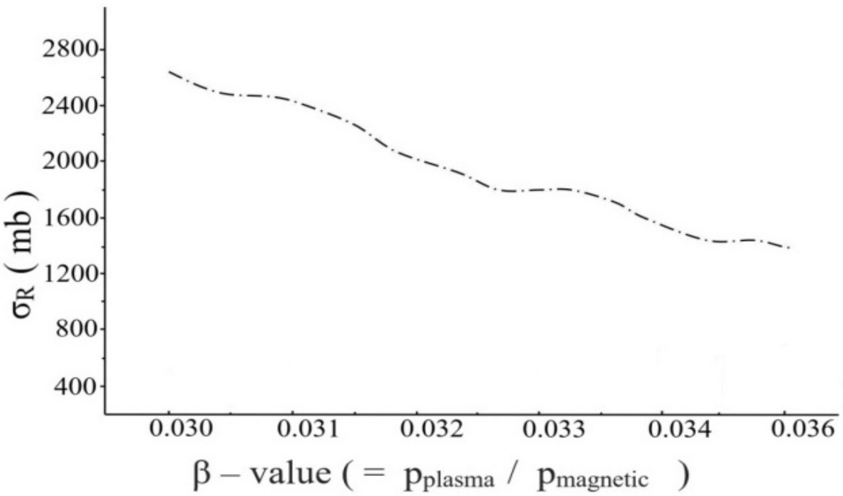

Figure 8. Variation of absolute collisional - cross section with plasma pressure or ($\boldsymbol{\beta}_{effective}$ -value).

The excitation functions were then calculated and derived from collisional cross sections and the energy of the medium which in turn was calculated from the various scales of temperatures registered for simulation (Figure 9).

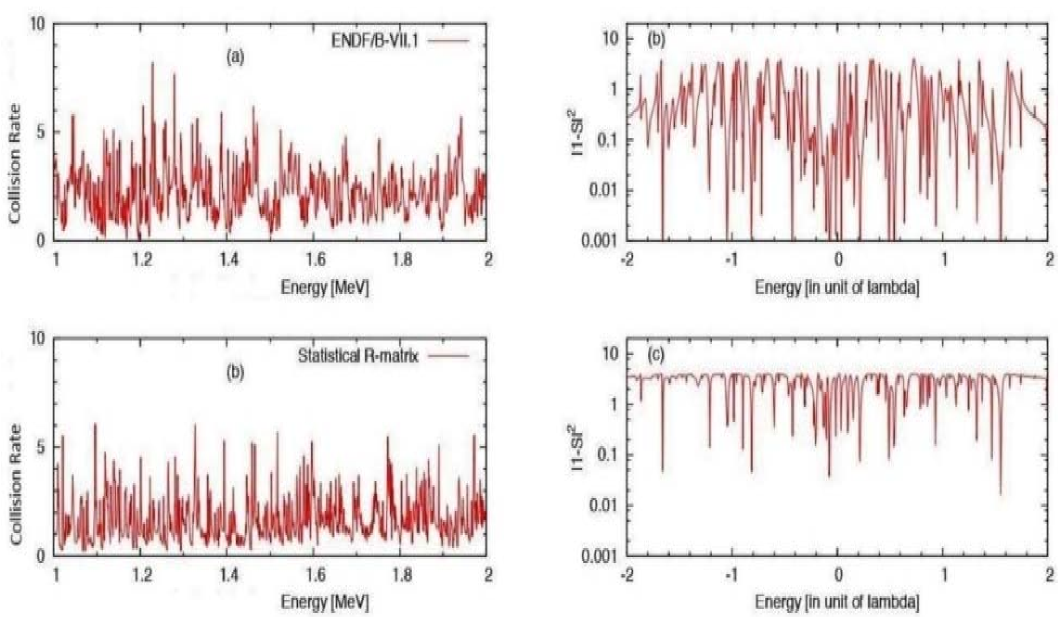

Figure 9. Computed cross -sections from theoretically predicted Hauser-Feshbach theory.

The calculated excitation functions were found in well agreement with the theoretical predicted cross sections when compared with statistical models codes based on Hauser–Feshbach Theory (Figure 10*)* which only accounts for the excitation function populated by complete fusion [18]. However, at lower energies a significant enhancement of the measurement was recorded that means the reaction channel at lower energies were populated as well. which is attributed to be populated by incomplete fusion.

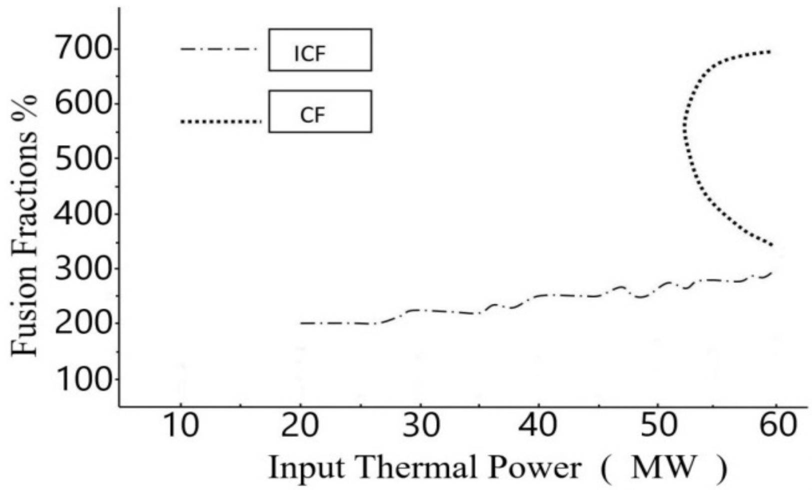

Figure 10. The contribution of complete and Incomplete Fusion fractions with respect to the input thermal power.

Thus, it can also be interpreted that heating the plasma beyond the ignition temperature escalates the chance of complete fusion reaction.

CONCLUSIONS

To probe the dependency of plasma density. pressure and temperature on the nuclear fusion. a binary nuclear fusion reaction has been assumed to achieving fusion by mediating metal electrons as screening agents to bring light fusion elements "closer". as in deuterated materials. and such lattice Confinement were utilised to measure the degree of Incomplete fusion and Complete fusion [19]. The collisional cross sections of interacting nuclei were analysed using TALYS -1.4 nuclear model code with altering profiles of plasma temperature. density and pressure. The Monte Carlo method has been employed for particle transport simulations [20]. It has been found that the collisional cross sections gradually decrease with increase of plasma parameters such as temperature. density and pressure. The corresponding excitation functions were then calculated and derived from collisional cross sections and the energy of the medium which in turn was calculated from the plasma temperatures at various scales during simulation. The calculated excitation functions were found in well agreement with the theoretical predicted cross sections when compared with statistical model codes based on Hauser–Feshbach theory. however, at lower energies a significant enhancement of the measurement was recorded and this increase in the experimental cross section over the theoretical prediction is attributed as a signature of incomplete fusion (ICF) reaction.

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