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FEASIBILITY OF NUCLEAR FUSION OF ${}^1_1$H + ${}^7_3$Li FOR GENERATION OF ELECTRIC POWER IN TCT FUSION REACTOR

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The feasibility of nuclear fusion reaction ${}^1_1H + {}^7_3Li \rightarrow 2{}^4_2He$ (17.5 MeV), for generation of electric power in nuclear reactors is presented. The fusion cross-section of nuclear reaction for the projectile beam of ${}^1_1H$ whose energy ranges from 1 keV to 1× 10^4 keV in the centre-of-mass frame is computed with the aid of GEMINI^{++} statistical decay model. The Maxwellian average of the product of the fusion cross-section and the relative velocity of projectile and target $\langle \sigma v \rangle$ gives the fusion reaction rate. The fusion reaction rate should be sufficiently high to produce more nuclear fusion electric power. The energy multiplication factor (ζ) of nuclear fusion is defined as the ratio of nuclear fusion energy (E_F) generated to injected energy of projectile beam (E_P), i.e., $\zeta = E_F/E_P$. The lower energy loss rate and higher fusion reaction rate should contribute higher value of the energy multiplication factor (ζ). The Energy multiplication factor (ζ) for nuclear fusion of ${}^1_1H + {}^7_3Li$,variation with projectile beam energy is presented. The energy multiplication factor can be enhanced by clamping (or fixing) of projectile beam energy at a suitable value. The clamping of the projectile beam energy defers slowing down process of projectile beam and compensates the Coulomb drag by the bulk plasma, thus the energy multiplication factor increases. The variation of the Energy multiplication factor (ξ) for nuclear fusion of ${}^1_1H + {}^7_3Li$, with projectile beam energy clamping (or fixing) is also presented.
Keywords: *Proton-Lithium fusion; TCT reactor; Energy multiplication factor; Projectile beam energy clamping*
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1. INTRODUCTION

In the future world enormous amount of electric power energy can be generated by nuclear fusion in nuclear reactors. The energy distribution of the ions of the plasma consists of two components in Two-component torus (TCT) fusion reactor, which is the torus type plasma-containment nuclear fusion reactor [1-3]. In TCT nuclear fusion reactor high energy ion beam is shot into target plasma, to cause the nuclear fusion reaction between the ions, electrons of the target plasma and the injected beam. The ions and electrons of plasma possess thermal energy and it can be converted into electrical energy with high efficiency in nuclear fusion reactor. The energy multiplication factor is an important parameter to optimise nuclear fusion reactions for the commercial production of electrical power energy. When energy multiplication factor $\zeta = 1$, the fusion power is equal to the thermal power to cause fusion and it is known as breakeven, and the plasma will not be cooled down without any external heating. If $\zeta > 1$, self-heating causes the process to become self-sustaining and ignition occurs at the high temperature. The high value of energy multiplication factor ζ is essential for commercially possible practical TCT fusion reactor. The fusion power density in a TCT fusion reactor can be much more than in thermal reactor of the same pressure. The most favourable injection energy of incident beam for nuclear fusion to occur is the energy which gives maximum energy multiplication factor ζ, as it yields maximum output energy.

Researchers studied the feasibility of energy multiplication factor of the ${}^2_1H + {}^3_1H$nuclear fusion reaction in detail [4-8]. K. Ogawa et.al studied the ${}^1_1H + {}^{11}_5B$ fusion reactionin the fusion reactor [9]. J. Bahmani studied the parameters related to the energy multiplication factor of ${}^3_2He + {}^6_3Li$ for two-component torus fusion plasma [10]. The energy multiplication factor should be high to produce nuclear electric power economically. The fusion reaction rate, the energy confinement time, the beam containment time, the impurities present in the target plasma, the beam energy clamping and the plasma density, influence the energy multiplication factor. In the present work, I have studied the feasibility of the fusion reaction of ${}^1_1H + {}^7_3Li$ in nuclear fusion reactor for the commercial production of electric power to meet the demand in the future.

2. THEORY

2.1The fusion cross section

The fusion cross-section at the centre-of-mass of ${}^1_1H$ projectile and ${}^7_3Li$ target system is given by [11]

$$\sigma(E) = \frac{\pi R^2(E)}{E}\int_0^E \frac{dE'}{1+exp\left[2\left(\frac{A_1}{E'} - A_2E' + A_3\right)\right]} \tag{1}$$

Here $\sigma(E)$ is fusion cross-section for projectile and target, E is projectile beam energy, $R(E)$ is the effective radius of the projectile and target system, A_1, A_2, A_3 are constants.

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2.2 The Rate of Nuclear fusion reaction

The rate of nuclear fusion reaction evaluated as the Maxwellian average of the product of the fusion cross-section and the relative velocity between projectile and target which is given by [12,13]

$$\langle\sigma v\rangle = \left(\frac{8}{\pi}\right)^{1/2}\left(\frac{\mu}{k_B T_i}\right)^{3/2}\frac{1}{m_p^2}\int_0^E E\sigma(E)exp\left[-\left(\frac{\mu E}{m_p k_B T_i}\right)\right]dE \tag{2}$$

Here v is the relative velocity between ${}^1_1H$ projectile and ${}^7_3Li$ target, μ is reduced mass of projectile and target, k_B is Boltzmann's constant, T_i is temperature of ion plasma, m_p is the mass of projectile, E is the energy of projectile beam.

2.3 Injected beam energy transfer to target plasma

When energetic injected ${}^1_1H$ beam collides with ions and electrons of ${}^7_3Li$ target plasma, the energy of injected beam is transferred to ions and electrons through Coulomb interactions, until thermal equilibrium is reached. The mean rate of energy loss of injected ${}^1_1H$ beam by all thermal electrons and ions of ${}^7_3Li$ target plasma is determined using Fokker-Planck slowing down model of Sivukhin as [14-17]

$$\langle\frac{dE}{dt}\rangle = \frac{4\pi n_T Z_P^2 Z_T^2 e^4 \Lambda}{v_P}\sqrt{\frac{m_P}{2E_P}}\sum_{T=i,e}F(x_T,\beta_{TP}) \tag{3}$$

Here n_T is the number density of ions or electrons of ${}^7_3Li$ target plasma, Z_P and Z_T are charge states of ions or electrons of ${}^1_1H$ projectile and ${}^7_3Li$ target respectively, e is charge of electron, Λ is coulomb logarithm of ${}^7_3Li$ target plasma, v_P is relative velocity of ${}^1_1H$ projectile w.r.t ${}^7_3Li$ target, m_P is mass of projectile, E_P is energy of projectile, $F(x_T,\beta_{TP})$ is related to the error function as

$$F(x_T,\beta_{TP}) = \phi(x_T) - (1+\beta_{TP})\phi'(x_T) \tag{3a}$$

Here

$$\phi(x_T) = \frac{2}{\sqrt{\pi}}\int_0^{x_T} e^{-t^2}\,dt,\ \beta_{TP} = \frac{m_T}{m_P},\ x_T = \beta_{TP}\frac{m_P}{2k_B T_T}$$

2.4 Energy Multiplication Factor (ζ) of Nuclear Fusion

When high energy projectile beam is injected into target plasma, nuclear fusion occurs. The energy multiplication factor of nuclear fusion is defined as the ratio of nuclear fusion energy (E_F) to injected energy of projectile beam (E_P) [12]

$$\zeta = \frac{E_{fusion}}{E_{projectile}} = \frac{Qn_T}{E_{{}^1_1H}}\int_{E_{Th}}^{E_{{}^1_1H}}\frac{\langle\sigma v\rangle}{\langle\frac{dE}{dt}\rangle}dE \tag{4}$$

Here, Q is fusion power gain of ${}^1_1H + {}^7_3Li$ nuclear fusion reaction, n_T is the number density of target plasma, E_{Th} is the threshold value of energy for fusion to occur and $E_{{}^1_1H}$ is the energy of ${}^1_1H$ projectile beam.

2.5 Projectile beam energy clamping

One mode of two-component ${}^1_1H + {}^7_3Li$ nuclear fusion uses an auxiliary energy input to maintain the super-thermal ions of ${}^7_3Li$ target at or near the injected energy of ${}^1_1H$ projectile beam by energy clamping, as it defers slowing down process and compensates the Coulomb drag by the bulk plasma of ${}^7_3Li$ target. The injected-ion energy is kept near the peak of the fusion cross section,when maximum fusion rate of nuclear reaction is achieved. The energy multiplication factor can be increased, even though the plasma temperature remains at the same value. The ions of plasma of ${}^7_3Li$ target can be maintained at optimum values of high energies for nuclear fusion reactions to occur for longer periods of time. The energy multiplication factor for projectile energy clamping (or fixing) is given by [12]

$$\xi = Qn_T\frac{[\sigma v]_{E_0}}{\left[\frac{dE}{dt}\right]_{E_0}}. \tag{5}$$

Here E_0 is clamped projectile beam energy.

3.Results and discussion

The fusion cross-section for ${}^1_1H + {}^7_3Li$ nuclear fusion is computed with the aid of GEMINI^{++} statistical decay model [18]. I have computed fusion-cross-section in the centre-of-mass projectile beam energy ranging from 1 keV to 1×10^4 keV for ${}^1_1H + {}^7_3Li$ nuclear fusion. The calculations of the fusion cross section, the reactivity, the energy loss rate, the energy multiplication factor and the beam energy clamped energy multiplication factor of ${}^1_1H + {}^7_3Li$ fusion are shown in Table 1.

The variation of fusion cross section with the projectile beam energy is as shown in Figure 1, it is observed that the fusion cross section is $5.3\times10^{-21}cm^2$ at $1\ keV$ energy, decreases gradually to $0.53\times10^{-21}cm^2$ at $10\ keV$ energy and remains almost a constant at $0.0053\times10^{-21}cm^2$ between $1\times10^2\ keV - 1\times10^3 keV$ energy, beyond which it is almost $10^{-25}\ cm^2$ up to $1 \times 10^3\ keV$. The nuclear fusion reaction rate is measured as the Maxwellian average $\langle \sigma v \rangle$ of the product of the fusion cross-section and the relative velocity of $_1^1H$ projectile w.r.t $_3^7Li$ target. The fusion reaction rate of nuclear reaction is enhanced to produce more fusion energy.

Table 1. Fusion cross section, Reactivity, Energy loss rate of projectile beam due to collisions with ions, electrons and both ions and electrons, Energy multiplication factor and Beam energy clamped Energy multiplication factor of $_1^1H + _3^7Li$ nuclear fusion

$E_{p(CM)}$ (keV)	σ $(10^{-21} cm^2)$	σv $(10^{-18} cm^3 s^{-1})$	$\left[\frac{dE}{dt}\right]_i$	$\left[\frac{dE}{dt}\right]_e$	$\left[\frac{dE}{dt}\right]_{i+e}$	ζ	ξ
1	5.29E+00	2.12E-02	-3.11E+03	-2.62E+00	-3.12E+03	-1.19E-02	-1.19E-02
2	2.64E+00	4.21E-02	-2.88E+03	-2.66E+00	-2.88E+03	-2.47E-02	-2.55E-02
3	1.76E+00	6.29E-02	-2.67E+03	-2.59E+00	-2.67E+03	-3.84E-02	-4.12E-02
4	1.32E+00	8.35E-02	-2.47E+03	-2.58E+00	-2.47E+03	-5.32E-02	-5.92E-02
5	1.06E+00	1.04E-01	-2.28E+03	-2.56E+00	-2.28E+03	-6.91E-02	-7.96E-02
6	8.81E-01	1.24E-01	-2.11E+03	-2.54E+00	-2.11E+03	-8.63E-02	-1.03E-01
7	7.55E-01	1.44E-01	-1.95E+03	-2.52E+00	-1.95E+03	-1.05E-01	-1.30E-01
8	6.61E-01	1.64E-01	-1.80E+03	-2.51E+00	-1.80E+03	-1.25E-01	-1.60E-01
9	5.87E-01	1.84E-01	-1.66E+03	-2.49E+00	-1.66E+03	-1.46E-01	-1.94E-01
10	5.29E-01	2.03E-01	-1.52E+03	-2.47E+00	-1.53E+03	-1.70E-01	-2.33E-01
20	2.64E-01	3.83E-01	-6.27E+02	-2.31E+00	-6.29E+02	-7.02E-01	-1.06E+00
30	1.76E-01	5.47E-01	-1.92E+02	-2.12E+00	-1.94E+02	-2.35E+00	-4.93E+00
40	1.32E-01	6.97E-01	1.45E+01	-1.95E+00	1.25E+01	2.20E+01	9.75E+01
50	1.06E-01	8.35E-01	1.09E+02	-1.78E+00	1.07E+02	2.48E+01	1.36E+01
60	8.81E-02	9.61E-01	1.49E+02	-1.60E+00	1.48E+02	2.67E+01	1.14E+01
70	7.55E-02	1.08E+00	1.64E+02	-1.41E+00	1.63E+02	2.83E+01	1.16E+01
80	6.61E-02	1.18E+00	1.66E+02	-1.23E+00	1.65E+02	2.99E+01	1.25E+01
90	5.87E-02	1.28E+00	1.63E+02	-1.06E+00	1.62E+02	3.14E+01	1.38E+01
100	5.29E-02	1.37E+00	1.58E+02	-8.82E-01	1.57E+02	3.29E+01	1.52E+01
200	2.64E-02	1.74E+00	1.15E+02	8.84E-01	1.15E+02	4.61E+01	2.64E+01
300	1.76E-02	1.90E+00	9.35E+01	2.65E+00	9.62E+01	5.76E+01	3.45E+01
400	1.32E-02	1.96E+00	8.10E+01	4.41E+00	8.54E+01	6.77E+01	4.02E+01
500	1.06E-02	1.99E+00	7.25E+01	6.17E+00	7.86E+01	7.65E+01	4.42E+01
600	8.81E-03	2.00E+00	6.61E+01	7.94E+00	7.41E+01	8.44E+01	4.72E+01
700	7.55E-03	2.00E+00	6.12E+01	9.55E+00	7.08E+01	9.15E+01	4.95E+01
800	6.61E-03	2.01E+00	5.73E+01	1.15E+01	6.87E+01	9.78E+01	5.11E+01
900	5.87E-03	2.01E+00	5.40E+01	1.32E+01	6.72E+01	1.04E+02	5.22E+01
1000	5.29E-03	2.01E+00	5.12E+01	1.50E+01	6.62E+01	1.09E+02	5.30E+01
2000	2.64E-03	2.01E+00	3.62E+01	3.25E+01	6.87E+01	1.34E+02	5.11E+01
3000	1.76E-03	2.01E+00	2.96E+01	4.99E+01	7.94E+01	1.49E+02	4.42E+01
4000	1.32E-03	2.01E+00	2.56E+01	6.71E+01	9.27E+01	1.59E+02	3.79E+01
5000	1.06E-03	2.01E+00	2.29E+01	8.43E+01	1.07E+02	1.65E+02	3.28E+01
6000	8.81E-04	2.01E+00	2.09E+01	1.01E+02	1.22E+02	1.70E+02	2.87E+01
7000	7.55E-04	2.01E+00	1.94E+01	1.18E+02	1.38E+02	1.74E+02	2.55E+01
8000	6.61E-04	2.01E+00	1.81E+01	1.35E+02	1.53E+02	1.77E+02	2.29E+01
9000	5.87E-04	2.01E+00	1.71E+01	1.52E+02	1.69E+02	1.79E+02	2.08E+01
10000	5.29E-04	2.01E+00	1.62E+01	1.68E+02	1.85E+02	1.81E+02	1.90E+01

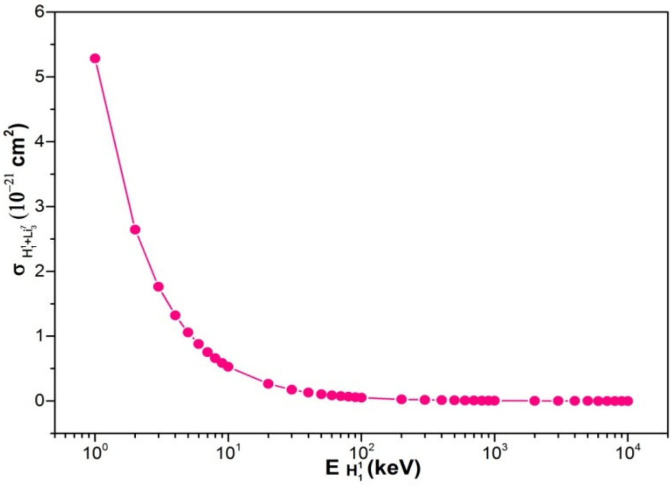

Figure 1. Fusion cross section of $_1^1H + _3^7Li$ as a function of $_1^1H$ projectile beam energy

The nuclear fusion $_1^1H + _3^7Li$ reaction rate is shown in the Figure 2, it is observed that the fusion reaction rate is $0.02 \times 10^{-17} cm^3 s^{-1}$ at $1\ keV$ energy, increases gradually to $2.0 \times 10^{-17} cm^3 s^{-1}$ at $1 \times 10^3\ keV$ and remains almost a constant at $2.0 \times 10^{-17} cm^3 s^{-1}$ in the range $1 \times 10^3\ keV - 1 \times 10^4\ keV$ energy.

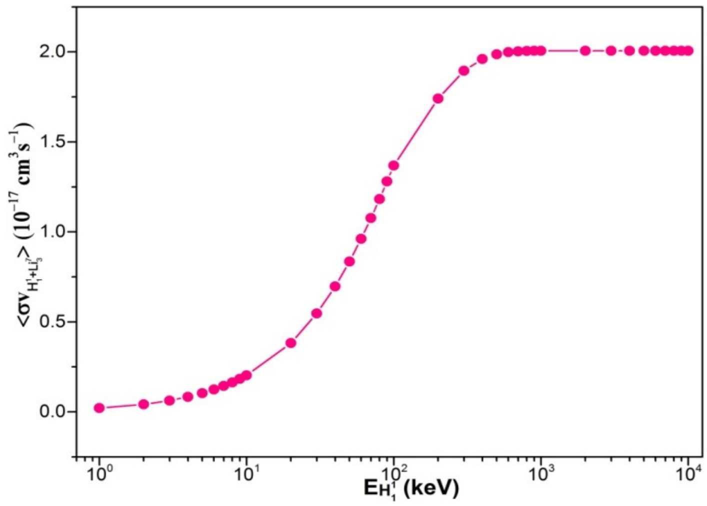

Figure 2. Fusion reaction rate of ${}^1_1H + {}^7_3Li$ as a function of ${}^1_1H$ projectile beam energy

The rate of total energy loss of ${}^1_1H + {}^7_3Li$ nuclear fusion reaction is shown in the Figure 3, it is observed that the rate of energy loss of ${}^1_1H$ projectile due to collisions with ions of ${}^7_3Li$ target plasma is $158.36\ keVs^{-1}$at $100\ keV$, decreases sharply to $51.2\ keVs^{-1}$ at $1 \times 10^3\ keV$, and decreases slowly from $36.2\ keVs^{-1}$ to $16.2\ keVs^{-1}$ in the energy range $2 \times 10^3\ keV - 1 \times 10^4\ keV$. The rate of energy loss of ${}^1_1H$ projectile due to collisions with electrons of ${}^7_3Li$ target plasma is $0.88\ keVs^{-1}$ at $200\ keV$ energy, increases linearly to $168.4\ keVs^{-1}$ at $1 \times 10^4\ keV$ energy. Therefore, the rate of total energy loss of ${}^1_1H$ projectile due to collisions with the ions and electrons of ${}^7_3Li$ target plasma is $157.5\ keVs^{-1}$ at $100\ keV$ energy, decreases gradually to $66.2\ keVs^{-1}$ at $1 \times 10^3\ keV$ energy, and increases linearly from $68.7\ keVs^{-1}$ to $184.6\ keVs^{-1}$ in the energy range $2 \times 10^3\ keV - 1 \times 10^4\ keV$. Thus, to generate more fusion power, the energy loss of the fusion reaction must be less.

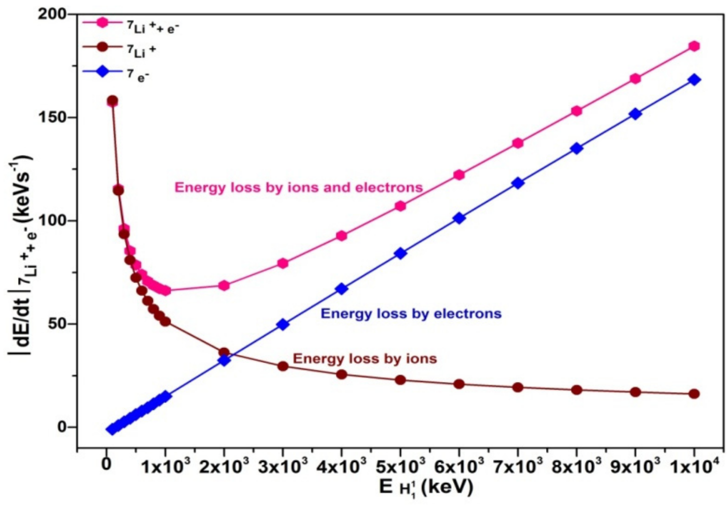

Figure3. Energy loss rates of ions and electrons of ${}^7_3Li$ as functions of ${}^1_1H$ projectile beam energy

The energy multiplication factor (ζ) of nuclear fusion is defined as the ratio of nuclear fusion energy (E_F) to injected energy of projectile beam (E_P). The energy multiplication factor (ζ) for ${}^1_1H + {}^7_3Li$ nuclear fusion is shown in the Figure 4, it is observed that the energy multiplication factor increases sharply from 22.04 at $40\ keV$ energy to 108.94 at $1 \times 10^3\ keV$ energy and it increases slowly from 134.5 at $2 \times 10^3\ keV$ to 180.75 at $1 \times 10^4\ keV$ projectile energy. The lesser the energy loss rate and more fusion reaction rate can contribute to higher value of the energy multiplication factor.

The energy multiplication factor of ${}^1_1H + {}^7_3Li$ nuclear fusion reaction can be enhanced by clamping (fixing) of ${}^1_1H$ projectile beam energy. The clamping of the ${}^1_1H$ projectile beam energy, defers slowing down process and compensates the Coulomb drag by the bulk plasma of ${}^7_3Li$ and consequently increases the energy multiplication factor (ξ). The variation of the energy multiplication factor with projectile beam energy being clamped is shown in Figure 5, it is observed that the energy multiplication factor with projectile beam energy clamping (ξ) for ${}^1_1H + {}^7_3Li$ nuclear fusion increases sharply from 11.4 at $60\ keV$ energy to 53.0 at $1000\ keV$ energy and decreases gradually from 51.1 at $2000\ keV$ energy to 19.02 at $1 \times 10^4\ keV$ projectile energy.

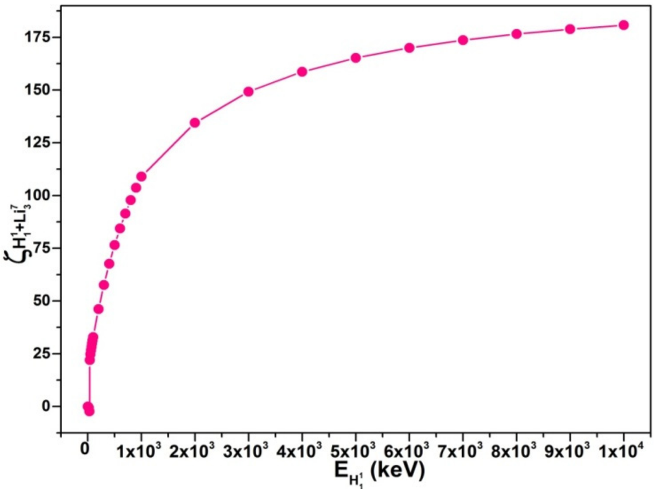

Figure 4. Energy multiplication factor of ${}_1^1H + {}_3^7Li$ as function of ${}_1^1H$ projectile beam energy

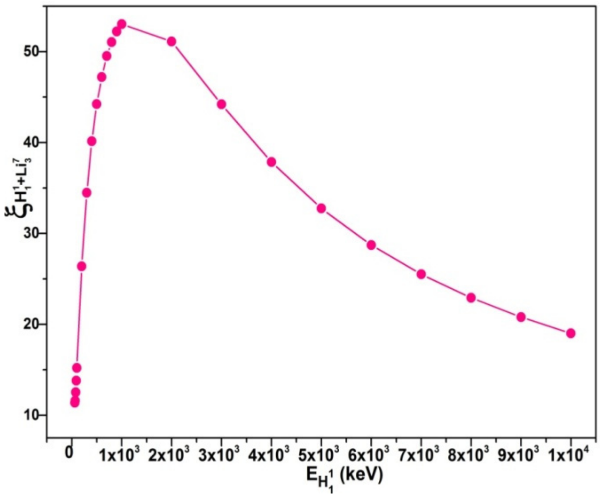

Figure 5. Energy multiplication factors of ${}_1^1H + {}_3^7Li$ as a function of projectile beam energy clamping

4. CONCLUSION

The nuclear fusion reaction ${}_1^1H + {}_3^7Li \rightarrow 2{}_2^4He\,(17.5\ MeV)$ for generation of electric power in nuclear reactors has been studied. The fusion cross-section was computed with the aid of GEMINI^{++} statistical decay model. I have computed fusion-cross-section in the centre-of-mass projectile beam energy range from 1 keV to 1×10^4 keV for ${}_1^1H + {}_3^7Li$ nuclear fusion. The fusion reaction rate is the Maxwellian average of the product of the fusion cross-section and the relative velocity of ${}_1^1H$ projectile and ${}_3^7Li$ target. The Energy multiplication factor (ζ) for ${}_1^1H + {}_3^7Li$ nuclear fusion variation with the projectile beam energy is presented. To generate more fusion power the fusion reaction rate should be higher, the energy loss rate due to collisions of the fusion reaction must be lower. The lower value of energy loss rate of projectile due to collisions with ions, electrons of plasma and more fusion reaction rate contribute higher value of the energy multiplication factor. The energy multiplication factor can be enhanced by clamping (fixing) of ${}_1^1H$ projectile beam energy. The clamping of the projectile beam energy defers slowing down process of fusing nuclei and compensates the Coulomb drag by the bulk plasma and consequently increases the energy multiplication factor. The variation of the Energy multiplication factor (ξ) with projectile beam energy clamping (fixing) also presented.

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МОЖЛИВІСТЬ ЯДЕРНОГО СИНТЕЗУ ${}_1{}^1H+{}_3{}^7Li$ ДЛЯ ГЕНЕРАЦІЇ ЕЛЕКТРОЕНЕРГІЇ У ТЕРМОЯДЕРНОМУ РЕАКТОРІ TCT

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Представлено можливість ядерної реакції синтезу ${}_1{}^1H + {}_3{}^7Li \rightarrow 2{}_2{}^4He$ (17,5 MeB) для генерації електроенергії в ядерних реакторах. Перетин термоядерної реакції для пучка, що налітає ${}_1{}^1H$, енергія якого в системі центру мас становить від 1 кеВ до 1×10^4 кеВ, обчислюється за допомогою статистичної моделі розпаду GEMINI++. Максвелловський середній твір перерізу синтезу та відносної швидкості атому що налітає та мішені $\langle\sigma v\rangle$ дає швидкість реакції синтезу. Швидкість реакції ядерного синтезу має бути досить високою, щоб виробляти більше електроенергії. Коефіцієнт множення енергії (ζ) ядерного синтезу визначається як відношення енергії ядерного синтезу (E_F), що генерується до інжектованої енергії пучка атомів (E_P), тобто $\zeta = E_F/E_P$. Нижча швидкість втрати енергії та більш висока швидкість реакції синтезу повинні вносити більш високе значення коефіцієнта множення енергії (ζ). Подано зміну коефіцієнта множення енергії (ζ) для ядерного синтезу ${}_1{}^1H + {}_3{}^7Li$ залежно від енергії пучка атомів що налітають. Коефіцієнт множення енергії може бути збільшений шляхом фіксації (або фіксації) енергії пучка на відповідному значенні. Фіксація енергії снарядного пучка затримує процес уповільнення пучка атомів та компенсує кулонівський опір об'ємною плазмою, таким чином, коефіцієнт множення енергії збільшується. Також представлено зміну коефіцієнта множення енергії (ξ) для ядерного синтезу ${}_1{}^1H + {}_3{}^7Li$ із затисканням (або фіксацією) енергії пучка що налітають.

Ключові слова: *протонно-літієвий синтез; реактор TCT; коефіцієнт множення енергії; фіксація енергії пучка що налітає*