Improved $D - {}^3He$ Fusion Reaction Characteristics Parameters

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Abstract
The most likely fusion reaction to be practical is Deuterium and Helium-3 ($D - {}^3He$), which is highly desirable because both Helium-3 and Deuterium are stable and the reaction produces a 14 MeV proton instead of a neutron and the proton can be shielded by magnetic fields. The strongly dependency of the basically hot plasma parameters such as reactivity, reaction rate, and energy for the emitted protons, upon the total cross section, make the problems for choosing the desirable formula for the cross section, the main goal for our present work.

Key words:- $D - {}^3He\ reaction$, proton energy, reactivity, reaction rate, fusion cross section , hot plasma

Introduction

The most likely fusion reaction to be practical is Deuterium and Helium-3 ($D - {}^3He$), which is highly desirable because both Helium-3 and Deuterium are stable and the reaction produces a 14 MeV proton instead of a neutron and the proton can be shielded by magnetic fields. This means it is possible to make a fusion reactor using $D - {}^3He$ reaction where the fuels and the the reactions produce no radioactivity and the reaction occurs in a magnetized plasma and can be engineered to release its energy directly into electricity. This means a very compact and efficient fusion power plant, suitable for aircraft and spacecraft is possible using $-{}^3He$. Because of the lack of radioactivity for direct power conversion to electricity, the practical use of $D - {}^3He$ fusion reaction for power is the long-range goal of most fusion researchers [1].

The difficulty of $D - {}^3He$ fusion relative to $D - T$ stems from the scarcity of Helium-3 on earth because the Helium-3 nuclei have two positive electric charges instead of the one in hydrogen isotopes, therefore, it requires higher collision energy for a Deuterium nuclei and Helium-3 nuclei to approach each other closely to fuse. This means $D - {}^3He$ requires higher plasma temperature and pressures than $D - T$ fusion so it is more technologically challenging. Also Helium-3 is found only in great abundance on the sun, so it is space rather than terrestrial resource. Therefore, $D - {}^3He$ fusion is most often associated with space propulsion and power and a future economy that includes ready acess to space resource [1]. One of the possible techniques to decrease neutron load on plasma facing components and superconducting coils in fusion reactor is to use fuel cycle based on $D - {}^3He$ as alternative to $D - T$ [2]. Taking into account that the thermal reactivity of $D - {}^3He$ is much lower than that of $D - T$, the approach such as ICRF catalyzed fusion should be developed. The main idea of this technique is to modify reagent distribution function in order to achieve favorable reaction rate for nuclear fusion energy production [3]. Recent experimental results show high efficiency of ICRH (Ion Cyclotron Resonance Heating) acceleration of He-3 minority in D plasma in order to increase fusion reaction rate, from the other hand this technique could be used to achieve the favorable distribution of T ions in D plasma and hence to reduce the amount tritium needed for sustainable fusion plasma burning [4].

The effect of transition to non-Maxwellain plasma is essential for reactor aspects studies both in tokamaks and heliotrons, and the study of this effect is done by means of numerical code, based on test-particle approach, this code solves the guiding center equation of a general vector form. To simulate the coulomb collisions of test-particle with the other species, the discretized collision operator based on binomial distribution is used. The possibility of increasing the average reactivity by modification of distribution function of He-3 and T minorities in D plasma due to selective ICRF (Ion Cyclotron Rang of Frequency) heating [5].

Theoretical models

By definition, the reaction rate $\boldsymbol{R}$ for reaction $\boldsymbol{i}$ in a space independent problem is given by

$$\boldsymbol{R = n_D\, n_{He} \iiint f(\vec{v}_D) F(\vec{v}_{He})\, g\, \frac{d\sigma_i}{d\Omega}\, d\Omega d\vec{v}_D d\vec{v}_{He}} \qquad (1)$$

Where n_D and n_{He} are the beam and target ions densities with unit-normalized distribution functions f and F respectively; g is the modulus of the relative velocity between beam and target ions and $\frac{d\sigma_i}{d\Omega}$ is the doubly differential cross section.

In the Bernstein – Comisar formalism, one can introduce the dummy variable E by use of a Dirac Delta distribution, so that

$$\boldsymbol{R = n_D\, n_{He} \iiint f(\vec{v}_D) F(\vec{v}_{He})\, g\, \frac{d\sigma_i}{d\Omega}\, \delta(E - E_p) d\Omega d\vec{v}_D d\vec{v}_{He}\, dE} \qquad (2)$$

Where E_p *is* the emitted proton energy. This is given, in the case of axially moving target ions. By the laws of conservation of energy and momentum, and from the general basic fundamental equation of calculating the energy for the emitted charge particles from any nuclear reaction is given below [6].

$$\sqrt[2]{E_3} = v \pm \sqrt[2]{v^2 + \omega} \qquad (3)$$

Where $v = \frac{\sqrt[2]{M_1 M_3 E_1}}{M_3+M_4}\cos\theta$ and $\omega = \frac{M_4 Q + E_1 (M_4 - M_1)}{M_3+M_4}$ (4)

For the case of the binary $D - {}^3He$ fusion reaction,

$$D + {}^3He \rightarrow {}^4He\,(3.712\ MeV) + P\,(14.641\ MeV)$$

Where

$$E_3 = E_p\ , M_1 = M_d\ , M_3 = M_p\ , M_4 = M_{^4He}\ , E_1 = E_d$$

And $Q = 18.353\ MeV$ is the Q-value of the above D-He fusion reaction, E is the deuteron bombarding energy.

Substituting the values for the quantities $v, \omega, M_1, M_2, M_3, M_4, E_1, Q$ as it is described above in equation (3), and taken into account some mathematical analysis steps to get or deduced a formula for evaluating the energy of the emitted neutrons that is given below.

$$E_p = \frac{20\,Q + 12\,E_d}{25}\left[\sqrt[2]{1 - \gamma^2 \sin\theta} + \gamma\cos\theta\right]^2 \qquad (5)$$

Where $\gamma^2 = \frac{2\,E_d}{20\,Q + 12\,E_d}$

Equation (5), explains the relationship between the energy of the emitted proton from the $D - {}^3He$ fusion reaction with the energy of bombarding deuterons and reaction angle $E_d\ , \theta$, respectively, and it's predominate recommended value is equal to 14.641.

A most important quantity for the analysis of nuclear reaction is the *cross section*, which measures the probability per pair of particles for the occurrence of the reaction. The cross section $\sigma_{12}(v_1)$ is defined as the number of reactions per target nucleus per unit time when the target is hit by a unit flux of projectile particles that is by one particle per unit target area per unit time. Actually, the above definition applies in general to particles with relative velocity v , and is therefore symmetric in the two particles, since we have $\sigma_{12}(v) = \sigma_{21}(v)$.

Cross section can also express in terms of the center of mass energy, and we have $\sigma_{12}(\epsilon) = \sigma_{21}(\epsilon)$. In most cases, however, the cross section are measured in experiments in which a beam of particles with energy , measured in the laboratory frame, hits a target at rest. The corresponding beam-target cross section $\sigma_{12}^{bt}(\epsilon_1)$ is related to the center-of-mass cross section $\sigma_{12}(\epsilon)$ by

$$\sigma_{12}(\epsilon) = \sigma_{12}^{bt}(\epsilon_1)$$

With $\epsilon_1 = \epsilon \cdot (m_1 + m_2)/m_2$

Where m_1 represents D *mass*, $(m_1 = 2)$, m_2 represents ${}^3He$ *mass*, $(m_2 = 3)$

If the target nuclei have density n and are at rest or all move with the same velocity, and the relative velocity is the same for all pairs of projectile-target nuclei, then the probability of reaction per unit times is obtained by multiplying the probability per unit path times the distance travelled in the unit time, which gives $n_2\,\sigma(v)v$.

Another important quantity is the ***reactivity***, defined as the probability of reaction per unit time density of target nuclei. It is just given by the product $\sigma\,v$. In general, target nuclei moves, so that the relative velocity v is different for each pair of interacting nuclei. In this case, we compute an ***averaged reactivity*** [7].

$$\langle \sigma\,v \rangle = \int \sigma(v) v\, f(v) dv, \qquad (6)$$

Where $f(v)$ is the distribution function of the relative velocities, normalized in such a way that $\int_0^\infty f(v)dv = 1$.

Both controlled fusion fuels and stellar media are usually mixtures of elements where species `1` and `2` have number densities n_1 , n_2 , *respectively*. the volumetric reaction rate, that is the number of reactions per unit time and per unit volume is then given by [7]:

$$\boldsymbol{R} = \frac{n_1 n_2}{1+\delta_{12}} \langle \sigma v \rangle = \frac{f_1 f_2}{1+\delta_{12}} n^2 \langle \sigma v \rangle \qquad (7)$$

Here n is the total nuclei number density and $f_1\, f_2$, are the atomic fraction of species "1" and "2",respectively.The Kronecker symbol δ_{12}(with $\delta_{12} = 1, if\ i = j\ and\ \delta_{12} = 0\ eleswhere$) is introduced to properly take into account the case of reaction between like particles. Equation 7 shows a very important feature for fusion energy research: the volumetric reaction rate is proportional to the square of the density of the mixture. For feature reference, it is also useful to recast it in terms of the mass density ρ of the reacting fuel

$$\boldsymbol{R_{12}} = \frac{f_1 f_2}{1+\delta_{12}} \frac{\rho^2}{\bar{m}^2} \langle \sigma v \rangle \qquad (8)$$

Where $\bar{m}$ is the average nuclear mass.

Here, the mass density is computed as $= \sum_j n\, m = n\bar{m}$, where the sum is over all species. We also immediately see that the specific reaction rate is proportional to the mass density, again the role of the density of the fuel is achieving efficient release of fusion energy [7].

Main controlled fusion reaction

The most important main controlled fusion reactions necessary as power source applications that are recently used in many interested countries which supported huge efforts are listed in Table (1).

In the present work, we concentrate on the study of the reaction between the hydrogen isotopes, namely, the deuterium and helium, which are the most important fuels for controlled fusion research.

$$\boldsymbol{D + {}^3He \rightarrow {}^4He\ (3.712\ MeV) + P\ (14.641\ MeV)}$$

The above reaction has a cross section, which reaches its maximum (about 0.9 barns) at the relatively modest energy of 250 keV (see fig. 1). Its $Q_{value} = 18.353\ MeV$ is one of the largest of this family of reactions [7].

Calculation and results

Our calculations concern the $D - {}^3He$ fusion reaction, because of its huge applications in power sources due to their high energy release, such as fusion reactors, (Tokomak), and other small systems like the dense plasma focus devices (DPF).

Clearly, as it is described previously, in order to calculate such hot parameters, i.e., reactivity, reaction rate, and energy emitted of neutrons are all controlled by the cross section, here represents the essential factor in the calculations. A widely used parameterization of fusion reaction cross section is [10]:

$$\boldsymbol{\sigma \approx \sigma_{goem} \times \mathcal{T} \times \mathcal{R}} \qquad (9)$$

Where σ_{goem} is a geometrical cross section, $\mathcal{T}$ is the barrier transparency, and $\mathcal{R}$ is the probability that nuclei come into contact fuse. The first quantity is of the order of the square of the de-Broglie wavelength of the system [10]:

$$\boldsymbol{\sigma_{goem} \approx \lambda^2 = \left(\frac{\hbar}{m_r v}\right)^2 \propto \frac{1}{\epsilon}}, \qquad (10)$$

Where $\hbar$ is the reduced Planck constant and m_r is the reduced mass. Equation (9) concerning the barrier transparency, and its often well approximated by

$$\mathcal{T} \approx \mathcal{T} = \exp\left(-\sqrt[2]{\frac{\epsilon}{\epsilon_G}}\right) \quad (11)$$

Which is known as the Gamow factor (after the scientist who first computed it) [10]: where

$$\epsilon_G = (\pi\alpha_f Z_1 Z_2)2m_r c^2 = 986.1\, Z_1{}^2 Z_2{}^2 A_r \quad keV \quad (12)$$

Is the Gamow energy, $\alpha_f = \frac{e}{\hbar c} = \frac{1}{137.04}$, is the fine structure constant commonly used in quantum mechanics, $A_r = m_r/m_p$

The reaction characteristics $\mathcal{R}$ contains essentially all the nuclear physics of the specific reaction [7]. it takes substantially different values depending on the nature of the interaction characterizing the reaction. It is the largest for reaction due to strong nuclear interactions; it is smaller by several orders of magnitude for electromagnetic nuclear interactions; it is still smaller by as many as 20 orders of magnitude for weak interactions. For most reactions, the variation of $\mathcal{R}(\epsilon)$ is small compared to the strong variation due to the Gamow factor. In conclusion the cross section is often written as

$$\sigma(\epsilon) = \frac{S(\epsilon)}{\epsilon}\ exp\left(-\sqrt[2]{\frac{\epsilon}{\epsilon_G}}\right) \quad (13)$$

Where the function $S(\epsilon)$ is called the astrophysical S factor, which for many important reactions is a weakly varying function of the energy [9]. Plasma reactivity calculations require reaction cross sections for energies well below those at which direct measurement are practicable, so it is necessary to extrapolate downwards using the theoretical formula [10]. A more convents or suitable formula for the calculation of the total cross section for D-T or others main controlled fusion reactions (listed below), which has a compatible agreement results with the really experimental results is given by.

$$D + D \rightarrow T\,(1.011) + P\,(3.022)\ \ probability(50\%)$$
$$D + D \rightarrow He\,(0.820) + n\,(2.449)\ \ probability(50\%)$$
$$P + T \rightarrow {}^3He + n - 0.764$$
$$D + T \rightarrow {}^4He\,(3.561\ MeV) + n\,(14.029\ MeV)$$
$$T + T \rightarrow {}^4He + 2n + 11.332\ MeV$$
$$D + {}^3He \rightarrow {}^4He\,(3.712\ MeV) + P\,(14.641\ MeV)$$
$$T + {}^3He \rightarrow {}^4He + n + P + 12.096\ MeV \quad probability(59\%)$$
$$T + {}^3He \rightarrow {}^4He\,(4.800\ MeV) + D(9.520\ MeV) \quad probability(41\%)$$
$${}^3He + {}^3He \rightarrow {}^4He\,(0.820\ MeV) + 2p + 12.860\ MeV$$

$$\sigma(\epsilon) = \frac{S(\epsilon)}{\epsilon}\ exp\left(-\frac{R}{\sqrt[2]{\in}}\right)\ \ with\ R = \pi\left(\frac{e^2}{\hbar c}\right)\sqrt[2]{2mc^2}\ Z_1 Z_2 \quad (14)$$

Where the cross section is expressed in centre of mass units, $\in = \frac{1}{2}mv^2$, $m = m_1 m_2/(,m_1 + m_2)$ and v is the relative velocity of the interacting particles which have masses $m_1 and\ m_2$ and charges $Z_1 and\ Z_2$ respectively.the constants $e, \hbar\ and\ c$ have their usual meaning. $S(\epsilon) = A\exp(-\beta \in)$ $and\ the\ parameters\ A, \beta\ and\ R$ are given in Table (2). Note that laboratory energies may be used if the substitution $\in = \left(\frac{m}{m_1}\right) \in_{lab}$ [7].

By testing equation 14, for the $D - {}^3He$ fusion reaction and in order to arrive to results which gives high agreement with the corresponding experimental published results, we find that it is very necessary to introduce a correction factor related to each deuterons energy ($\in$) in the above equation, and in this case is completely described in Table (3).

Theoretically, the energy of the emitted protons from the $D - {}^3He$ fusion reaction can be exactly determined from equation (5) as a function of both the incident deuteron energy E_d and the reaction angle θ. The calculated results are completely described in table (4) and completely described in figure (2).

Finally, the reactivity as a function of the temperature, obtained by numerical integration of the following equation with the best available cross section for the reactions of interest to controlled fusion.

$$\langle\sigma v\rangle = \left[\left(\frac{m_1+m_2}{2\pi k_B T}\right)^{3/2} \int dV_c \, exp\left(-\frac{m_1+m_2}{2k_B T}V_c^2\right)\right] \times \left(\left(\frac{m_r}{2\pi k_B T}\right)^{3/2} \int dV_c \, exp\left(-\frac{m_r}{2k_B T}V^2\right)\sigma(v)v\right)$$

The term in square bracket is unity, being the integral of a normalized Maxwellain, and we left the integral over the relative velocity. By writing the volume element in velocity space as $= 4\pi v^2 dv$, and using the definition of center of mass energy ϵ , we finally get

$$\langle\sigma v\rangle = \frac{4\pi}{(2\pi m_r)^{1/2}} \frac{1}{(k_B T)^{3/2}} \int_0^\infty \sigma(\epsilon) \in exp(-\epsilon/k_B T) d$$

For the $D - {}^3He$ fusion reaction, which is by far the most important one for present fusion research, the following expression is used to calculate the reactivity [7]. And the present calculated results are completely described in figure 3.

$$\langle\sigma v\rangle = 4.98 \times 10^{-16} \, exp\left(-0.152 \left|ln \frac{T}{802.6}\right|^{2.65}\right) \quad cm^3/s \qquad (15)$$

Which is 10% accurate for temperature in the range 0.5-100 keV

Discussion and conclusion

Clearly, from the results about the total cross section for the $D - {}^3He$ fusion reaction calculated by equation 14, it appears a common shift from the published experimental results and one can interpret that by some physical reasons that directly correlated with the fundamental parameters deal with the system or device designing, geometrical dimension for the cathode and anode, and the operating factors, such as the fuel pressure, initial power, and we can add another reason which deals with the construction time for building the experiment, in which that any system exactly differs in all covering physical conditions with the recent ones. In other words, it is necessary to give empirical formula for each system (experimental devices). Therefore, we concluded that it is important and necessary to modify the formula for the total cross section for the $D - {}^3He$fusion reaction by introducing a fixed correction factor for certain deuteron energy/or energy intervals to avoid the disagreement between the theoretical and experimental results.

From Table (1) and Table (3), we see that our calculated results about the total reaction cross section, after introducing the correction factors are more compatible with the published results. Also, from Fig. 3, the calculated results about the $D - {}^3He$ fusion reaction reactivity by using equation (15) give or reflect a physical behavior that is more suitable with the corresponding published results, and this case can be interpreted for the reason of the cross section data which are available in the reactivates equation. Finally it's useful to suggest the recommendation of the modified formulas instead of the previously described ones to be applied in the recent systems.

From Table (4), it is clear that the energies of emitted proton, which are calculated by our expressed formula at incident reaction angle of $9O^o$ degree are of quite agreement with the recommended value of (14.029 MeV), and this case can be interpreted as, there exists a small percentage of incident deuterons which are scattered from its original direction, and all the really occurring physical experimental phenomenon can be explained at this angle instead of other angles.

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Table No.(1). Main controlled fusion reactions [7]

Reaction	$\sigma(10\ keV)$ barn	$\sigma(100\ keV)$ barn	σ_{max} barn	ϵ_{max} keV
$D+T \rightarrow \alpha+n$	2.72×10^{-2}	3.43	5.0	64
$D+D \rightarrow T+p$	2.81×10^{-4}	3.3×10^{-2}	0.096	1250
$D+D \rightarrow {}^3He+n$	2.78×10^{-4}	3.7×10^{-2}	0.11	1750
$T+T \rightarrow \alpha+2n$	7.90×10^{-4}	3.4×10^{-2}	0.16	1000
$D+{}^3He \rightarrow \alpha+p$	2.20×10^{-7}	0.1	0.9	250

Table No. (2). Low energy cross section parameterization [7]

Reaction	$A(\ barns-keV)$	$\beta\ (keV^{-1})$	$R\ keV^{1/2})$
$D-D_p$	52.6	-5.8×10^{-3}	31.39
$D-D_n$	52.6	-5.8×10^{-3}	31.39
$D-T$	9821	-2.9×10^{-2}	34.37
$T-T$	175	9.6×10^{-3}	38.41
$D-{}^3He$	5666	-5.1×10^{-3}	68.74
${}^3He-{}^3He$	5500	-5.6×10^{-3}	153.70

Table No.(3): The recommended correction factors necessarily for calculations the D-^{3}He fusion reaction cross section

Deutron Energy keV	Cross section Barn	Deutron Energy keV	Cross section Barn	Deutron Energy keV	Cross section Barn
10	2.162 x10^{-7}	100	9.759 x10^{-2}	190	0.536
20	6.624 x10^{-5}	110	0.128	200	0.608
30	7.801 x10^{-4}	120	0.164	210	0.686
40	3.308 x10^{-3}	130	0.204	220	0.768
50	8.773 x10^{-3}	140	0.249	230	0.856
60	1.794 x10^{-2}	150	0.296	240	0.950
70	3.126 x10^{-2}	160	0.349	250	1.049
80	4.894 x10^{-2}	170	0.407		
90	7.105 x10^{-2}	180	0.469		

Table No.(4): The calculated energy of emitted neutrons as a function of the reaction angle

$\theta = 0\ degree$		$\theta = 45\ degree$		$\theta = 60\ degree$		$\theta = 90\ degree$	
$E_d\ keV$	$E_n\ MeV$	$E_d\ keV$	$E_n\ MeV$	$E_d\ keV$	$E_n\ MeV$	$E_d\ keV$	$E_n\ MeV$
20	15.000	20	14.909	20	14.845	20	14.691
30	15.075	30	14.962	30	14.884	30	14.695
40	15.138	40	15.008	40	14.917	40	14.699
50	15.195	50	15.049	50	14.947	50	14.703
60	15.247	60	15.087	60	14.975	60	14.707
70	15.296	70	15.122	70	15.000	70	14.711
80	15.341	80	15.155	80	15.025	80	14.715
90	15.384	90	15.186	90	15.048	90	14.719
100	15.425	100	15.216	100	15.069	100	14.723

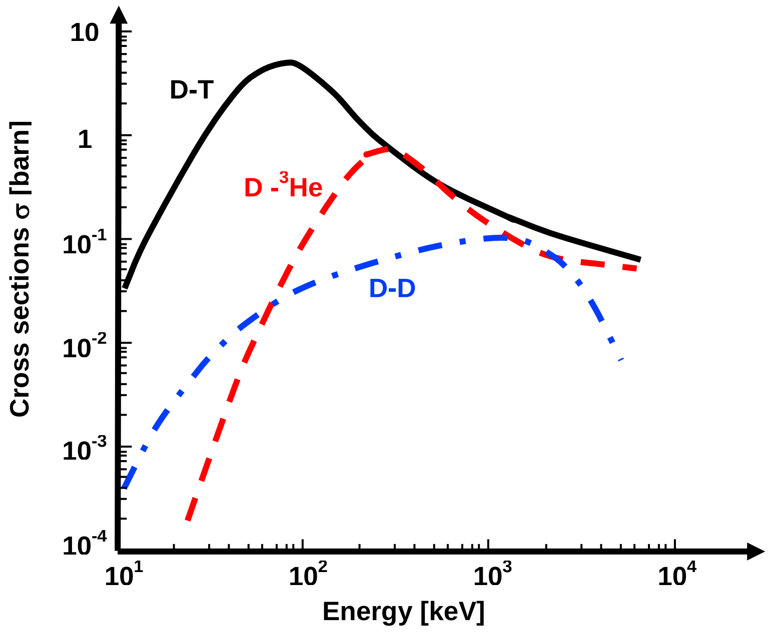

Figure No.(1) : Measured cross sections for different fusion reactions as a function of the averaged centre of mass energy. Reaction cross sections are measured in barn (1 barn= 10^{-28} m^2) [8].

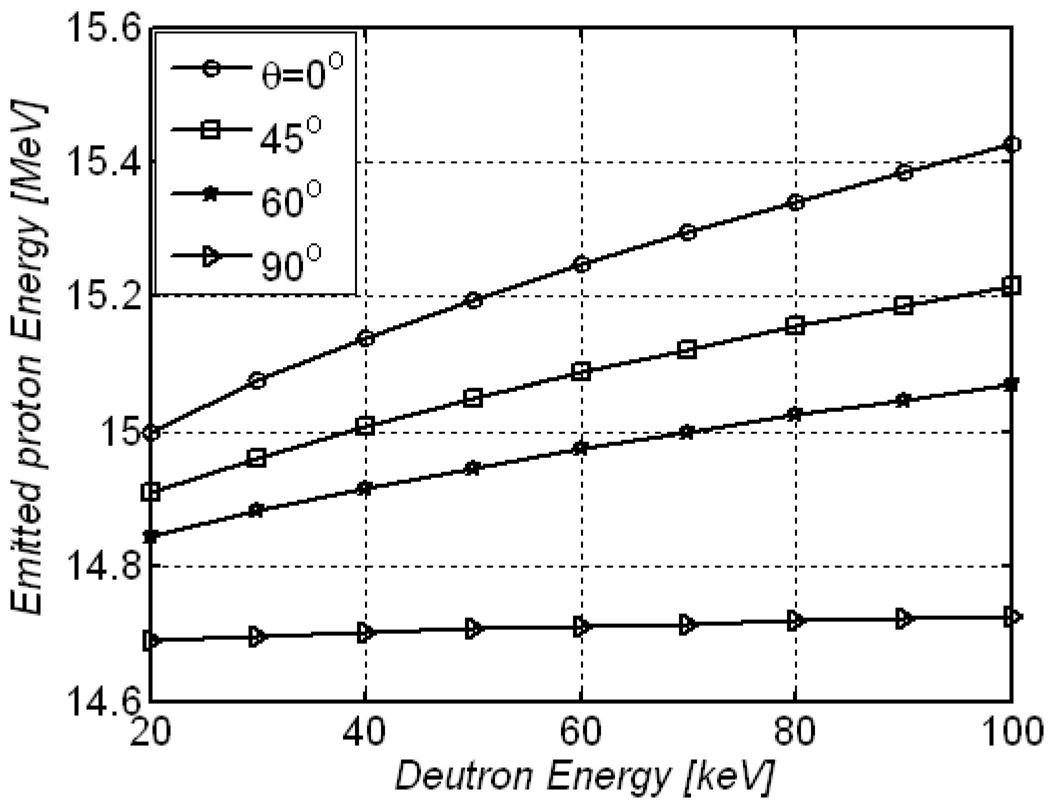

Figure No.(2) : Variation of the emitted proton energy versus the incident deuteron energy

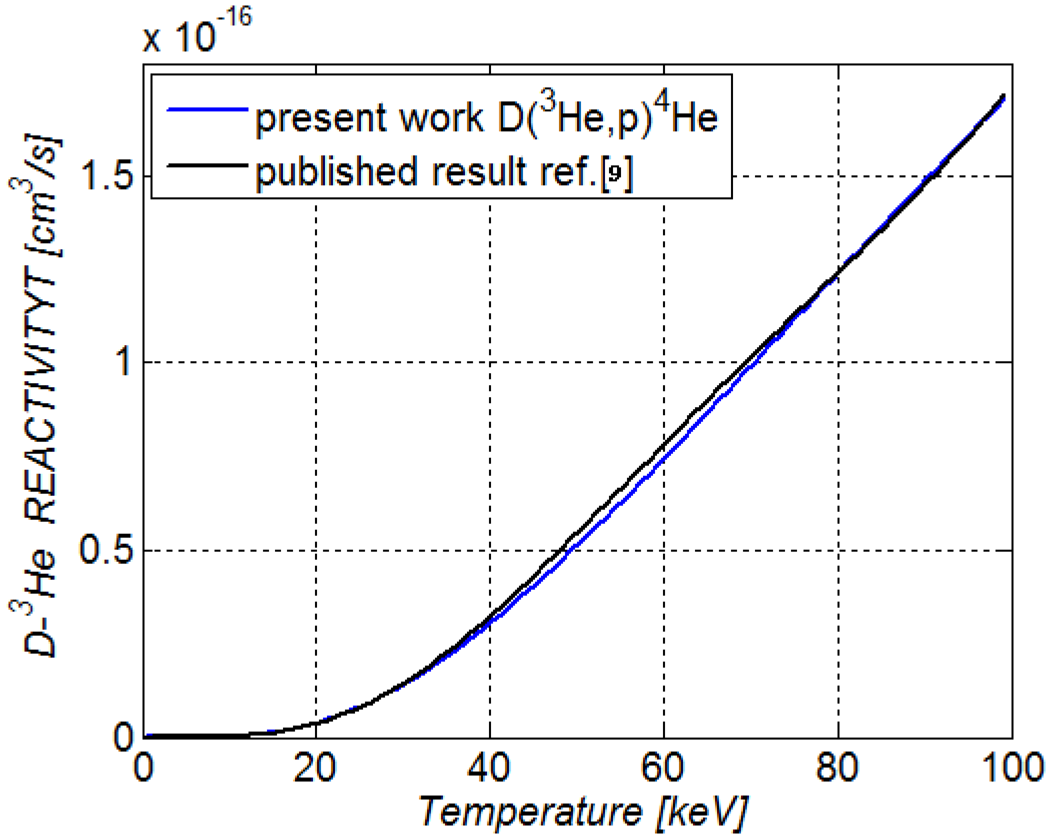

Figure No.(3) : Variation of the D-He Reactivity versus the incident deuteron temperature

المعلمات المميزة للتفاعل النووي الاندماجي نوع $D - {}^3He$

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الخلاصة

يعد التفاعل النووي الاندماجي نوع D-^3He من التفاعلات التجريبية المرغوبة والمفضلة لدى الدول المهتمة بانتاج الطاقة والبحوث العلمية وذلك لكون كلا من الديتريوم والهليوم يعد من المواد المستقره وتفاعلهما الاندماجي ينتج البروتونات وبطاقة تصل الى 14 MeV بدلا من انتاج النيوترونات للتفاعل من نوع D-T ، فضلا عن امكانية درع او حصر البروتون الناتج بوساطة المجال المغناطيسي. الاعتمادية العالية الدرجة لعوامل البلازما الحاره مثل التفاعلية، ومعدل التفاعل، وطاقة البروتونات المنبعثة على المقطع العرضي الكلي للتفاعل النووي الاندماجي تجعل خصوصية بحث او اختيار علاقات تجريبية ملائمة قدر الامكان لهذه المقاطع العرضية ومن ثم امكانية تحويرها نظريا لاجل الوصول الى توافق عال جدا مع نظيرتها العملية المنشورة حديثا، يعد من اهداف البحث الحالي .

الكلمات مفتاحية: التفاعل D-^3He ، التفاعلية ، معدل التفاعل ، طاقة البروتون ، البلازما الحاره ، المقطع العرضي الاندماجي