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Transport Theory of Muonic Atoms in Hydrogen Isotope Media

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Abstract: The resonance muonic molecular formation is highly dependent on the energy of muonic atoms. The energy loss of muonic atoms depends on the range of distance traveled in a medium. The resonance molecular formation rate for μdt is maximum if the kinetic energy of the muonic atoms (such as μt) which enter the D_2 medium is in the range of 0.4-0.6 eV. In this research, the transport theory is used to study the effect of thickness of the suggested multi-layer system (H/T and D_2) on the output kinetic energy of the muonic atoms, μt. The optimum thickness of multi-layer system is also calculated for μdt resonance formation. Finally, the obtained results of the used theoretical method are compared with the experimental results. It is shown that the used transport theory is a good and acceptable theory for studying the transport of muonic atoms in hydrogen isotope media.

Keywords: Transport theory, Muonic atoms, Resonance molecular formation, Thickness layers.

PACS: 36.10.Ee; 72.10.Bg; 31.30.jr.

Introduction

When a negative muon is injected into a hydrogen target, it will slow down and form a small atomic system, muonic deuterium atom, μd or muonic tritium atom, μt, by replacing the electron in the atom. If a muonic deuterium atom, μd, is formed, the muon will be transferred to a tritium atom, due to its deeper Coulomb potential. The muonic tritium atom, μt, will collide with a deuterium molecule and form the muonic molecule μdt. Molecular formation occurs predominantly *via* a resonant mechanism, in which the energy released from the formation of the μdt molecule is absorbed in the rotational and vibrational excitation of the molecular complex [(μdt)dee], where the compact object μdt acts as a pseudonucleus. Because the size of the muonic molecule is smaller than that of ordinary molecules by its mass ratio (m_μ/m_e) in zeroth order, the internuclear distance in μdt is small enough for the fusion to take place within 10^{-12} s; a phenomenon known as muon catalyzed fusion (μCF)[1,2].

The target of a suggested solid heterogeneous multi-layer H/D/T is shown in Fig.1. When a negative muon enters the first layer of hydrogen (H/T) with a small admixture of tritium (concentration ratio, $c_t \approx 0.001$), the muons are initially captured in excited atomic states of muonic hydrogen (μp or μt) in a characteristic time of pico-seconds. The subsequent de-excitation of the muonic atom occurs *via* Stark, Auger, scattering, radiative and transfer processes, which occur on the 100 ps time scale and the μp atom reaches its ground state (1s)[3, 4]. Because of the impurity (of tritium), transfer from the lighter to the heavier isotopes competes with de-excitation to ground state as[5];

$$(\mu p)_n + t \rightarrow (\mu t)_n + p + \frac{183}{n^2}\, eV \qquad (1)$$

where n is an excitation level. Elastic collisions moderate the energy of μt or μd atoms until

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thermal equilibrium is established with the surrounding medium. The muonic atoms have a kinetic energy of about 45 eV, which they subsequently lose *via* elastic collisions, mainly with protium, until they reach 20-30 eV, when the scattering cross-section falls below 10^{-20} cm^2, Fig. 2 [6, 7]. The mean distance between collisions becomes very large, especially at 4-20 eV and the hydrogen layer becomes effectively transparent to the muonic atoms. In all solid muonic hydrogen systems, thermalization at very low energies is inhibited, because the muonic atom interacts elastically with hydrogen "fcc" crystal (a lattice structure), which cannot absorb the kinetic energy efficiently [8]. This effect is due to Ramsauer-Townsend mechanism. Thermalization is much slower and the muonic atoms travel appreciable distances. In a thin solid layer, the μt atoms may escape from the H/T layer into the first D_2 layer with a high probability [9]. Since the size of the μt is almost 9 times larger than the neutron, the transport theory for μt atom in the H/T and D_2 layers is used in this research in the same manner as the neutron interacts on hydrogen media. In the present work, a calculation method is introduced to estimate an appropriate thickness for the targets.

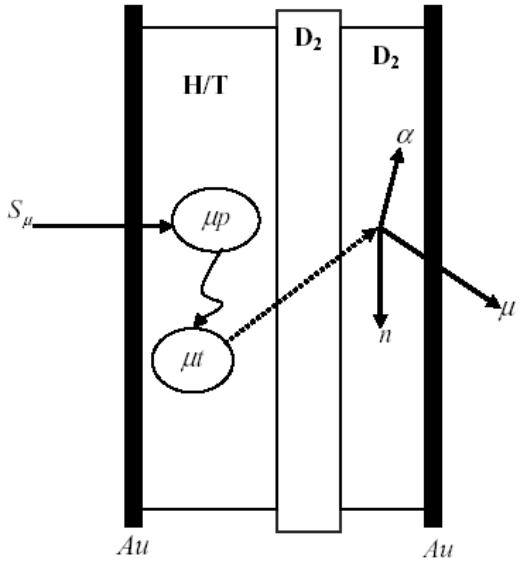

FIG. 1. The design of solid heterogeneous H/D/T mixture.

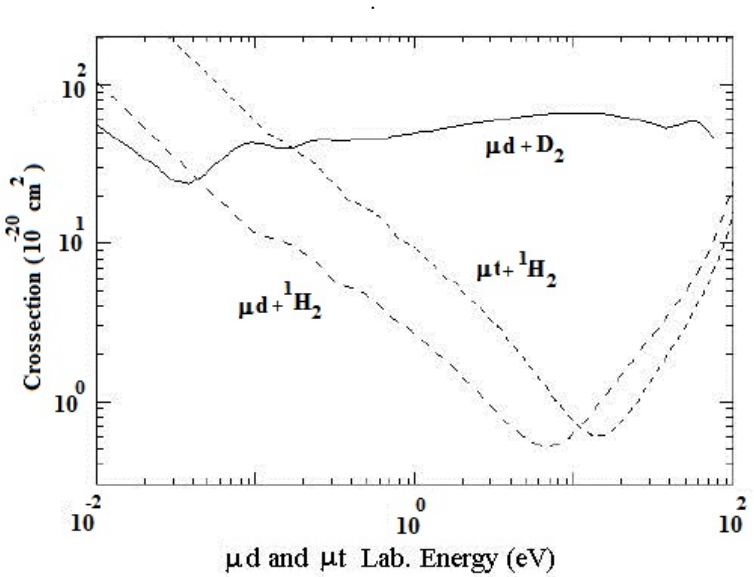

FIG. 2. The elastic scattering cross-section of μt and μd with H_2 and D_2 molecules *versus* lab. kinetic energy [13].

Macroscopic Cross-Section of μt Atoms in Multi-Layer Hydrogen Isotopes

The muonic atom in passing through the H/T layer has elastic and inelastic interactions with the target (protium and tritium). The μt loses its energy mainly by elastic collisions on protons until it reaches an energy range around 10 eV, where by the μt + p scattering, the μt atom either finds the chance to escape into the first D_2 layer (moderation layer) or muonic molecules such as μtt and μpt are formed. The non-resonance formation rate of the muonic molecules is much smaller than the resonance formation rate of complex molecules. Also, the resonance formation rate of these molecules is smaller than the elastic scattering rate of μt in the H/T layer. Hence, the transport equation can be applied for μt in the H/T layer as a weak absorbing medium, with a good approximation [9]. The macroscopic absorption cross-section in the H/T layer can be written as follows:

$$\Sigma_a = \Sigma_{\mu tt} + \Sigma_{\mu pt} \quad (2)$$

$\Sigma_{\mu tt}$ and $\Sigma_{\mu pt}$ are the macroscopic cross-sections. Also, we have:

$$\Sigma_{\mu ij} = \sigma_{\mu ij}\, N \quad (3)$$

where N is the atom density of the projectile therein, $\sigma_{\mu ij}$ is the microscopic cross-section of μij (i and j are hydrogen isotopes) muonic molecular formation. The muonic molecular formation rate of μtj (j is a hydrogen isotope) is given by [10]:

$$\lambda_{\mu tj} = \rho\, v_{\mu t}\, \sigma_{\mu tj} \quad (4)$$

where $v_{\mu t}$ is the relative velocity of μt in the H/T layer and ρ is the density of target. According to classical kinetic energy, ($E_{\mu t} = \frac{1}{2} m_{\mu t} v^2$). Using Eqs. (3) and (4), we have:

$$\Sigma_{\mu tj}(E) = \left(\frac{m_{\mu t}}{2}\right)^{\frac{1}{2}} (E_{\mu t})^{-1/2} \frac{N\, \lambda_{\mu tj}}{\rho} \quad (5)$$

where $m_{\mu t}$ and $E_{\mu t}$ are the mass and kinetic energy of muonic tritium atom, respectively.

Energy Loss theory of μt Atoms in Multi-Layer Hydrogen Isotopes

Suppose that the muonic tritium atom (μt) with a mass of $m_{\mu t}$ and kinetic energy E_1 has an elastic collision with a target at rest (first layer; protium or tritium, mass of m_p in the H/T layer). The kinetic energy of μt after collision E_2 can be written as:

$$E_2 = \frac{1+ A^2+2A\cos\psi}{(1+A)^2}\, E_1 \,. \quad (6)$$

The angle of scattering in the lab., θ, and C. m., Ψ systems are related as follows:

$$cos\theta = \frac{A+cos\,\psi}{(1+A^2+2Acos\psi)^{1/2}} \quad (7)$$

Considering the α parameter as:

$$\alpha = \left(\frac{m_{\mu t}-m_p}{m_{\mu t}+ m_p}\right)^2 = \left(\frac{A-1}{A+1}\right)^2 \quad (8)$$

The energy of μt after collision is:

$$E_1 = \frac{1}{2}[(1+\alpha) + (1-\alpha)cos\Psi] \quad (9)$$

According to Eq. (9), the energy of the muonic atom after collision is dependent on the angle of scattering in the C.m. system. Therefore, the probability of the μt atom with initial energy E_1 to reach E_2 and $E_2 + dE_2$ after collision can be written as:

$$g(E_1 \to E_2)\, dE_2 = P(cos\Psi)d(cos\Psi) \quad (10)$$

The right side of Eq. (10) is the probability that the cosine of the scattering angle be between cosΨ and cosΨ + d cosΨ in the C.m. system. Since the hydrogen medium is a good moderator, it is supposed that the elastic scattering is isotropic in the C.m. system, then we have P(cosΨ) = ½. Hence, we have:

$$g(E_1 \to E_2)\, dE_2 = \frac{1}{2} d(cos\Psi)$$

$$g(E_1 \to E_2) = \frac{1}{2}\frac{d(cos\Psi)}{dE_2} = \frac{1}{(1-\alpha)E_1} \quad (11)$$

The average angle of scattering in the lab. system, $\overline{\cos\theta}$, can be calculated as follows:

$$\overline{cos\theta} = \int_{-1}^{+1} \cos\theta\, P(cos\Psi)d(cos\Psi)$$

$$= \int_{-1}^{+1} \frac{(A+cos\psi)}{2\sqrt{1+A^2+2\alpha cos\Psi}}\, d(cos\psi) = 1 - \frac{2}{3A^2} \quad (12)$$

Therefore, the forward scattering angle for the scattering of the μt atom in the H/T layer in the lab. system is $\overline{\cos\theta}$ = 0.93. The average energy of the μt atom in the interval of one collision, $\overline{E_2}$ can be calculated as:

$$\overline{E_2} = \int_{\alpha E_1}^{E_1} E_2 g(E_1 \to E_2) dE_2 = \int_{\alpha E_1}^{E_1} \frac{E_2 dE_2}{(1-\alpha)E_1} = 0.63E1 \quad (13)$$

The average reduced energy per collision is equal to:

$$\Delta E = \overline{E_1 - E_2} = \frac{(1-\alpha)}{2} E_1 = 0.37E_1 \quad (14)$$

and the average reduced logarithmic energy, ξ is defined by:

$$\xi = \overline{ln\frac{E_1}{E_2}} = 1 + \frac{\alpha}{1+\alpha} ln\alpha \quad (15)$$

For the μt atom in the H/T layer, the transport equation can be written as:

$$\frac{\partial J(\vec{r},E)}{\partial x} + \Sigma_t \Phi(\vec{r},E) = \int_E^{45} \Sigma_s(E' \to E\ \Phi r, E' dE' + Sr, E \quad (16)$$

where J, Φ and S are the current density, flux and power source of μt atom in H/T layer, respectively.

Energy Loss of μt Atoms in the H/T Layer

The flux of muonic atoms in the H/T layer is calculated supposing that the Fick's low is valid in the H/T layer; namely:

$$\vec{J}(\vec{r},E) = -D(E)\vec{\nabla}(\vec{r},E) \quad (17)$$

D(E), Φ($\vec{r}$, E) and $\vec{J}(\vec{r}.E)$ are the diffusion constant, flux and vector current density, respectively. The time-independent transport equation (steady state) is valid in the presence of μt atom in the H/T layer. Hence:

$$\frac{\partial q(\vec{r},u)}{\partial u} + \Sigma_a(u)\Phi(\vec{r},u) - D(u)\nabla^2\Phi(\vec{r},u) = S(\vec{r},u) \quad (18)$$

where $q(\vec{r}.u)$ represents the slowing down density of μt atom in the H/T layer and u is lethargy. According to the definition, we have:

$$u = lu\frac{E_1}{E_2} \quad (19)$$

where E_1 and E_2 are the kinetic energy of the μt atom before and after collision with hydrogen media in the lab. system, respectively.

Since in the H/T layer, the elastic scattering cross-section is larger than the absorption cross-section, the transport equation is valid for the μt atom in passing through the H/T layer. According to Eqs. (2) and (5), the absorption cross-section of the μt atom with protium and tritium can be written as:

$$\Sigma_a(E) = \sqrt{\frac{m_{\mu t}}{2}} \frac{N_t\lambda_{\mu tt} + N_p\lambda_{\mu pt}}{\rho} E_2^{-1/2} \quad (20)$$

The absorption cross-section is dependent on $E_2^{-1/2}$. Hence, we have a suitable solution for the transport equation.

The slowing down density, $q(\vec{r}.u)$, is equal to the resonance escape probability of muonic molecular μtt and μpt formations (P(u)), at lethargy u. Therefore, the number of μt atoms that are absorbed in one cubic centimeter per second to produce μpt and μtt muonic molecules during slowing down to lethargy u is (1-P(u)). For the collision density, ψ(u), we have[11,12]:

$$\Psi(u) = \frac{P(u)}{\xi} = \frac{1-(1-P(u))}{\xi} = \frac{1}{\xi} - \frac{1-P(u)}{\xi} \quad (21)$$

In Eq. 21, the first term describes the collision density for unit power source in non-absorbing media, while the second term is for negative source whit ((1-P(u))) power source, respectively.

In order to calculate P(u), the collision density is written as:

$$\Psi(u) = \frac{1}{\xi} + \int_0^u \frac{dP}{du'} \Psi(u')\, du' \quad (22)$$

$$\Psi(u) = \int_u^{u+ln\frac{1}{\alpha}} \frac{\Sigma_s(u')}{\Sigma_a(u')+\Sigma_s(u')} \Psi(u') \frac{e^{-(u'-u)}}{1-\alpha}\, du' \quad (23)$$

$$q(u) = \int_u^{u+ln\frac{1}{\alpha}} \frac{\Sigma_s(u')}{\Sigma_a(u')+\Sigma_s(u')} \Psi(u') \frac{e^{-(u'-u)}-\alpha}{1-\alpha}\, du' \quad (24)$$

$$\frac{dq(u)}{du} = -\frac{\Sigma_a(u)}{\Sigma_a(u)+\Sigma_s(u)} \Psi(u) \quad (25)$$

The differential integral for the formation of muonic molecules of μpt and μtt, P(u), can be calculated from Eqs. (21) and (23) as follows:

$$\frac{dP(u)}{du} = -\frac{\Sigma_a(u)}{\gamma\Sigma_a(u)+\xi\Sigma_s(u)} P(u)$$

$$P(u) = \exp\left(-\int_0^u \frac{\Sigma_a(u')}{\gamma\Sigma_a(u')+\xi\Sigma_s(u')}\,du'\right)$$

$$= \exp\left(-\int_E^{E_1} \frac{\Sigma_a(E')}{\gamma\Sigma_a(E')+\xi\Sigma_s(E')}\frac{dE'}{E'}\right) \quad (26)$$

where $\gamma = 1 - \frac{\alpha\, ln^2(\frac{1}{\alpha})}{2(1-\alpha)\xi}$.. Using Fig. 2, the elastic scattering cross-section in the region of various energies can be written as follows:

$$\Sigma_{s1}(E) = N_P\sigma_{s1}(E) = 34.2E - 200.53$$

$$10\ eV \le E \le 45\ eV \quad (27)$$

$$\Sigma_{s2}(E) = N_P\sigma_{s2}(E) = -616E - 862.5$$

$$0.5\ eV \le E \le 10\ eV \quad (28)$$

With the use of the previously defined Σ_S and Σ_a, we have:

$$P(u) = \exp(-\Upsilon) \quad (29)$$

where

$$\Upsilon = -\int_E^{45} \frac{\Sigma_a(E')}{\gamma\Sigma_a(E')+\xi\Sigma_s(E')}\frac{dE'}{E'} \quad (30)$$

or

$$\Upsilon = -\int_E^{10} \frac{\Sigma_a(E')}{\gamma\Sigma_a(E')+\xi\Sigma_s(E')}\frac{dE'}{E'} - \int_{10}^{45} \frac{\Sigma_a(E')}{\gamma\Sigma_a(E')+\xi\Sigma_s(E')}\frac{dE'}{E'} \quad (31)$$

In order to find the dependence of the output energy of μt atom on the thickness of the H/T layer, Eqs. (16) and (18) are used and the mean square of the slowing down length, $\overline{r_E^2}$, is calculated [10].

The root-mean-square of the slowing down length, $\sqrt{\overline{r_E^2}}$, is the average distance in which the μt atom with 45 eV kinetic energy slows down to the energy of about 10 eV in the H/T layer. $\overline{r_E^2}$ is defined by:

$$\overline{r_E^2} = \frac{\int r^2\Phi(\vec{r},E)\,d^3r}{\int \Phi(\vec{r},E)d^3r} \quad (32)$$

Using Eq. (18), we can write:

$$\frac{\partial q(\vec{r},u)}{\partial u} = \xi\Sigma_s(u)\,\Phi(\vec{r},u) - q(\vec{r},u) \quad (33)$$

and

$$\Phi(\vec{r},u) = \frac{1}{\xi\Sigma_s}\left[\frac{\partial q(\vec{r},u)}{\partial u} + q(\vec{r},u)\right] \quad (34)$$

Substituting Eqs. (33) and (34) in Eq. (18), we have:

$$\frac{\partial q(\vec{r},u)}{\partial u}\left(1+\frac{\gamma\Sigma_a(u)}{\xi\Sigma_s(u)}\right) + \frac{\gamma\Sigma_a(u)}{\xi\Sigma_s(u)}\,q(\vec{r},u) - \frac{D(u)}{\xi\Sigma_s(u)}\nabla^2\left(\frac{\partial q(\vec{r},u)}{\partial u} + q(\vec{r},u)\right) = S(\vec{r},u) \quad (35)$$

The Fourier transform of the slowing down density can be written as:

$$q(\vec{r},u) = \frac{1}{(2\pi)^3}\int f(\omega,u)\exp(-i\omega r)\,d^3r \quad (36)$$

$$\frac{\partial q(\vec{r},u)}{\partial u} = \frac{1}{(2\pi)^3}\int \frac{\partial f(\omega,u)}{\partial u}\exp(-i\omega r)\,d^3r \quad (37)$$

$$S(\vec{r},u) = S(\vec{r})S(u) = \delta(\vec{r})\delta(u) \quad (38)$$

$$\delta(\vec{r}) = \frac{1}{(2\pi)^3}\int \exp(-i\omega r)\,d^3r \quad (39)$$

$$\nabla^2 q(\vec{r},u) = \frac{1}{(2\pi)^3}\int(-\omega^2)f(\omega,u)\exp(-i\omega r)\,d^3r \quad (40)$$

Substituting Eqs.(36)-(39) in Eq. (35), we get:

$$\frac{\partial f(\omega,u)}{\partial u}\left[\left(\frac{\xi\Sigma_s(u)+\gamma\Sigma_a(u)}{\xi\Sigma_s(u)}\right) + \frac{D(u)\omega^2}{\xi\Sigma_s(u)}\right] + f(\omega,u)\left[\frac{\gamma\Sigma_a(u)+D(u)\omega^2}{\xi\Sigma_s(u)}\right] = \delta(u) \quad (41)$$

then:

$$f(\omega,u) = f(\omega,u=0)\exp\left(-\int \frac{\gamma\Sigma_a(u') + D(u')\omega^2}{\xi\Sigma_s(u') + \gamma\Sigma_a(u') + \omega^2 D(u')}\,du'\right) \quad (42)$$

$$f(\omega,u=0) = \left[\frac{\gamma\Sigma_a(u)+\gamma\Sigma_a(u)}{\xi\Sigma_s(u)+\gamma\Sigma_a(u)+\omega^2 D(u)}\right]_{u=0} \quad (43)$$

By expanding f(ω,u) in terms of ω^2, we derive $\overline{r_E^2}$ for the μt atom in the H/T layer. Thus we have:

$$f(\omega,u) = \sum_{s=0}\frac{(-1)^s}{(2s+1)!}r_E^{2s}\omega^{2s} = 1 - \frac{1}{6}r_E^2\omega^2 + \frac{1}{120}\,r_E^4\omega^4 - \cdots \quad (44)$$

$$\frac{1}{6}\overline{r_E^2} = -\left(\frac{\partial f(\omega,u)}{\partial\omega^2}\right)_{\omega=0} \quad (45)$$

Differentiating Eq. (44) with respect to ω^2, we obtain:

$$\frac{1}{6}\overline{r_E^2} = \frac{1}{3(\gamma\Sigma_a(E_1)+\xi\Sigma_s(E_1))^2} + \int_E^{45} \frac{\xi\Sigma_s(E')}{(\gamma\Sigma_a(E')+\xi\Sigma_s(E'))^3}\frac{dE'}{E'} \times \exp -E>1045 \quad \Sigma aE'\gamma\Sigma aE'+\xi\Sigma s1E'dE'E'-E<1010\,\Sigma aE'\gamma\Sigma s2E'dE'E' \quad (46)$$

where γ and ξ parameters are constant. Knowing the energy variation of Σ_a and Σ_s, the integral of Eq.(46) is determined. Hence, the effective thickness of the layer becomes:

$$x_{rms} = \sqrt{\overline{x_E^2}} = \sqrt{\overline{r_E^2}}\ \overline{\cos\theta} \quad (47)$$

The calculated values of effective thickness of the H/T layer, x_{rms}, *versus* the laboratory kinetic energy of μt are shown in Fig. 3. The only experimental value shown in Fig. 3 is in good agreement with the calculated values.

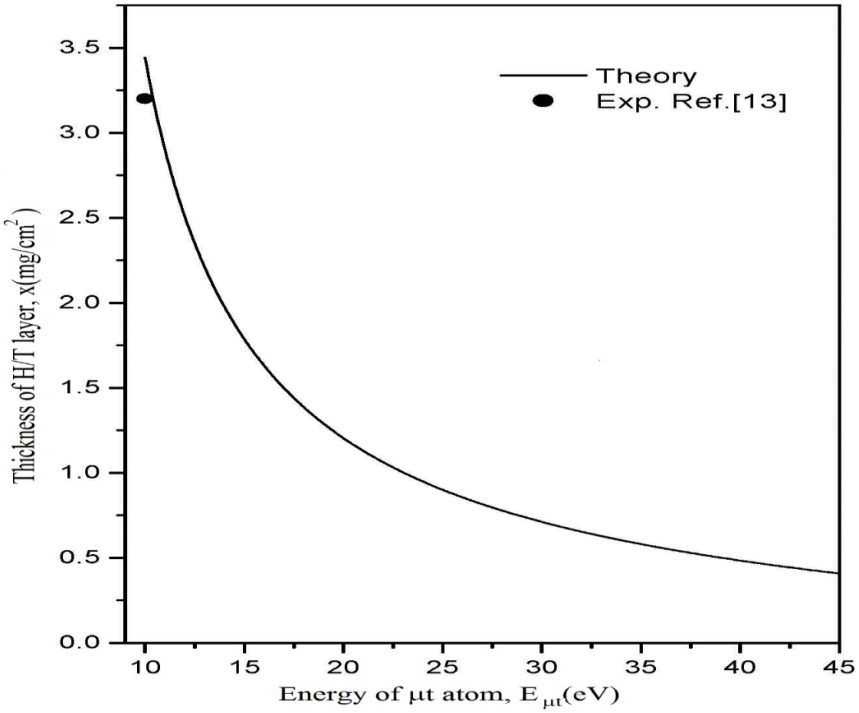

FIG. 3. Thickness of H/T layer for various output energies of μt atom in lab. system.

Energy Loss of μt Atoms in D_2 Layer

The transport conditions of μt atom in the first D_2 layer will be studied in the second stage and the mean-square-length in which the muonic atom slows down from 10 eV to 0.5 eV can be calculated by transport theory. Consequently, the optimum thickness of the first D_2 layer will be determined for the resonance formation of the muonic molecule.

The non-resonance formation rate of muonic molecule μdt is much smaller than the resonance molecular formation rate. Hence, in this calculation, the non-resonance molecular formation rates are ignored. The first layer of D_2 acts as a moderator and the mean kinetic energy of the μt atom arriving at the second D_2 layer depends on the thickness of the first D_2 layer. The angular scattering distribution of the μt atoms after collision in the lab. system is determined by Eq. (12) as; $\overline{\cos\theta} = 0.322$. The kinetic energy of the μt atom per collision can be calculated by Eq. (13) as; $\overline{E_2} = 0.661E_1$. Also, the average reduced logarithmic energy, ξ, and γ in the D_2 layer are 0.754 and 0.8636, respectively. Since the μt atoms collide only elastically with the D_2 molecules, then $\Sigma_a \approx 0$; therefore, we write the transport equation as:

$$\frac{\partial q(\vec{r},u)}{\partial u} - \frac{D(u)}{\xi\Sigma_s(u)}\nabla^2\left(\frac{\partial q(\vec{r},u)}{\partial u}\right) = S(\vec{r},u) \quad (48)$$

The elastic scattering cross-section of μt atom with the D_2 molecules in the energy region 0.5 eV - 10 eV is almost constant (Σ_s=0.1 cm^{-1}) [5, 12].

Using Fourier transform, slowing down density is calculated and the mean-square-length of slowing down from 10 eV to 0.5 eV is calculated by:

$$\frac{1}{6}\overline{r_E^2} = -\left(\frac{\partial f(\omega,u)}{\partial \omega^2}\right)_{\omega=0} = \frac{1}{\xi_s \Sigma_s^2}\ln\frac{10}{E} \qquad (49)$$

and

$$r_{rms} = \sqrt{\overline{r_E^2}} = \sqrt{\frac{2}{\xi_s \Sigma_s^2}\, ln\frac{10}{E}} \qquad (50)$$

$$x_{rms} = r_{rms}\ \overline{\cos\theta} = 0.33\sqrt{\frac{2}{\xi_s \Sigma_s^2}\, ln\frac{10}{E}} \qquad (51)$$

The calculated theoretical values of the mean kinetic energy of μt atoms in the lab. system arriving at the various thicknesses of the first D_2 layer are shown in Fig. 4 and are compared with the available experimental values. It is shown that the transport theory is an acceptable method for studying the transport theory of muonic atoms in hydrogen isotope media in low energy limit. It seems that the difference between the theoretical and the experimental data, in high energy limit, is due to consideration of the approximate method for cross-section calculation.

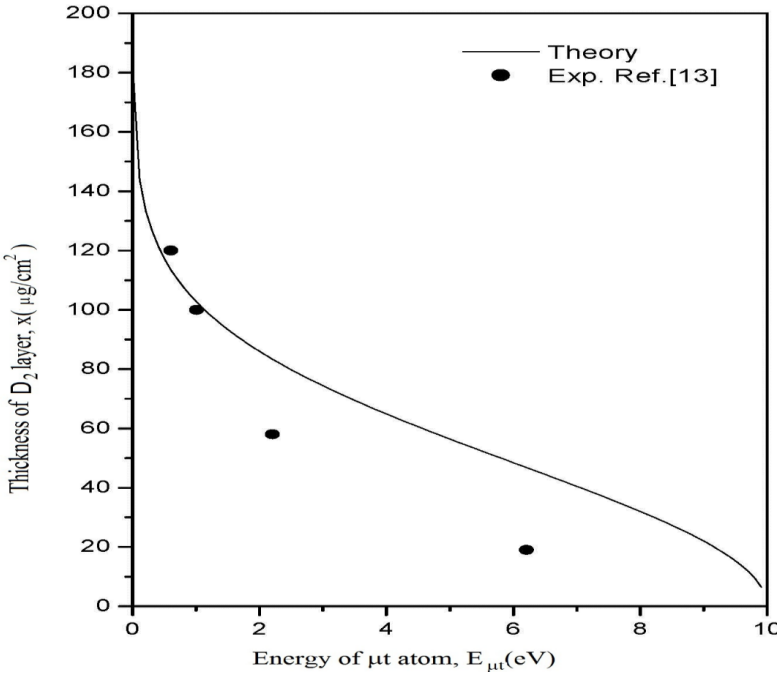

FIG. 4. Dependence of the thickness of D_2 layer on the output energy of μt atom in Lab. system.

Results of Calculations and Discussion

The results of this study using the transport theory and available experimental values are shown in Figs. 3 and 4. The comparison shows an acceptable agreement between our method and available experimental values at low energies (E < 1 eV). For high energies (E > 1 eV), there are discrepancies which may occur due to the limitations of the media. These limitations include; non-resonance formation rate, absorption cross-section for H/T layer, motion of the target nucleus and energy dependence of elastic scattering cross-section for the first D_2 layer, which is ignored. If the thicknesses of H/T and D_2 layers are selected to be ~ 3.2 mg/cm^2 and 0.1 mg/cm^2 for the suggested system (heterogeneous solid H/D/T mixture), respectively, the μdt molecule formation in the second D_2 layer (reaction layer) is in resonance. This study shows that the theoretical method is good and acceptable for the use of transport theory of muonic atoms in hydrogen isotope media.

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