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Laser Enhancement of Resonance [dtμ,d2e]*([ddμ,d2e]*) Formation†

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Abstract

The enhancement of resonance molecular formation rates of [dtμ,d2e] and [ddμ,d2e] by strong laser irradiation have been studied. The formation rates decrease until the laser intensity reaches the order of $10^8 \approx 10^9$ W/cm^2, and they increase substantially for the intensity range of 10^{10} W/cm^2 $\approx 10^{11}$ W/cm^2. The [dtμ,d2e] formation rate using the angular frequency laser such as 11.4×10^{13} rad/sec becomes 4×10^{10} 1/sec for the laser intensity of 3×10^{10} W/cm^2. Further increase of laser intensity reduces the formation rate due to the mismatch of the resonance condition.

The formation rate is very sensitive to the frequency of the laser and the formation rate of [ddμ,d2e] becomes comparable with one of [dtμ,d2e] for the cases of $w = 22.8 \times 10^{13}$ rad/sec. For the case of dt initial molecule, there is the possibility of enhancing the formation rate by exciting the vibrational motion by laser field.

Introduction

The number of fusions catalyzed by one muon depends on the formation rate of the muonic molecule. The fast resonance formation rate for the $dt\mu$ molecule due to shallow bind energy of (v=1, J=1) state produces more than 140 fusions per one muon for liquid hydrogen density dt mixture.(1,2,3) The formation rate of the $dt\mu$ molecule is very sensitive to the vibrational and rotational level difference between $[D_2]$ and $[(dt\mu)d2e]$ molecules.(4,5) The density effect of the normalized reaction rate has been studied by the resonance broadening due to collisional quenching.(6,7,8) The resonance formation rate can be enhanced by using the strong laser beam. In this paper, the formation rate under the high intensity laser irradiation is calculated by using the Vinitskii's model(4) and by treating the laser as the classical electric field.(9)

Applying the laser to the $t\mu$ - dd (or dt) system, the kinetic part of the Hamiltonian $\frac{1}{2m_i} P_i^2$ is replaced by $\frac{1}{2m_i} (P_i + \frac{e_i}{c} A)^2$, where A is the vector potential corresponding to the laser field. The terms come from this Hamiltonian $\frac{1}{2m_i} \frac{e_i^2}{c^2} A^2$ can be neglected, because they change only the phase of the wave function. By using the coordinate system as shown in Figure 1, the interaction terms between laser the $t\mu$ - dd system can be expressed as

$$H_{Ai} = -\frac{e}{c} A \left[\frac{P_a}{m_a} \quad \frac{P_b(m_3 - m_4)}{m_b} - \frac{P_c}{m_c}\right] \tag{1}$$

In Eq. (1), Pa, Pb, and Pc are momenta associated with coordinates r_a, r_b, and r_c with the following reduced masses:

$$\frac{1}{m_a} = \frac{1}{m_1} + \frac{1}{m_2}, \quad \frac{1}{m_b} = \frac{1}{m_3} + \frac{1}{m_4}, \quad \frac{1}{m_c} = \frac{1}{(m_1 + m_2)} + \frac{1}{(m_3 + m_4)} \tag{2}$$

The first term of Eq. (1) is the interaction of the laser with the relative motion of the μt atom and it can be neglected in our consideration. The excitation energy of the muon in the μt atom is of the keV order and is very high compared with the interaction energy for the laser field which is studied in this paper. Therefore, a motion of μ is not affected by this interaction. The second term of Eq. (1) expresses the one for the relative motion of third (d) and fourth (d or t) particles. When the fourth particle is deuteron nuclei, this term vanishes. The third term expresses the interaction for relative motion of the $t\mu$ atom and dd (or dt) nuclei. This affects the wave function of the translational motion of the D_2 molecules. As studied by Leon,[10] the initial wave function has the wave function expressing the translational motion of d_2 nuclei relative to the $t\mu$ atom. From this wave function, he derived the effect of molecular rotation on the molecular formation rates.

In the same way, we can derive the initial wave function which expresses the translation motion under laser irradiation, but here only the time dependent part of the initial wave function of relative motion ($t\mu$) - (dd) system due to laser interaction is considered and the effect on the molecular rotation is neglected to simplify the discussion. Thus the wave function of exh $[i \frac{e}{c} \frac{P_c}{m_c} \int_{-\infty}^{t} A(t')dt']$ is inserted into the initial wave function used by the Vinisky et al. calculation. By using the vector field of $A(t)$ as $A_0 \cos \omega t$ the wave function is expressed as

$$\text{exh}\ [i \frac{e}{c} \frac{P_c}{m_c} \frac{A_o}{\omega} \sin \omega t] = \sum_{n=-\infty}^{\infty} J_n (\frac{e}{c} \frac{P_c}{m_c} \frac{A_o}{\omega})\ e^{in\omega t} \tag{3}$$

We get the formation rate as

$$\lambda[\sec^{-1}] = \beta \frac{8\pi^2}{3} (N_0 a_0{}^3) (\frac{m_e}{m_\mu})^5 (\frac{m_\mu}{m_a})^3 |d_{fi}|^2 \frac{m_c e^4}{\mu^3}$$

$$\sum_{\nu} \sum_{n} I_{\nu}^2 \frac{1}{2} \int_{-1}^{1} d\mu \left| J_n (\frac{e}{h\omega^2} \sqrt{\frac{8\pi\varepsilon I}{md_2}}\ \mu) \right|^2 \gamma (\varepsilon_{on}, \varepsilon_T)$$

where

$$\varepsilon_{on} = \varepsilon_{11} + \varepsilon_{\nu} - \varepsilon_0 + n\omega \tag{4}$$

In Eq. (4) I and ω are, respectively, the laser intensity in units of (Watt/ cm^2) and angular frequency in units of (rad/sec), and m_{d2} is the mass of d_2 nuclei. The other nomenclatures are the same as defined in Ref. (4).

When the laser field is applied to the $t\mu$-D_2 (or $d\mu$-D_2) mixture, the resonance energy deficit of $\varepsilon_{11} + E_\nu - E_0$ can be reduced to near zero by multiphoton (n) deexcitation in order to get the high formation rate. The factor of $J_n^{\ 2}\left(\frac{e}{h\omega^2}\sqrt{\frac{8\pi\varepsilon_o nI}{m_{d2}}}\ \mu\right)$ in Eq. (4) determines the laser intensity required to produce the n-th multiphoton deexcitation mode, and the factor for $n \neq 0$ is very small for the small argument value. Thus, for the small laser intensity, only the n=0 component contributes to the formation. Different from the enhancement of formation rates by three body interaction or collisional quenching, this laser enhancement can produce the energy balance with a lower vibrational frequency of [dtμ,d2e] molecules than the nonlaser formation. The integral of I_ν with lower ν is larger than the one with higher ν. Therefore, the formation rates increase substantially in the laser intensities of the order of 10^{10} W/cm^2 which creates the energy balance with the low ν vibration mode as shown in the figures 2 and 3.

Figures 2 and 3 show respectively the dtμ and ddμ formation rates as a function of laser intensity for $\varepsilon_T = 0.025$ eV, and $\omega = 7.6 \times 10^3$ rad/sec 22.8×10^{13} rad/sec. The parameters used in this calculation are taken from Ref. (4), and the maximum number of $|n|$ is taken as 10. Both dtμ and ddμ formation rates do not change until the laser intensity I reaches 10^5 W/cm^2. In the ranges of $I = 10^5 \sim 10^8$ (or 10^9) W/cm^2, the only term of n=0 is appreciable contribution and the formation rates decrease due to the fact that the value of $|J_0(x)|^2$ becomes smaller than $|J_0(0)|^2$ in the range of $0<x<2$. Increasing the intensity to the range of 10^9 W/cm^2 - 10^{11} W/cm^2 the formation rate increases substantially due to the contribution of low ν vibrational mode. For the (dtμ) case, the rate becomes 4×10^{10} 1/sec for $I = 3 \times 10^{10}$ W/cm^2, and $\omega = 11.4 \times 10^{13}$ rad/sec and 19.0×10^{13} rad/sec. In this study we did not search for the most effective frequency value (ω) which can maximize the formation rates. The formation rate of (dtμ) for both frequency lasers of $\omega = 7.6 \times 10^{13}$ rad/sec and 11.4×10^{13} rad/sec are higher than the (ddμ) formation rate, so that the muon catalyzed fusion mostly occurs through (dtμ) formation. The wrong choice of frequency $\omega = 22.8 \times 10^{13}$ rad/sec gives a comparable rate of (ddμ) molecular formation as the (ddμ) one. Further increases of laser intensity reduce the formation rate because resonance matching does not occur by the large n valued multiphoton process even for low r vibration mode.

So far, we have discussed the case of (dtμ) formation rate through the [dtμ,d2e) molecule. When this formation occurs through [dtμ,t2e] molecule due to the nonzero interaction of the dt (fourth particle is triton) relative coordinate r_b with laser, the vibrational mode of the initial dt molecule can be excited by the laser from the ground state to the excited (ν') states. Therefore, the integral of I_ν used in Viniski's paper(4) is replaced by the integral

$$\int \phi_\nu(\rho)\phi_{\nu'}(\rho,A)\,\frac{1}{\rho^2}\,d\rho = I_{\nu\nu'}\,(A) \tag{3}$$

and the value of $I_{\nu\nu'}(A)$ for some $\nu' \approx \nu$ becomes larger than the value of I_ν, so that there is the possibility of increasing the formation rate using dt molecules. The function of $\phi_\nu'(\rho,A)$ in Eq. (3) can be determined by solving the Schrodinger equation of

$$i h \frac{\partial\phi(r_b)}{\partial t} = \left[\frac{1}{2m_b}\nabla^2 + \bar{U}(r_b) + \frac{h\bar{A}(r,t)\bar{\nabla}}{2m_b}\right]\phi(r_b) \tag{4}$$

where $\bar{U}(r_b)$ is a potential function for the dt molecule. This possibility will be discussed in a future study.

In this paper, we treated the laser field as the classical field with a single frequency, assuming that the laser is completely coherent. This is too idealistic, and the real laser has some band width and the envelope function of A depends on the position and time. Therefore, the formulation requires more elaborate study, and some experimental analysis will be required for studying the real effect of the laser on the formation rates.

Back decay [11] from the molecular formed state and the electron screening effect which is neglected in this calculation should also be studied. As shown in Figures 2 and 3, the laser intensity required to enhance the formation rate is very high, but the energy required for this formation is a product of intensity and the formation time ($1/\lambda$). For the case of $\omega = 11.4 \times 10^{13}$ rad/sec, intensity $I = 3 \times 10^{10}$ W/cm^2, this energy becomes on the order of 1 Joule/cm^2, which is not so large. Due to the very high molecular formation rate, the mixture density can be reduced far below from the liquid hydrogen density to low gas density, which is suitable for the engineering design for energy production.[12,13,14,15]

Conclusion

This study shows that the high intensity laser of 10^{10} W/cm^2 ≈ 10^{11} W/cm^2 with angular frequencies of 11.4×10^{13} rad/sec and $19. \times 10^{13}$ rad/sec can enhance the resonance formation rate of the dtμ molecule from 10^8 rad/sec to 3 ~4 x 10^{10} rad/sec which is a substantial increase. This is very sensitive to the frequency of the laser and the most effective frequency for getting the maximum molecular formation rate was not searched in this paper. There is also the possibility of a way of enhancing the formation rate for the initial (dt) molecule. In this paper, we study only the positive effect of the laser irradiation, but the laser also enhances the back decay, and the screening effect of the electrons in D_2 and DT molecules. These effects should be studied in future work.

For the study of muon catalyzed fusion physics, the sudden enhancement of the (dtμ) rate in the muon cycle by applying the strong laser can provide useful information by taking the time correlation between the laser signal and the other detector signal such as neutron or X-ray data. It is worthwhile to pursue the study of using the laser field in the muon catalyzed fusion process.[16]

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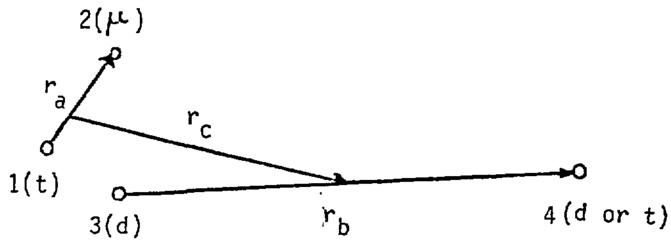

Figure 1 Relative coordinate of [(μt)(dd)] ([(μt)(dt)]) system. [t = 1, μ = 2, d = 3, d (or t) = 4].

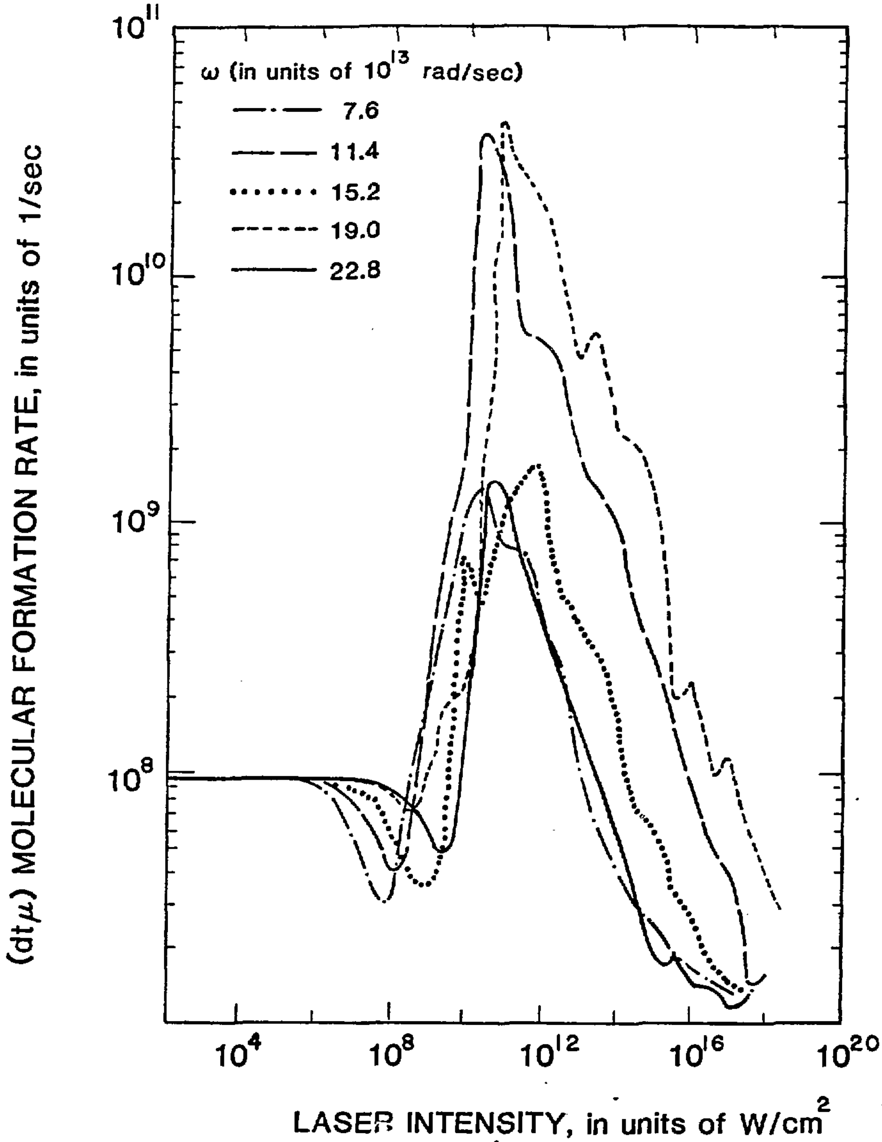

Figure 2 Molecular formation rate of (dtμ) as the function of laser intensities with the angular frequencies of $\omega = 7.6 \times 10^{13}$ rad/sec to 22.8×10^{13} rad/sec.

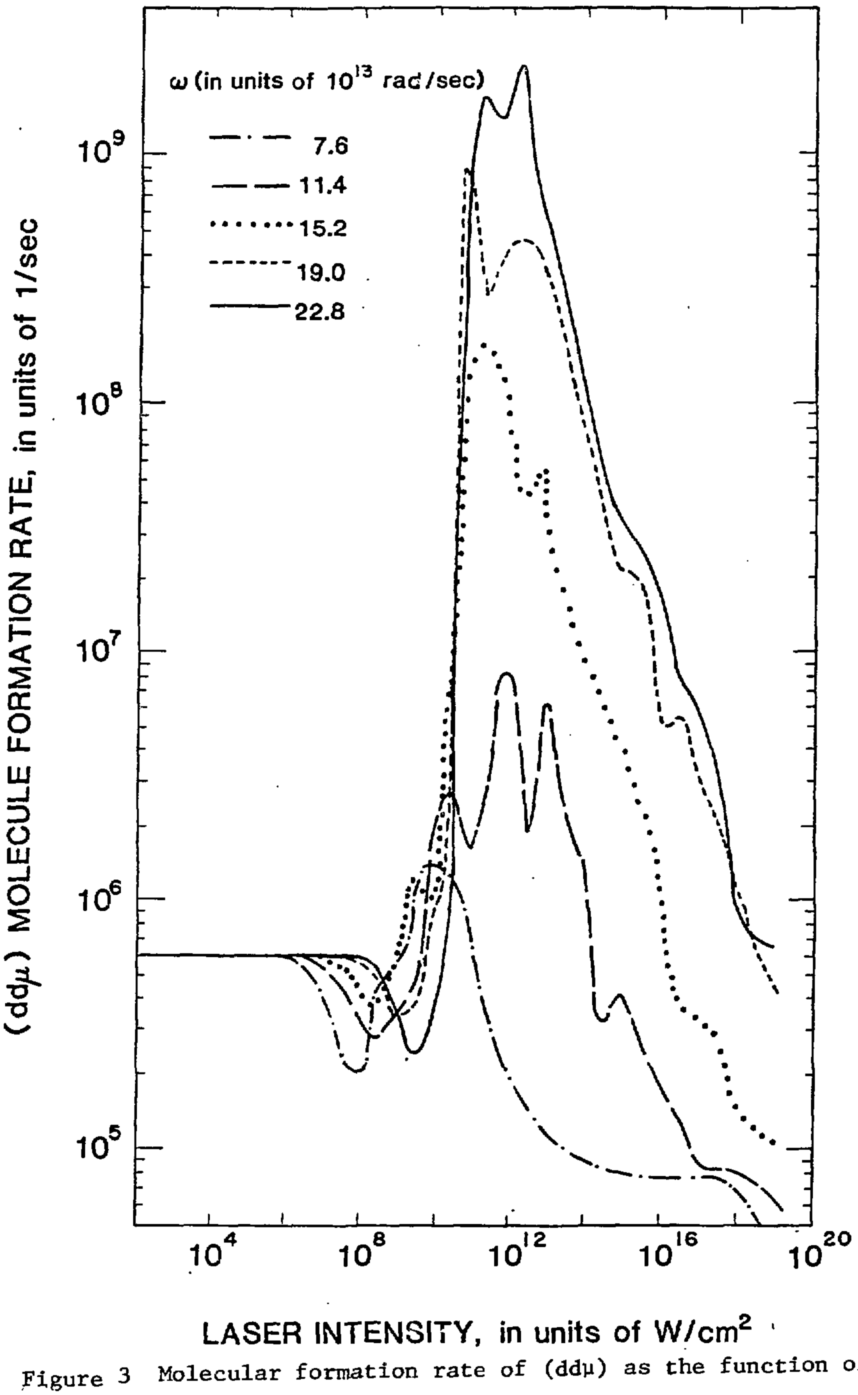

Figure 3 Molecular formation rate of (ddμ) as the function of laser intensities with the angular frequencies of $\omega = 5.7 \times 10^{13}$ rad/sec to 22.8×10^{13} rad/sec.