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Nuclear Fusion Induced by Coulomb-Hydrodynamic Explosion of Deuterium Clusters in Intense Laser Pulses*

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Considering the Coulomb-hydrodynamic explosion induced by the interaction of a deuterium cluster target with an ultra-intensity femtosecond laser, we analyse the mechanism of generating energetic deuterium nuclei for the fusion. We propose formulae for expansions of deuterium ion cluster which are driven by Coulomb-hydrodynamic explosion. Hence the kinetic energies of deuterium nuclei, the expansion time and exploding efficiency of deuterium ion cluster have been estimated.

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The rapid development of laser technologies has given widespread access to lasers with high intensity and short pulses. This opens the door to new areas of research in many fields of physics and, of course, also in cluster physics.[1−6] Irradiating clusters by intense laser pulses may lead to exceptionally large energy deposits which produce at once a hot and dense plasma state. This, in turn, can generate keV electrons,[7] as well as x-rays in the keV range.[8] Perhaps the most remarkable is the discovery that these large clusters, when irradiated at intensities above 10^{15} W/cm^2, eject ions with substantial kinetic energy; ions with energy as high as 1 MeV have been seen from exploding Xe clusters.[1,9] These fast ions with large kinetic energies can efficiently overcome the Coulomb repulsive barrier and drive nuclear fusion if deuterium clusters are irradiated by such a high-intensity femtosecond laser. Recently, Ditmire *et al.* have observed such fusion reactions in deuterium clusters (an average cluster diameter of $\sim$ 50 Å), which are irradiated by a table-top laser producing 120 mJ of laser energy in pulses with 35-fs pulse width, wavelength of 820 nm and an estimated peak intensity of 2×10^{16} W/cm^2.[10] In this Letter, we analyse the ionization process of the deuterium cluster in a strong laser field ($I \sim 2\times10^{16}$ W/cm^2, $\tau \sim 35$ fs, $\lambda \sim 820$ nm), and propose a mechanism that deuterium clusters undergo an ordinal Coulomb-hydrodynamic expansion process, in which Coulomb explosion closely follows hydrodynamic expansion, providing a source of high-energy deuterium ion to induce DD nuclear fusion.

As some deuterium clusters ($R = 25$ Å) are irradiated with the intense laser pulse ($I \sim 2\times10^{16}$ W/cm^2, $\tau \sim 35$ fs, $\lambda \sim 820$ nm), deuterium atoms in the cluster can be stripped of almost all their bound electrons by the laser pulse due to the deuteron electrostatic barrier suppression mechanism,[11] which generates plasma inside the cluster. Subsequently, every unbound electron inside the cluster obtains the ponderomotive potential of the laser. One knows that the ponderomotive potential is [11]

$$U_{\rm pond}({\rm eV}) = 9.33\times10^{-14}(1+\alpha^2)I\lambda^2, \qquad (1)$$

where $I = 2\times10^{16}$ w/cm^2, $\lambda = 0.82\,\mu$m, and $\alpha = 1$ for circularly polarized light, and then $U_{\rm pond} = 2.51$ keV. Hence the electron gains the tantamount kinetic energy. Let us now consider an ion which is located on the surface of the deuterium ion cluster sphere with a uniform density; its Coulomb repulsive energy is [12]

$$U_c = \frac{4\pi}{3}B\rho R^2, \qquad (2)$$

where ρ (in Å^{-3}) is the uniform atomic density, R in units of Å is the deuterium cluster radius and $B = 14.4$ eV·Å (when $R = 25$ Å and $\rho = 3\times10^{-2}$/Å^3, then $U_c = 1.1$ keV).

On the other hand, the mean free path of the unbound electrons with kinetic energy inside the deuterium cluster is given by the Spitzer formula:[13] $\lambda_e = (k_BT_e)^2/[4\pi n_e(Z+1)e^4\ln\Lambda]$. We can estimate the mean free path λ_e to be three orders of magnitude larger than the deuterium cluster size ($2R = 50$ Å) for $k_BT_e = 2.51$ keV, $n_e = 3\times10^{28}$/m^3, and $\ln\Lambda = 20$, if we assume $k_BT_e = U_{\rm pond}$. In this case, electrons can freely escape out the cluster surface in a very short time due to $U_{\rm pond} > U_c$. While moving inside the cluster, heated electrons expand and pull cold ions outward with them. Hydrodynamic expansion is generated in the cluster, and the characteristic speed for hydrodynamic expansion is the ion sound speed:[14]

$$C_s = (\gamma k_BT_e/m_i)^{1/2}, \qquad (3)$$

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where m_i is the ion mass, and γ is the specific heat ratio. The average sound energy density in the D^+ ion cluster is

$$\varepsilon = p^2/(\rho_0 C_s^2), \quad (4)$$

where ρ_0 is the cluster mass density and $p = n_i k_B T_e$ is the sound pressure. From Eqs. (3) and (4), we can obtain the following formula for the energy per ion in the sound wave:

$$E_s = k_B T_e/\gamma. \quad (5)$$

Because the time for electrons to escape from the cluster is very short, the time and size of the hydrodynamic expansion can be neglected, while the ion energy E_s gained from hydrodynamic expansion is considerable. When taking $k_B T_e = 2.51\,\mathrm{keV}$, $\gamma = 5/3$, then the D^+ ion sound energy is $E_s = 1.51\,\mathrm{keV}$. After electrons escape out the cluster surface, the space-charge distribution is built up in the cluster and the Coulomb energy U_c of the ion at the cluster surface is described by Eq. (2). At this moment the total energy per D^+ ion at the surface is described by

$$E_{\mathrm{tot}} = E_s + U_c. \quad (6)$$

Taking $I = 2 \times 10^{16}\,\mathrm{W/cm^2}$, $\lambda = 820\,\mathrm{nm}$, $\rho = 3 \times 10^{-2}/\mathrm{Å}^3$ and $R = 25\,\mathrm{Å}$ in Eqs. (2), (5) and (6), we can obtain $E_{\mathrm{tot}} = 2.6\,\mathrm{keV}$. This is close to the result (2.5 keV) in Ref. [9]. The escape of these hot electrons from the cluster produces a strong radial electric field which accelerates ions in the cluster, and the deposited energy is therefore transferred from the light electrons to the more massive ions.[15] The total energy per D^+ ion is ultimately released to the ion kinetic energy during the cluster expansion, and multi-keV ions have sufficient energy to drive fusion events.[10] As mentioned previously, $E_s \propto I$, and $U_c \propto R^2$; consequently, we can increase the intensity of the femtosecond laser pulse or the size of the deuterium clusters to raise the energy of D^+ ions, and the probability of the DD fusion ratio can be improved.

We have estimated the expansion time for the D^+ ion cluster by considering the energy conservation of an expanding sphere with a uniform density. The ejecting time of a D^+ ion which is located on the cluster surface and with the preliminary energy E_s from the initial R to r ($r > R$) can be found to be

$$\tau_c(r) = \int_R^r dr/v = \int_R^r (m_i/2[E_s + U_c(r)])^{1/2} dr, \quad (7)$$

where v is the D^+ ion velocity and $U_c(r)$ is the change in the Coulomb potential from R to r,

$$U_c(r) = \frac{\rho e^2}{3\varepsilon_0} R^3 \Big(\frac{1}{R} - \frac{1}{r}\Big), \quad (8)$$

where ρ is the initial ion density in the cluster. Performing the integration we obtain

$$\tau_c = \sqrt{\frac{m_i}{2}} R[F(\xi) - F_0], \quad (9)$$

where

$$F(\xi) = \frac{\sqrt{\alpha - \beta\xi}}{\alpha\xi} + \frac{1}{2}\frac{\beta}{\alpha^{3/2}} \ln\Big(\frac{1 + \sqrt{1 - \beta\xi/\alpha}}{1 - \sqrt{1 - \beta\xi/\alpha}}\Big),$$

$$\xi = \frac{R}{r} \leq 1, \quad (10)$$

$$F_0 = \frac{\sqrt{E_s}}{\alpha} + \frac{1}{2}\frac{\beta}{\alpha^{3/2}} \ln\Big(\frac{1 + \sqrt{1 - \beta/\alpha}}{1 - \sqrt{1 - \beta/\alpha}}\Big). \quad (11)$$

Here $\beta = \rho e^2 R^2/3\varepsilon_0$ and $\alpha = E_s + \beta$. For the interaction strength of the ultrashort laser pulse with the cluster, the rising time of the laser pulse can be estimated from the time required for a uniformly charged sphere expanding due to the Coulomb force, which grows twice its initial radius,[16] and this time is defined as the Coulomb explosion time.[17]

The calculated results for the Coulomb explosion time τ_c and the final kinetic energy T_i per ion are presented in Table 1. The explosion time τ_c decreases with the increasing intensity of the laser pulse, and increases with the cluster size. The time scale for Coulomb explosion is indeed ultrashort, being femtoseconds for the cluster $R \leq 35\,\mathrm{Å}$. The D^+ ion kinetic energy T_i increases linearly with the increasing intensity of laser pulses, and increases superlinearly with the increasing cluster size because the Coulomb energy is proportional to R^2. We infer that the D^+ ion kinetic energy can increase to tens of keV or hundreds of keV of the energy scale with sufficient further increases of the intensity of the laser pulse and the cluster size, providing a source of high-energy D^+ ions which is suitable to induce DD nuclear fusion.

Table 1. The Coulomb explosion time τ_c in units of fs and the final kinetic energy T_i on the surface of the D^+ ion cluster. Here τ_c is determined by taking $r = 2R$ in Eqs. (9)–(11). T_i is determined by Eq. (6). The cluster density is $\rho = 3 \times 10^{-2}/\mathrm{Å}^3$, and the wavelength of the laser pulses is $\lambda = 820\,\mathrm{nm}$.

R (Å)		15		20		25		30		35	
		τ_c (fs)	T_i (eV)	τ_c (fs)	T_i (eV)	τ_c (fs)	T_i (eV)	τ_c (fs)	T_i (eV)	τ_c (fs)	T_i (eV)
I (W/cm^2)	2×10^{16}	3.79	1917	4.90	2234	5.92	2640	6.85	3139	7.68	3732
	4×10^{16}	2.73	3427	3.59	3744	4.41	4150	5.51	4649	5.88	5237
	6×10^{16}	2.25	4937	2.95	5254	3.64	5660	4.32	6159	5.01	6747
	8×10^{16}	1.94	6447	2.59	6764	3.24	7170	3.88	7669	4.53	8257

In addition, we should consider the exploding efficiency of the deuterium ion cluster. The exploding efficiency is defined by

$$\eta = \frac{N\langle W_i\rangle}{W_{ab}}, \text{ or } \eta = \frac{\langle W_i\rangle}{\langle W_i\rangle + \langle W_e\rangle}, \tag{12}$$

where $W_{ab} = N(\langle W_i\rangle + \langle W_e\rangle)$ is the D cluster absorbing energy from the laser pulse, N is the atomic number in the cluster, and $\langle W_i\rangle$ and $\langle W_e\rangle$ are the average energy of the ion and the electron during the cluster explosion, respectively ($\langle W_e\rangle = U_{\rm pond}$). Similarly to Eq. (6), we can obtain

$$\langle W_i\rangle = E_s + \langle U_c\rangle, \tag{13}$$

where $\langle U_c\rangle$ is the average Coulomb energy per ion in the D cluster, and

$$\langle U_c\rangle = \frac{1}{N}\int_0^\infty \frac{1}{2}\varepsilon_0 E^2 dV = \frac{4\pi}{5}B\rho R^2, \tag{14}$$

where E is the static electric field strength due to the deuterium ion cluster. Taking Eqs. (13) and (14) in Eq. (12), we obtain the formula for the exploding efficiency of the deuterium ion cluster:

$$\eta = \Big(1 + \frac{U_{\rm pond}}{E_s + 4\pi B\rho R^2/5}\Big)^{-1}, \tag{15}$$

where E_s and $U_{\rm pond}$ are given by Eqs. (5) and (1), respectively. For example, in the case we are considering here we have $E_s = 1.51\,\text{keV}$, $U_{\rm pond} = 2.51\,\text{keV}$, $R = 25\,\text{Å}$ and $\rho = 3\times 10^{-2}/\text{Å}^3$, and hence the exploding efficiency η of the deuterium cluster is $\eta = 46.4\%$. According to Eq. (15), the exploding efficiency η increases with decreasing intensity of the laser pulse ($E_s \propto I$, and $U_{\rm pond} \propto I$), and with increasing cluster size. Consequently, by increasing the deuterium cluster size, we can increase not only the exploding efficiency but also the D^+ ion kinetic energy during the cluster explosion.

In conclusion, we have divided the expansion of small deuterium clusters into two stages when the clusters are irradiated by an intense femtosecond laser pulse. The first stage is mainly the hydrodynamic expansion during which unbound electrons move out the cluster. The time of electrons escaping from the cluster is so short that the cluster expansion time and size can be neglected, but the ion energy in the expansion stage is considerable, thereby this expansion stage makes provision for the next stage. The second stage is pure Coulomb expansion after electrons escape from the cluster. The Coulomb explosion time is multi-femtosecond, which is approximately equal to the rising time of the laser pulse to irradiate the D cluster. In particular, the increasing intensity of the laser pulse which is irradiated on the deuterium cluster can increase the D^+ ion energy, but reduces the exploding efficiency. On the other hand, increasing D cluster size can raise both the exploding efficiency of the D cluster and the D^+ ion energy, so as to drive DD nuclear fusion more effectively.

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