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Nuclear fusion from Coulomb explosions of deuterated methane clusters subjected to ultraintense femtosecond laser pulses*

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This paper reports that Coulomb explosions taken place in the experiment of heteronuclear deuterated methane clusters ($(CD_4)_n$) in a gas jet subjected to intense femtosecond laser pulses (170 mJ, 70 fs) have led to table-top laser driven DD nuclear fusion. The clusters produced in supersonic expansion had an average size of about 5 nm in radius and the laser intensity used was 3×10^{17} W/cm^2.The measured maximum and average energies of deuterons produced in the laser–cluster interaction were 60 and 13.5 keV, respectively. From DD collisions of energetic deuterons, a yield of $2.5(\pm 0.4)\times 10^4$ fusion neutrons of 2.45 MeV per shot was realized, giving rise to a neutron production efficiency of about 1.5×10^5 per joule of incident laser pulse energy. Theoretical calculations were performed and a fairly good agreement of the calculated neutron yield with that obtained from the present experiment was found.

Keywords: molecular clusters, Coulomb explosion, DD nuclear fusion, intense femtosecond lasers
PACC: 2588, 3640, 5250J

1. Introduction

Ultrashort intense laser interactions with clusters have become a subject of interest for more than a decade, see Ref.[1] for a review. Among other things, one of the most remarkable findings of this field is the nuclear fusion neutron production from Coulomb explosion of deuterium clusters ($(D_2)_n$) driven by a table-top femtosecond laser pulse.[2] Nuclear fusion reactions are caused by DD collisions of energetic deuterium ions ejected from neighbouring clusters in a gas jet. This novel laser–cluster 'beam–beam' fusion neutron generation is of contemporary interest as a potential sub-nanosecond neutron source for time-resolved material damage studies. The neutron yield reported due to laser–cluster interactions under some typical experimental conditions lies at about 5×10^3 for $(D_2)_n$ clusters of ∼3 nm in radius irradiated by ∼120 mJ(35 fs) laser pulses.[3−5] For larger $(D_2)_n$ clusters, the neutron yield was reported to be restricted to less than $\sim 10^4$ per shot for the laser pulse energy within 400 mJ.[6] The limit of the neutron production is considered to be associated with the moderate kinetic energy of the deuterons which are generated in the laser–cluster interaction.[7] In order to increase the neutron production, an alternative gas medium composed of heteronuclear clusters was proposed by Last and Jortner.[8−10] Based on theoretical calculations, they demonstrate that the neutron yield can be enhanced substantially in Coulomb explosions of the deuterated methane clusters ($(CD_4)_n$) in comparison with homogeneous $(D_2)_n$ clusters.[10,11] The enhancement in neutron yield for the heteronuclear $(CD_4)_n$ clusters is attributed to the increase of the average energy of deuterons because of the energetic and kinematical effects. The reported experimental results show that the neutron yield with $(CD_4)_n$ clusters were not as high as that expected from theory,

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generally, less than 10^4 per laser pulse, with the pulse energy being 400[6] and 800 mJ.[12]

In the present study, we report a more efficient fusion neutron production from Coulomb explosions of $(CD_4)_n$ clusters driven by a 170 mJ (70 fs) laser pulse. An experimental yield of $2.5(\pm 0.4)\times 10^4$ neutrons per shot was found. Meanwhile, the energy spectrum of deuterons ejected from explosions of $(C^{4+}D_4^+)_n$ clusters was measured and as high as 60 keV kinetic energy was obtained. Finally, theoretical calculations were performed, which demonstrated a fairly good agreement of the calculated results with the experimental data.

2. Experimental

The experimental setup is shown schematically in Fig.1. To conduct the experiment, we used an 800 nm Ti:sapphire laser system based on 10 Hz chirped pulse amplification. The laser pulses of 70 fs in duration and with the energy of up to 440 mJ were used in the present experiment. The laser was focused by an off-axis f/5 parabolic mirror onto a gas flow of $(CD_4)_n$ clusters 2.5 mm below the nozzle exit. About 40% of the output laser pulse energy was measured by a calorimeter after the focus. The laser focus spot size was measured to be about 30 μm full width at half maximum (FWHM) in diameter. In the experiment, a home-made pulsed valve and a supersonic conical nozzle were used at a backing pressure of 64 bar to produce the cluster flow at room temperature. The purity of the used CD_4 gas (Spectra Gases Inc.) is 99%. The nozzle throat diameter is 310 μm, with a length of 26 mm, nozzle exit diameter of 4.5 mm, and a half-opening- angle of 4.6°. The average cluster size in the flow was estimated to be about 5 nm by Rayleigh scattering methods.[13−15] The kinetic energy of ions ejected from Coulomb explosion of the ionized $(CD_4)_n$ clusters was characterized by a time-of-flight (TOF) scheme. A dual micro-channel plate (DMCP) detector placed behind a skimmer and a 2.25 m long drift tube was used to detect the velocity of the ions, consequently, the energy distribution of the ions can be obtained.

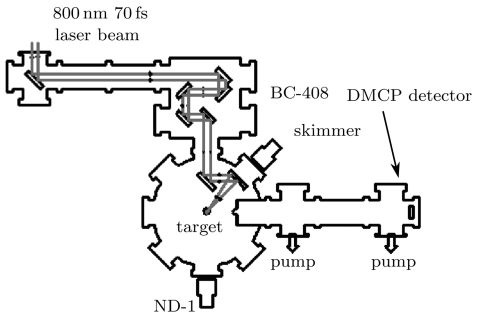


Fig.1. The scheme of the experimental setup for the laser–cluster interaction.

3. Results and discussion

The TOF spectrum of deuterons and carbon ions, which were produced in Coulomb explosions of ionized $(CD_4)_n$ clusters, was shown in Fig.2(a), and the corresponding energy spectrum converted from the TOF spectrum in Fig.2(a) was given in Fig.2(b). As discussed in Refs.[10, 16], the maximum energy E_C of the carbon ions (mass m_C) is about 2.5–3 times of the maximum energy E_A of the lighter species (mass m_A).

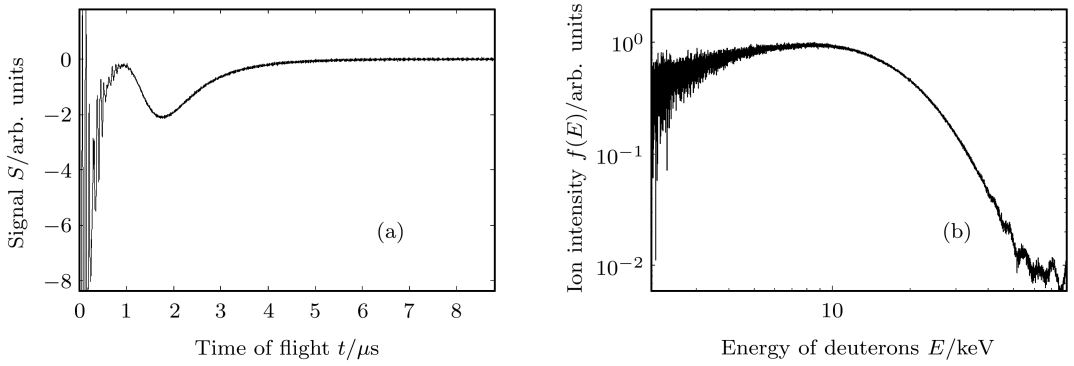


Fig.2. (a) The TOF spectrum of ions ejected from Coulomb explosion of heteronuclear $(CD_4)_n$ clusters at a deuterium gas backing pressure of 64 bar. The average radius of the $(CD_4)_n$ clusters is about 5 nm and the laser intensity in the experiments is about 3×10^{17} W/cm^2. (b) The energy spectrum of the ions, converted from the TOF spectrum in Fig.2(a). The maximum energy of the deuterons estimated is about 60 keV, and the average energy is 13.5 keV.

From the maximum energy of the deuterons, which is found to be about 60 keV from Fig.2(b), a minimum flight time for the carbon ions can be estimated. The energy $E_{\min} = E_C m_A/m_C$ is defined such that above which any signal in Fig.2(b) is attributed to deuterons only. If a log-normal size distribution is taken into account and the size width of the clusters of σ is given, an average cluster size can be estimated from the average energy of the deuterons $\bar{E} = E_{\rm av} e^{(5/9\sigma^2)}$[6] or through Coulomb explosion of $(C^{4+}D_4^+)_n$ clusters under the single size assumption.[10] In the present experiment, an average size of the $(CD_4)_n$ clusters was estimated to be 4.8 nm for $\sigma = 0.4$.[17]

Neutrons were generated from nuclear fusion through the D+D→He^3+n reaction resulting from Coulomb explosion of ionized $(CD_4)_n$ clusters and detected by two plastic scintillators, each of which is coupled to a photomultiplier tube. The signal from the photomultiplier was recorded by a digital oscilloscope (Tektronix DPO7254) and averaged over 11 shots. The detectors ND-1 (Laser Fusion Research Center, Mianyang, China) and BC-408, were located outside the target chamber, with a distance of 39.5 cm and 41.5 cm from the laser-target interaction area, respectively. From the signals in Fig.3, a yield of $2.5(\pm0.4)\times10^4$ 2.45 MeV neutrons into 4π per shot (170 mJ, 70 fs) was estimated under the assumption that the neutrons are emitted isotropically.[2,6] A small anisotropy of fusion neutron emission from Coulomb explosions of $(CD_4)_n$ clusters was revealed, it was attributed to a low density interaction regime in the experiment.[12] However, this is not the case for the present experiment. The yield of 2.5×10^4 neutrons per shot, which was a result averaged over 11 shots, indicates that the efficiency in fusion neutron production of $\sim 1.5 \times 10^5$ per joule of incident laser pulse energy was realized. By comparison with the neutron yield Y reported by Madison *et al*[6] for $(CD_4)_n$ clusters which was characterized by a power dependence on the laser pulse energy E through $Y = 3.0\times10^4 E^{1.12}$ (it leads to $Y = 4.1 \times 10^3$ with $E = 170$ mJ), an increase of about 6 times of the neutron yield in the present work has been found. This increase is considered to be related to the larger kinetic energy of the deuterons in comparison with the previous work.[6] This can be seen in the calculations given below.

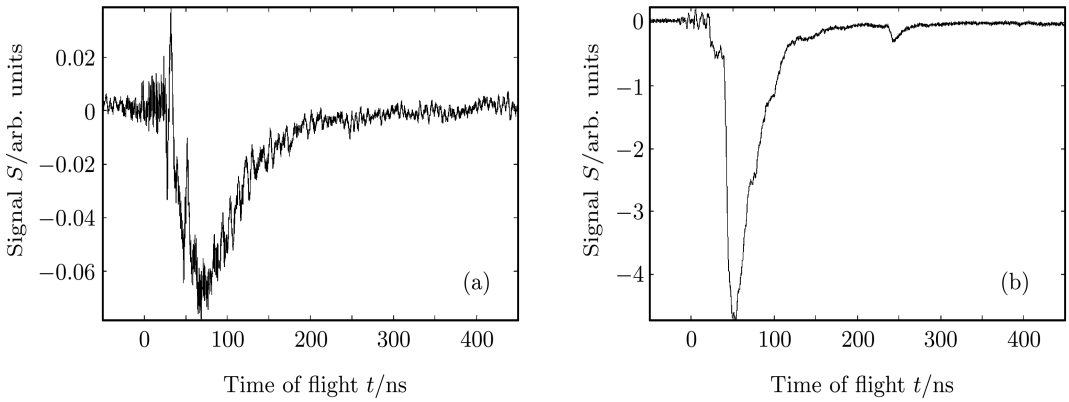


Fig.3. Neutrons produced from Coulomb explosions of the ionized $(CD_4)_n$ clusters of an average radius of about 5 nm were detected by two plastic scintillators, ND-1 and BC-408. (a) Neutron signal from ND-1 located 39.5 mm from the target. (b) Neutron signal from BC-408 located 41.5 mm from the target.

We have performed a theoretical calculation to estimate the neutron production based on the present experimental conditions. The total fusion neutron yield Y in the experiments includes contributions from deuteron-deuteron collisions occurring inside the plasma filament $Y_{\rm filament}$, and from collisions between the energetic deuterons emitted from the plasma and the cold deuterium gas surrounding the filament $Y_{\rm bt}$.[6,10] These two contributions can be estimated by

$$Y = Y_{\rm filament} + Y_{\rm bt} \approx \frac{\tau}{2}\rho^2 \langle\sigma v\rangle V + \frac{l}{2}\rho^2 \langle\sigma_v\rangle V, \quad (1)$$

where ρ is the average deuterium density within the plasma filament and is considered to be nearly the same as the deuterium density inside the gas jet, τ is the disassembly time of the filament, and $V = \pi d^2 l/4$ is the volume of the cylindrical plasma filament, with d and l being the diameter and length of the filament cylinder respectively. The fusion reactivity $\langle\sigma v\rangle$ can

be estimated by averaging over energies E_1 and E_2 of the colliding particles with the energy distribution $F(E)$ and over the collision angle θ, which is given by

$$\langle \sigma v \rangle = \frac{\iiint v\sigma(E)F(E_1)F(E_2)\mathrm{d}E_1\mathrm{d}E_2\mathrm{d}\theta}{\iiint F(E_1)F(E_2)\mathrm{d}E_1\mathrm{d}E_2\mathrm{d}\theta}. \quad (2)$$

The fusion reaction cross section of the deuterons in the plasma filament $\langle \sigma_v \rangle$ is written as

$$\langle \sigma_v \rangle = \frac{\int \sigma(E)F(E)\mathrm{d}E}{\int F(E)\mathrm{d}E}. \quad (3)$$

The collision energy E of two colliding particles can be written by $E = E_1 + E_2 - 2\sqrt{E_1E_2}\cos\theta$, θ is the collision angle of the two particles with the energy of E_1 and E_2, respectively. The relative velocity of the colliding particles can be calculated from the collision energy E through $v = \sqrt{2E/m}$, where m is the mass of deuterium.

For $\mathrm{D} + \mathrm{D} \rightarrow \mathrm{He}^3\ (0.82\,\mathrm{MeV}) + \mathrm{n}(2.45\,\mathrm{MeV})$ reaction, we have

$$\sigma(E) = \frac{482\left[(1.177 - 3.08 \times 10^{-4}E)^2 + 1\right]^{-1}}{E\left[\exp(47.88E^{-1/2}) - 1\right]}, \quad (4)$$

where energy E is in keV, and the total cross section σ in barns ($1\ \mathrm{barn} = 10^{-24}\,\mathrm{cm}^2$).

An estimation of the fusion neutron yield was made through calculations performed on Eqs.(1)–(4). Before carrying out the calculations, the deuterium density ρ and the dimensions of the plasma filament should be estimated. According to the theory of free jet expansion,[18] combined with the concept of the equivalent diameter of a conical nozzle for isentropic adiabatic expansion,[19] the deuteron density under the present experimental condition is estimated to be about $\rho = 7 \times 10^{18}\,\mathrm{cm}^{-3}$, which is close to the value given in Ref.[6]. We take the length of the plasma filament l to be 2 mm, and the diameter d to be $100\,\mu$m, according to our experimental conditions and referring to the data in Refs.[2–4]. Then, with the aid of the deuteron energy experimentally acquired, we obtain the average fusion reactivity $\langle \sigma v \rangle = 3.13 \times 10^{-19}\,\mathrm{cm}^3/\mathrm{s}$, and a resulting neutron yield of 3.0×10^4 per shot, which is in fairly good agreement with the experimental results.

4. Conclusion

In conclusion, we have demonstrated experimentally table-top laser driven nuclear fusion resulted from Coulomb explosions of ionized heteronuclear $(CD_4)_n$ clusters. The efficiency of fusion neutron production of the present laser–cluster interaction experiment was improved remarkably in comparison with the previous work,[6] owing to the larger cluster size used in the present work. This result is found to be in good agreement with that obtained by theoretical calculations. To improve the efficiency in fusion neutron production, the larger sizes of clusters, a denser gas jet, and a more proper laser spot size[20] will be considered in the further study.

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