Nuclear Fusion Driven by Coulomb Explosions of Large Deuterium Clusters

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Recent experiments on the interaction of intense, ultrafast laser pulses with large van der Waals bonded clusters have shown that these clusters can explode with substantial kinetic energy. By driving explosions in deuterium clusters with a 35 fs laser pulse, we have accelerated ions to sufficient kinetic energy to produce DD nuclear fusion. By diagnosing the fusion yield through measurements of 2.45 MeV fusion neutrons, we have found that the fusion yield from these exploding clusters varies strongly with the cluster size, consistent with acceleration of deuterons via Coulomb explosion forces.

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A number of experiments have been conducted in recent years examining the interactions of intense ultrafast laser pulses with large (10^2–10^6 atoms) van der Waals bonded clusters. Many research groups have reported that these interactions can be very energetic, with a variety of experimental manifestations. Studies on the interaction of a cluster target with laser pulses focused to an intensity between 10^{16} and 10^{18} W/cm^2 have shown that very bright x-ray emission in the 100 to 5000 eV range resulted from the plasmas produced [1,2]. This is a result of the efficient coupling of the laser light to the cluster medium, coupling which was found to be absent when irradiating monatomic gas at these intensities. This efficient coupling has also been observed in measurements of laser energy absorption in clustering gases [3,4]. These experiments illustrated that nearly 100% of an intense laser pulse could be absorbed by a modest average density gas jet ($\sim 10^{19}$ cm^{-3}) over a few mm when clusters were present. This greatly enhanced absorption is a consequence of the near solid density within the individual clusters, leading to the large absorption efficiency usually associated with solid targets. These absorption measurements indicated that many keV of energy per atom can be deposited in the clustering gas.

In addition, a number of groups have examined the dynamics of femtosecond laser pulse interactions with individual clusters. These studies have included measurement of ionization charge states produced in the cluster [5], pump-probe experiments which have shown that large clusters disassemble on a picosecond time scale [6–8], and photoelectron energy measurements which indicated that multi-keV electrons were ejected from large Xe clusters [9]. Perhaps most remarkable has been 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 [10,11]. This large release of kinetic energy in fast ions can be harnessed to drive nuclear fusion if deuterium clusters are irradiated in a gas of sufficient average density. We have recently observed such fusion reactions in deuterium clusters with an average diameter of ~ 50 Å [12]. In this Letter we report on measurements of fusion yield from these deuterium cluster explosions and show that the fusion yield is strongly related to the size of the deuterium clusters. The rapid increase in fusion yield with increasing cluster size can be attributed to the greater ion energies associated with the Coulomb explosion of the larger clusters and the rapid variation in fusion cross section with ion energy.

Although large, high Z clusters typically exhibit a "plasmalike" behavior [6,13] due to the fact that space charge forces confine many of the photoionized electrons to the body of the cluster, we expect that, provided the laser has a fast enough rise time and a high enough ponderomotive potential (U_p), D_2 clusters can be stripped of almost all their electrons by the laser pulse before the cluster explodes. The rise time of the laser pulse required can be estimated from the time required for a uniformly charged sphere expanding under Coulomb forces to grow to roughly twice its initial radius. For a sphere of ionized deuterons, this time is

$$t_{\mathrm{dis}} \approx 0.8\sqrt{\frac{4\pi\epsilon_0 m_{\mathrm{D}}}{n_D e^2}}\,, \qquad (1)$$

where n_D is the initial ion density ($\sim 3 \times 10^{22}$ cm^{-3} for D_2), e is the electron charge, and m_{D} is the mass of deuterium. This time is independent of the cluster initial radius and is equal to 20 fs for deuterium clusters. The initial radius of the cluster, r, determines the maximum energy produced in the explosion. For a uniform density deuterium cluster this energy is

$$E_{\mathrm{max}} = \frac{\langle q\rangle n_D e^2 r^2}{3\epsilon_0}\,, \qquad (2)$$

where $\langle q\rangle$ is the average charge state in the cluster. From this we see that fully stripped deuterium clusters with radii greater than 25 Å will be sufficient to produce the multi-keV ions necessary for fusion ($E_{\mathrm{max}} = 1.1$ keV when $r = 25$ Å). If an ultrashort laser irradiates the cluster and the rise time from the initial ionization intensity ($\sim 10^{13}$ W/cm^2 for deuterium) to an intensity sufficient to remove the majority of the electrons in the cluster ($U_p \geq E_{\mathrm{max}}$) is comparable to t_{dis}, the cluster will explode while the charge density is maximum, releasing the large electrostatic energy available as ion kinetic energy. If the rise time is significantly greater than this time or the peak intensity is too low, the cluster will disassemble before all electrons can be removed. The smaller charge density means there will be less energy available to drive the explosion and therefore the maximum velocity of the high energy ions will be reduced.

The resulting Coulomb explosion can isotropically accelerate deuterium ions to a sufficient energy such that they will have a significant probability of fusing when they collide with ions from a nearby cluster. Only the ions on the surface of the cluster will have the maximum energy. The full energy distribution will be

$$f(E)dE = K\sqrt{E}\,dE, \qquad E < E_{\max}, \tag{3}$$

where K is a normalization constant. This distribution is skewed toward the maximum energies; the average energy is equal to $3/5\ E_{\max}$. Clearly, a large Coulomb explosion of this nature can efficiently produce high energy ions. The strongly nonlinear relation between fusion cross section and ion energy [14], coupled with the r^2 scaling in maximum energy, will cause a rapid increase in neutron yield with increasing cluster size.

To examine this scaling, we have conducted experiments with variable size deuterium clusters. These experiments were performed with a 35 fs, Ti:sapphire laser system based on chirped pulse amplification delivering up to 120 mJ of energy per pulse. The beam was focused with a f/12 lens into a spherical vacuum chamber, producing focal intensities up to $5 \times 10^{17}\ \mathrm{W/cm^2}$. Deuterium clusters are created with a sonic gas jet, cryogenically cooled, and backed with up to 70 atm of deuterium gas. In order to cool the jet, a cooling jacket was placed around the jet housing and either liquid nitrogen or liquid helium were flowed through the jacket. The temperature was monitored with a type T thermocouple placed on the jet body and could be controlled by adjusting the flow rate of the cryogen. This thermocouple measures the temperature of the jet body and not the absolute temperature of the gas. However, it does provide a usable reference for comparing different stagnation conditions.

To monitor the DD fusion we measure the 2.45 MeV neutrons that result from the D(D,n)He^3 reaction. We conducted neutron time-of-flight (TOF) measurements using 7 mm thick, 10 cm square plastic scintillators coupled to fast photomultiplier tubes arrayed at various distances from the target. The intrinsic time resolution of these detectors was determined by measuring the signal width when the laser was focused onto a solid target, generating an ultrafast hard x-ray burst. The temporal resolution was found to be roughly 1 ns. In addition, single shot neutron yield was measured with a low time resolution, 10 cm diameter, 15 cm thick plastic scintillation detector placed 19 cm from the target. This detector subtended approximately 1.7% of the solid angle and detected a sufficient number of neutrons to provide good counting statistics on a single shot. The detection efficiency of this detector was calibrated against TOF detectors operating in single particle detection mode. We checked this calibration by measuring the average pulse height produced when single neutrons strike the detector. Both methods yielded nearly equal values for the neutron yield calibration. In addition, the energy in the transmitted laser beam was measured with a pyroelectric energy meter. A photodiode was used to check for backscattered light (none was observed).

In our experiments, the 35 fs laser pulse was focused into the gas jet of deuterium clusters. This process creates a plasma filament under the jet nozzle with a diameter of roughly 200 μm and a length comparable to the extent of the gas jet plume (~2 mm). The fast deuterium ions ejected from the exploding clusters can collide with ions ejected from other clusters in the plasma. Figure 1 shows the neutron time-of-flight spectrum 62 cm from the plasma ($t = 0$ occurs when the laser pulse interacts with the target). The large peak shows the presence of 2.45 MeV neutrons at a flight time of 28.6 ± 1 ns. Detectors placed at different distances and angles from the laser axis show a peak at flight times corresponding to the same energy. We also see uniform neutron production at all angles indicating that fusion is occurring from the high temperature, isotropic ions in the plasma, rather than beam target fusion as seen in recent experiments by Pretzler *et al.* examining femtosecond laser irradiation of deuterated polyethylene targets [15].

To study the scaling of fusion yield with cluster size, we exploit the well known fact that gas reservoir temperature affects cluster size [16,17]. We have characterized the variation of cluster sizes by performing Rayleigh scattering measurements on the clustering gas plume. A continuous wave 543 nm laser was scattered off the cluster target,

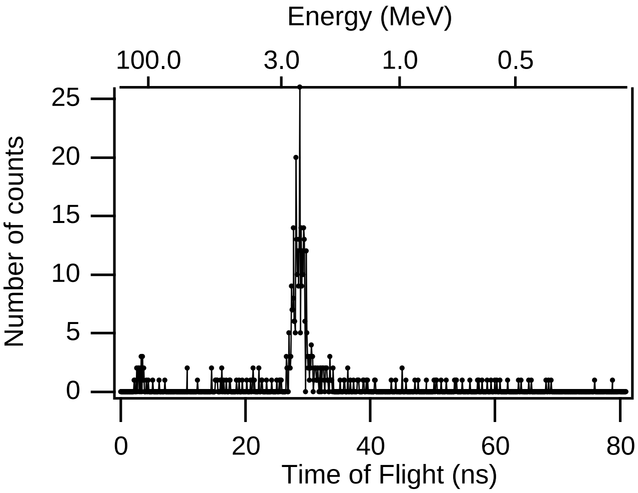

FIG. 1. Neutron time-of-flight spectrum. Neutrons were detected 62 cm from the target using a 7 mm thick plastic scintillator. The peak occurs at 2.45 ± 0.2 MeV, characteristic of DD fusion.

and the scattered light was imaged onto a calibrated photomultiplier tube. The estimated average cluster size as a function of measured temperature (at 55 atm) is shown in Fig. 2. We can vary the average cluster diameter from 10 to 100 Å. Since we have no direct information on the cluster distribution of this jet we assumed a single cluster size to calculate the diameter from the scattering data. This simplifying assumption yields a reasonable number for the average cluster size. Studies of the cluster distribution have shown that there is a broad distribution of cluster sizes with a tail of large clusters extending out to several times the average radius [17]. These larger clusters will produce a tail of hot ions which will have a very high probability of fusing.

First, we observe that larger clusters lead to higher absorption. Figure 3 shows the measured laser absorption as a function of jet temperature with a reservoir backing pressure of ~70 atm. There is a marked increase in absorption with decreasing jet temperature (increasing cluster size). At 100 K the absorption approaches 90%. At this point, we estimate (using interferometric images of the plasma to measure the volume and total number of deuterium ions produced [12]) that ~5 keV of energy per atom is deposited in the plasma. Though we do not know the exact distribution of energy between electrons and ions, the simple Coulomb explosion model described above argues that the majority of the energy is contained in the ions.

Using Fig. 2 to calibrate the average absolute cluster diameter, Fig. 4 shows the measured absolute yield as a function of cluster size. Neutrons are first detected at a jet temperature of about 125 K (average cluster diameter of 25 Å). As the temperature continues to decrease there is an initial rapid increase in yield. The maximum yield occurs around 100 K and then starts to decrease as the jet is cooled further. Below an indicated temperature of 80 K the jet stops working reliably.

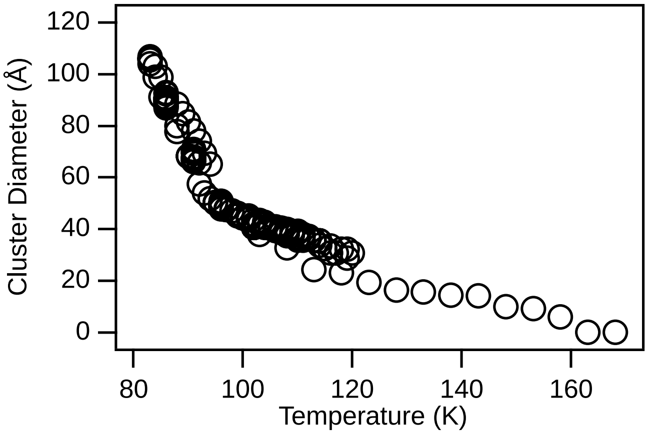

FIG. 2. Average cluster diameter as a function of jet temperature from Rayleigh scattering measurements. The cluster diameter increases and the jet temperature decreases. The gas pressure was 55 atm.

We see that for cluster diameters from 30 to 50 Å there is an increase in neutron production greater than an order of magnitude. We can make an approximate estimate on the total neutron yield. Since the laser energy is constant, the volume of the plasma decreases as the energy deposited per atom increases. The disassembly time of the fusion plasma can be estimated by the time for a deuteron to traverse the plasma filament. Using these we can write the yield as

$$\text{yield} \approx \frac{\overline{\sigma v} n_D l E_{\text{laser}} \alpha}{2\langle E \rangle} \sqrt{\frac{m_\text{D}}{2\langle E \rangle}}, \tag{4}$$

where $\overline{\sigma v}$ is the Maxwellian averaged fusion cross section, l is a characteristic distance free streaming ions will traverse and can be estimated as the plasma filament radius, E_{laser} is the incident laser energy, α is the fraction of energy absorbed, and $\langle E \rangle$ is the average ion energy. Since we have no direct information on the ion energy distribution (which will be dependent on the cluster size distribution) we used the Maxwellian averaged cross section formula, using an average ion energy derived from Eq. (2) for a given average cluster size. Inserting the experimental parameters into Eq. (4) the calculated yield is drawn in Fig. 4. Though this simple model is crude, it reproduces the trend observed in the data (below the rollover point) quite well and indicates that it is the Coulomb explosion dynamics of the clusters which control the fusion yield below the rollover point.

This model indicates that the neutron yield should continue to increase with the decreasing temperature as shown by the line in Fig. 4. However, we observe that the yield begins to decrease as the temperature is lowered below 100 K (cluster diameter of ~50 Å). Interferometric and plasma emission images indicate that macroscopic propagation effects begin to alter the interaction at lower temperatures [18]. As the temperature decreases beyond the point at which absorption nears 100% (~100 K), the plume absorbs the laser pulse further forward in the gas jet. Hence the laser energy is being absorbed in the lower

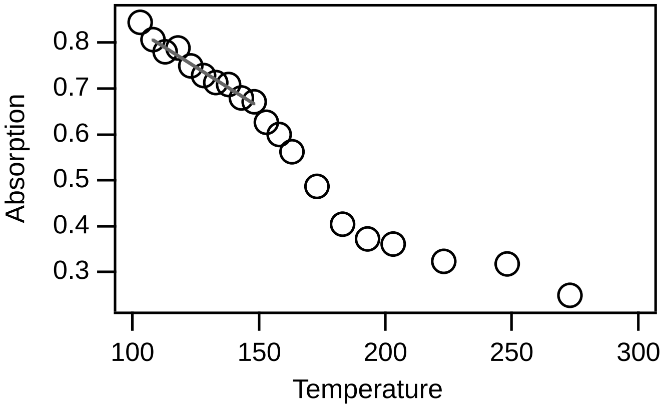

FIG. 3. Absorption of the laser energy as a function of jet temperature. The gas pressure was ~70 atm.

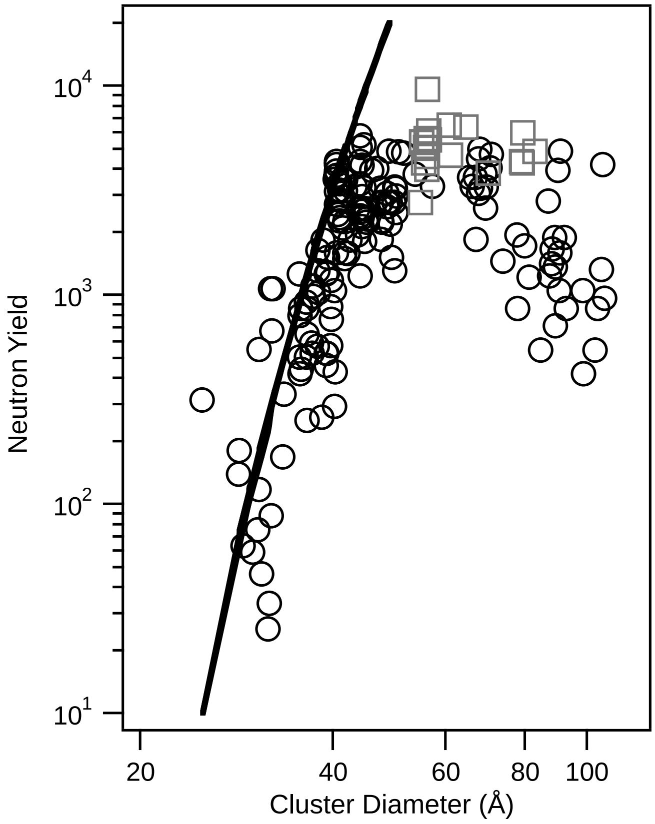

FIG. 4. Neutron yield is plotted as function of cluster diameter at 55 atm. The circles show an initial increase in yield as the ion energies from the Coulomb explosion increase rapidly with cluster size. As the size increases further, propagation effects prevent the laser from penetrating to the high density regions of the jet and the yield goes down. The square markers are under the same jet conditions but the jet has been moved along the propagation axis to the point where yield is optimized at the larger cluster sizes. The solid line shows the expected scaling.

density region. The highest laser intensity cannot reach the high density region of the jet and the yield decreases. Under such conditions we can reoptimize the jet location to improve yield. The square markers in Fig. 4 are data taken under the same jet conditions; however, the jet has been moved, along the laser propagation axis, to the position where the yield is maximized. (The details of these propagation effects will be discussed in a future publication.)

In conclusion we have shown that cluster formation in a deuterium gas jet can give rise to nuclear fusion when irradiated by an intense, femtosecond laser pulse. We find that cluster size, controlled through reservoir temperature, dramatically affects neutron production in the deuterium fusion. This fusion yield enhancement is due primarily to the greater ion energies produced in the Coulomb explosion of larger clusters. The scaling of the fusion yield is roughly consistent with a simple model for the Coulomb explosion. We also find that there is a maximum yield which is reached and the yield decreases as the cluster size is further increased through jet cooling. We believe that this is due to propagation and absorption effects of the laser pulse as it enters the cluster plume. With further optimization of the gas jet design and the use of higher energy pulses we believe these limits can be overcome and the neutron yield can be increased.

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