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Characterization of deuterium clusters mixed with helium gas for an application in beam-target-fusion experiments

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Abstract
We measured the average deuterium cluster size within a mixture of deuterium clusters and helium gas by detecting Rayleigh scattering signals. The average cluster size from the gas mixture was comparable to that from a pure deuterium gas when the total backing pressure and temperature of the gas mixture were the same as those of the pure deuterium gas. According to these measurements, the average size of deuterium clusters depends on the total pressure and not the partial pressure of deuterium in the gas mixture. To characterize the cluster source size further, a Faraday cup measured the average kinetic energy of the ions resulting from Coulomb explosion of deuterium clusters upon irradiation by an intense ultra-short pulse. The deuterium ions indeed acquired similar amount of energy from the mixture target, corroborating our measurements of the average cluster size. As the addition of helium atoms did not reduce the resulting ion kinetic energies, the reported results confirm the utility of using a known cluster source for beam-target-fusion experiments by introducing a secondary target gas.

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I. Introduction

Production of energetic ions from laser-heated atomic or molecular clusters has been an active area of research in laser-plasma physics over the past two decades [1-8]. In particular, theoretical and experimental studies have been made of nuclear fusion reactions generated using deuterium clusters or deuterated methane clusters [7-18]. In a typical laser-cluster-fusion experiment involving deuterium, an intense femtosecond laser pulse irradiates deuterium clusters, 1–10 nm radius aggregates of deuterium molecules, bound at liquid density by van der Waals forces. These clusters are produced by forcing cold (80–100 K) deuterium gas under high backing pressure (~50 bar) through a supersonic nozzle into vacuum. If the laser field is strong enough for the existing deuterium cluster size, the interaction between the laser pulse and the clusters leads to an explosion of the clusters generating energetic deuterium ions.

The so-called Coulomb explosion model explains this process successfully, showing both qualitative and quantitative agreement with experiments [6-11]. According to this model, the electrons in a deuterium cluster first absorb the laser pulse energy as the atoms are ionized. These electrons then continue to absorb laser energy through several absorption mechanisms [2], and ultimately escape from the cluster on a time scale that is short compared with the ion motion. After the electrons escape from the clusters, the highly charged clusters of deuterium ions at liquid density promptly explode by Coulomb repulsion, creating a hot plasma. The resultant deuterium ions are energetic enough to generate nuclear fusion reactions during their collisions within the plasma, producing a burst of 2.45 MeV neutrons from D(d, ^{3}He)n reaction and 3.02 MeV protons from the D(d, t)p reaction.

According to the Coulomb explosion model, the average kinetic energy of ions from a given deuterium cluster increases quadratically with the size of the cluster [10]. Therefore, the distribution of cluster sizes within the jet determines the kinetic energy distribution of the deuterium ions in the resulting laser-induced fusion plasma [19,20]. Furthermore, since the DD fusion cross-section increases very quickly with the ion temperature in the 1–30 keV range [21], accessible in laser-cluster-fusion experiments, larger deuterium clusters can result in a higher fusion yield.

For these reasons, many researchers have put much effort into characterizing their cluster sources [22-34], especially into determining the average cluster size either by developing empirical formulae or by measuring the average size directly [20,22-32]. Past characterizations, however, were limited to the use of a single gas species, and little information is available regarding the cluster dynamics when a second gas species is present [35-37]. Yet we know that the cluster size can change when a gas mixture is used. As shown in Ref. [37], for example, the average size of CO_2 clusters varies with the concentration of CO_2 in Ar gas. Moreover, the addition of a small amount of another gas species can significantly change the chemical properties of the original gas [38,39]. Therefore, the formation of clusters has to be experimentally verified if clusters are mixed with another gas for certain applications.

In our recent work [40-42], we reported on the use of ^{3}He atoms as targets for energetic deuterium ions, which allowed for the generation of three types of nuclear fusion reactions occurring simultaneously in the interaction volume: D(d, ^{3}He)n, D(d, t)p, and ^{3}He(d, p)^{4}He. These experiments showed the feasibility of performing beam-target-fusion experiments by the addition of a secondary gas into deuterium clusters.

In this paper, we examine whether the average deuterium cluster size differs if there is a secondary helium gas mixed into the deuterium gas. We do this by comparing the average size of a deuterium cluster + helium gas mixture with that of pure deuterium clusters under similar gas jet conditions. We present Rayleigh scattering measurements and calculate average cluster size as a function of gas jet temperature for both a deuterium cluster + helium gas mixture and pure deuterium clusters. Then, we show Faraday cup measurements of the average ion energy from the laser-heated deuterium cluster + 3He gas mixture, from which we infer the average cluster size assuming complete Coulomb explosion of the clusters. We compare this cluster size with that found in Ref. [16] for pure deuterium clusters at a similar laser intensity.

II. Experimental setup

In the first part of the experiment, we used a commercial He-Ne laser for the cluster size measurements. Figure 1 shows the schematic of the 90° Rayleigh scattering setup for this experiment. A linearly polarized 0.98 mm beam from a 17 mW continuous-wave He-Ne laser at 632.8 nm illuminated clusters formed at the center of the target chamber after a pulse valve (Parker, series 99) released either deuterium gas or a deuterium + ^{4}He gas mixture. A Hamamatsu photomultiplier tube (PMT), R928, with a -1000 V bias collected the scattered laser light from the clusters at 90° from the laser propagation direction, converting it into an amplified electrical signal. A Tektronix 1 GHz oscilloscope recorded this signal after receiving the same trigger signal as the pulse valve for the gas jet. To improve the light-collection efficiency of the PMT, a 51 mm diameter lens with a focal length of 75.6 mm collected the He-Ne light scattered from the clusters at an angle 90° relative to the incoming laser beam. This lens imaged the scattered light onto the photocathode of the PMT. Two 632.8 nm laser line filters with a full-width-at-half-maximum (FWHM) of 3 ±0.5 nm and one neutral density (ND) filter with an optical density (OD) of 1.0 suppressed background light and stray laser light at the entrance of the PMT.

For the Rayleigh scattering measurements, a mixture of deuterium and ^{4}He gas at equal partial pressures served as the target. A residual gas analyzer (RGA) measured the partial pressures of deuterium and helium gases in the mixture inside the target chamber, and we adjusted the partial pressures to be equal. The gas mixture was introduced at a pressure of 54 ±1 bar into a conical supersonic nozzle with a throat diameter of 790 μm, an exit diameter of 5 mm, and a half angle of 5 degrees, generating deuterium clusters. Since deuterium gas does not form clusters at room temperature even at 54 bar, we cooled the gas mixture to 87 K by flowing liquid nitrogen around the nozzle assembly.

After performing a series of Rayleigh scattering measurements, we conducted the remaining part of the experiment on the Texas Petawatt laser (TPW) [43]. The TPW irradiated the clusters with 140–180 J, 150–200 fs, 1.06 μm wavelength pulses. An f/40 focusing mirror with a 10 m focal length created a large interaction volume with laser intensity sufficiently high for a near-complete Coulomb explosion of deuterium clusters [16,44].

For this part of the experiment, mixtures of deuterium and ^{3}He gas at varying proportions served as the targets. Again, the RGA recorded partial pressures of several gas species inside the target chamber, from which we calculated the ratio of number densities of deuterium and ^{3}He for each shot. Figure 2 shows an example of these RGA measurements, where the number density of ^{3}He was 6.7 (±0.4)% of that of deuterium during and after the gas jet firing. The gas jet fired 827 seconds after the start of the recording in this particular example. The signals before and after this time originate from a small gas leak at the nozzle, which became prominent at low temperatures (~87 K) according to the RGA measurements. Since the leak was relatively small, the target chamber pressure remained below 2×10^{-5} Torr except during the firing of the gas jet, at which time the chamber pressure rose quickly to as high as 1×10^{-3} Torr. Understandably, the composition of the gas jet during the gas jet firing was close to the composition calculated from the small leak.

Figure 2 also shows a few abrupt changes in the partial pressures of deuterium and ^{3}He, which represent changes in the backing pressure of the gas mixture. For example, we increased the total backing pressure of the gas mixture from about 50 bar to 54 bar at around 600 seconds, which caused an increased leak level thereafter. The partial pressure of the nitrogen background remained largely unchanged during the course of the measurements.

A Faraday cup, located 1.07 m from the nozzle exit, provided the time-of-flight (TOF) measurements of the energetic deuterium ions arriving from the deuterium fusion plasma. A ground mesh at the entrance of the Faraday cup maintained a field-free region, while a -400 V bias on the 16 mm diameter collector repelled slow electrons that could affect the TOF measurements by arriving at the same time as the ions. We assumed isotropic emission of the ions [16,20] to calculate the total number and energy spectrum of deuterium ions in the fusion plasma. This is reasonable because the clusters undergo Coulomb explosion in this experiment rather than ambipolar expansion as per the criteria in Ref. [8]. In fact, the measurements of fusion products in our previous experiment under similar experimental conditions indicated isotropic emission of neutrons and protons within the measurement errors [41].

III. Cluster size determination from Rayleigh scattering measurements

Previous studies show that Rayleigh scattering measurements are valid for determining the average size of clusters if the clusters are much smaller than the laser wavelength [25-30]. Since Rayleigh scattering theory is well established, we take it as a starting point to derive a simple proportionality that is particularly useful for determining deuterium cluster sizes using a method which varies the temperature of the gas mixture at a constant backing pressure.

The differential cross section, $d\sigma/d\Omega$, for Rayleigh scattering from a sphere of radius r for a linearly polarized laser light perpendicular to the scattering plane takes the form [45],

$$\frac{d\sigma}{d\Omega} = \frac{16\pi^4 r^6}{\lambda^4}\left(\frac{n_r^2-1}{n_r^2+2}\right)^2, \tag{1}$$

where λ is the wavelength of the laser and n_r is the refractive index of the sphere.

Using the number density of liquid deuterium, n=4.86×10^{22} atoms/cm^3, a deuterium cluster with N_c atoms per cluster has radius $r = 0.17\times N_c^{1/3}$ [nm]. Based on Eq. (1), the Rayleigh scattering signal from a single cluster with radius r is proportional to $N_c^{\,2}$, and the total amount of scattered light from clusters, S_{RS}, depends on the gas jet parameters.

$$S_{RS} \propto n_c N_c^2, \tag{2}$$

where n_c [clusters/cm^3] is the cluster number density. For large deuterium clusters, one typically assumes that no monomers are present and therefore the number density of deuterium atoms in the cluster gas jet, n_D [atoms/cm^3], holds the following relation [25-30] (although there are recent studies that indicate otherwise, at least for argon clusters [32-34]):

$$n_D = n_c N_c. \tag{3}$$

Equation (3) simplifies Eq. (2) to $S_{RS} \propto n_D N_c$. The theoretical work of Dorchies *et al.* [23] relates n_D to known gas jet parameters through a thorough one-dimensional analysis of the gas jet conditions before and after the nozzle using an ideal gas law and assuming adiabatic expansion of the gas [23]. According to section III of their paper, the number density of deuterium at the nozzle output has a linear dependence on the initial number density before the nozzle which, using an ideal gas law, is proportional to P_0/T_0 where P_0 is the backing pressure and T_0 is the absolute temperature of the gas. Then, Eq. (2) can be rewritten as

$$S_{RS} \propto \frac{P_0}{T_0} N_c, \tag{2a}$$

a useful form because now the cluster size is the only unknown quantity in our measurements.

Before we proceed, we want to show that the ideal gas assumption used in Ref. [23] and in Eq. (2a) is valid under our gas jet conditions. Figures 3(a) and 3(b) compare the deuterium gas density as a function of pressure and temperature, respectively, using SESAME table #5265 (solid black lines) [46-48] and the ideal gas equation of state (EOS) (dashed red lines) for deuterium gas. Figure 3(a) shows the mass density of deuterium in g/cm^3 when the temperature of the deuterium gas is fixed at 87 K and backing pressures are varied from 0 to 100 bar. Figure 3(b) shows the mass density of deuterium for different temperatures from 40 K to 300 K at a fixed backing pressure of 54 bar. The figures show large deviations from the ideal gas EOS at high pressure and at low temperature. For example, the deviation becomes as large as -17% in Fig. 3(a) at a backing pressure of 100 bar and -19% in Fig. 3(b) at 40 K. For the gas jet conditions used in our experiment, however, the deviations from an ideal gas EOS are smaller than -9%.

IV. Rayleigh scattering measurements and analysis

Prior to the actual size measurements, we varied the position of the nozzle and maximized the scattering signal using deuterium cluster targets. Figure 4(a) shows the signal strength for various horizontal positions of the nozzle (varying in the x-direction in Fig. 1). The scattering signal peaks at the center, x=0, and a Gaussian fit with a FWHM of 4.6 mm (dashed line) describes the trend well. The PMT detected scattering signals from the clusters for nozzle positions from -4 mm to +3.5 mm, which is roughly consistent with signals expected from the 5 mm nozzle output diameter swept by the 1 mm diameter He-Ne beam. Also, the observed trend qualitatively agrees with the total swept volume of the gas jet by the He-Ne laser beam at each position. Since the total number of clusters seen by the He-Ne beam increases linearly with the swept volume, so does the scattering signal. When the He-Ne beam goes through the center of the gas jet (x=0), the volume swept by the beam is approximately $\pi(0.5\ \mathrm{mm})^2(5\ \mathrm{mm})$ whereas the beam going through x=±2 mm, for example, sweeps less than 60% of that volume.

Since other factors such as overall gas jet density or cluster size may have position dependence as well, we fixed the position of the nozzle at x=0 for subsequent measurements. A similar position scan of the nozzle in the vertical direction showed less dramatic changes, and the nozzle exit was 2.5 mm above the He-Ne laser beam for the size measurements. We also varied the time duration of nozzle opening and fixed the duration at 1 ms. Figure 4(b) illustrates an oscilloscope trace of the Rayleigh scattering after these optimization processes using deuterium clusters. The signal shown in Fig. 4(b) is a 10-shot average at the same gas jet conditions, at

87 K with a backing pressure of 54 bar. It shows a fast rising signal (in the negative direction owing to the negative bias) with about a 400 μs rise time and a peak height of 2.8 V. Scattered laser light was detected while the pulse valve opened for 1 ms in Fig. 4(b) [31].

When the temperature of the gas is fixed, Eq. (2a) gives a simple relationship, $S_{RS} \propto P_0 N_c$, which can be simplified further as $S_{RS} \propto P_0^{\beta}$ because N_c also depends on P_0. Previous studies observed pressure scaling laws with the exponent, β, ranging from 1.8 to 3.4 [25-30], with lower values mostly for conical nozzles with bigger equivalent sonic-nozzle diameters, defined by d_{eq}=0.87 d/tan α for a diatomic gas, where d is the nozzle throat diameter and α is the half angle of the conical nozzle. To confirm whether our pressure scaling law agreed with those found in previous studies [25-30], we performed a pressure scan using pure deuterium gas at 87 K. Since our nozzle had a very big equivalent diameter of d_{eq}=7.9 mm to produce large deuterium clusters, we expected the exponent to be smaller than 2.8 calculated from Eq. (16) in Ref. [23]. Figure 5(a) displays the measured scattering signals along with a power law fit (dashed red line) for different backing pressures. Indeed, the signal increased following a power law of $P_0^{2.1}$ with deuterium gas pressure ranging from 0 to 40 bar. Figure 5(b) shows the average diameter of deuterium clusters calculated from the data in Fig. 5(a). The dashed red line represents expected cluster diameters with the $P_0^{2.1}$ power law fit.

Figure 6(a) shows the measurements of Rayleigh scattering signals varying the temperature of deuterium gas while keeping the backing pressure at 54 bar. Each point in the figure represents a 10-shot average of scattering signals at the same gas jet conditions. A power law fit (dashed red line), $1/T_0^{5.7}$, reproduces the general trend although it lacks quantitative agreement at temperatures above 140 K. The errors in the temperature measurements are estimated to be ±2 K. Figure 6(b) shows the resulting cluster diameters at different gas temperatures with upper and lower bounds of the cluster diameters indicated by vertical error bars. From these measurements, we find that we had $16.6^{+4.2}_{-3.5}$ nm deuterium clusters at 87 K with a backing pressure of 54 bar.

Figure 7(a) shows similar measurements of Rayleigh scattering signals for different temperatures of a deuterium + ^{4}He gas mixture at the same fixed backing pressure of 54 bar. The RGA measurements confirmed that the deuterium gas and ^{4}He gas had equal partial pressures within the gas jet. Again, a 10-shot average of the scattering signals was used for each temperature, and a power law fit (dashed red line), $1/T_0^{5.7}$, reproduced the overall trend. The contribution from individual ^{4}He atoms to the scattered light is expected to be small because Rayleigh scattering depends strongly on the size of the scattering particle. Figure 7(b) shows the average diameter of deuterium clusters within the gas mixture, and the vertical error bars represent upper and lower bounds of our calculations using the method described below. Again, the temperature of the gas mixture was stable within ±2 K. According to the measurements and to our calculations, $16.3^{+4.5}_{-3.3}$ nm deuterium clusters formed at 87 K with a backing pressure of 54 bar when using the gas mixture. Since the partial pressure of deuterium within the gas mixture in Fig. 7(b) was half that of pure deuterium gas in Fig. 6(b), this close agreement at 87 K indicates that the cluster size depended predominantly on the total pressure of gas and not just on the partial pressure of deuterium.

To calculate the average diameters of deuterium clusters from the raw data in Figs. 5(a), 6(a), and 7(a), we need another assumption regarding the onset of clustering. This is because the Rayleigh scattering technique provides only a relative size measurement, as is implicit from Eq. (2a). We assumed N_{c0}=200 atoms per cluster at the initiation of cluster formation. This is based on previous studies that observed the onset of clustering at N_{c0}=100–300 [25-27,49], when the onset of clustering was defined as the point when the Rayleigh scattering signal to background noise ratio was 2. With this assumption, Rayleigh scattering measurements at two points yield

$$V_{onset} = k\,\frac{P_{onset}}{T_{onset}} N_{c0}, \tag{4a}$$

$$V_0 = k\,\frac{P_0}{T_0} N_c, \tag{4b}$$

where k is a proportionality constant, V_{onset} is the measured scattering signal height at the onset of clustering with a backing pressure of P_{onset} and temperature of T_{onset}, V_0 is the signal height with the deuterium gas at pressure P_0 and temperature T_0, and N_c is the average number of atoms in a cluster under this condition.

From Eqs. (4a) and (4b), we can express N_c as

$$N_c = \frac{V_0}{V_{onset}} \frac{P_{onset}}{P_0} \frac{T_0}{T_{onset}} N_{c0}. \tag{4c}$$

Therefore, the average diameter of deuterium clusters is given by

$$2r = 0.34\left(\frac{V_0}{V_{onset}} \frac{P_{onset}}{P_0} \frac{T_0}{T_{onset}} N_{c0}\right)^{1/3} \text{ [nm]}, \tag{4d}$$

which was used to generate Figs. 5(b), 6(b), and 7(b) from the raw data in Figs. 5(a), 6(a), and 7(a), respectively. In Fig. 5(b), the measurements were performed at a constant temperature, giving $T_0 = T_{onset}$ in Eq. (4d). Then, we measured P_{onset} experimentally by varying the gas jet backing pressure. In Figs. 6(b) and 7(b), however, the backing pressures of both pure deuterium and deuterium + helium gas mixture were kept at 54 bar, and we put $P_0 = P_{onset}$ in Eq. (4d). Then, we determined T_{onset} experimentally by varying the temperature of the gas jet. To calculate the errors in the average diameter measurements, we put N_{c0}=200 ±100 atoms per cluster in Eq. (4d) and found upper and lower bounds. In addition to this consideration, we adjusted the upper bound of the cluster diameter at each temperature assuming the gas jet density could exhibit a non-ideal gas behavior, $n_D \propto P_0/\sqrt{T_0}$, which had been observed experimentally in Ref. [26].

V. Ion TOF measurements and analysis

When an intense laser pulse irradiates deuterium clusters, the clusters absorb the pulse energy very efficiently and undergo Coulomb explosions. The kinetic energies of the resulting deuterium ions easily exceed several keV and often reach 10–20 keV depending on the cluster size and the incident laser intensity [16,44]. In contrast, helium atoms do not form clusters at

86 K [50], and do not absorb the laser pulse energy efficiently. Therefore, they remain relatively cold (< 200 eV) even after irradiation by an intense laser pulse.

As a consistency check, we examined whether helium atoms affect the Coulomb explosion of deuterium clusters. We measured the kinetic energies of deuterium ions when laser pulses with intensities of 2–3×10^{16} W/cm^2 irradiated deuterium clusters + ^{3}He gas mixture targets. Here the main motivation for mixing ^{3}He gas rather than ^{4}He gas was to study ^{3}He(d, p)^{4}He nuclear fusion reactions within the plasma [40,41].

Figure 8 shows a Faraday cup ion TOF measurement using a gas mixture target with a partial pressure ratio, deuterium : ^{3}He, = 2:1. Ions with different kinetic energies arrive at the Faraday cup at different times, resulting in the observed TOF spectrum. The Faraday cup also responds to the fast x-ray burst originating from the hot electrons produced within the plasma, and displays a strong narrow peak near the time of laser arrival. At later times energetic deuterium ions arrive at the Faraday cup and produce the ion TOF signals as shown in Fig. 8. A dashed red line in the figure represents a two-source fit with an exponentially rising and decaying curve accounting for the initial x-ray peak and a Maxwellian distribution of the energetic deuterium ions.

The incident laser intensity on the target was 2.2×10^{16} W/cm^2, comparable to the intensity used in Ref. [16] that resulted in an average ion kinetic energy of 14 keV from pure deuterium clusters. On the shot shown in Fig. 8, we observed an average deuterium ion kinetic energy of 14.5 ±1.5 keV, or kT_{TOF} = 9.6 ±1 keV defined as two thirds of the average kinetic energy of deuterium ions, confirming the insignificant influence of the helium atoms on the Coulomb explosion of the deuterium clusters. The close agreement in the measured average kinetic energies of deuterium ions is consistent with the results of our Rayleigh scattering measurements, which indicated that the average diameter of deuterium clusters within a gas mixture was equal, within errors, to that within a pure deuterium gas when both gases were under the same total backing pressure and at the same temperature.

Since the kinetic energies of deuterium ions from a perfect Coulomb explosion depend on the size of deuterium clusters based on the confirmatory measurements presented above, an ion TOF measurement of the average kinetic energy can actually be used to determine the average cluster size. The average kinetic energy of ions from a single deuterium cluster with radius of *r*, for example, can be expressed as [10]

$$< E >= \frac{ne^2r^2}{5\varepsilon_0}, \tag{5}$$

where *n* is assumed to be the number density of liquid deuterium, *e* is the charge of the deuterium ion, and ε_0 is the vacuum permittivity. Using $< E >$=14.5 ±1.5 keV, we expect the average diameter of deuterium clusters within the gas mixture to be 18.2 ±0.9 nm. This value lies within the error bars of Fig. 7(b) at 87 K, corroborating both cluster size determination methods.

Note, however, that the measured deuterium cluster sizes are far smaller than the average sizes calculated using the Hagena parameter [22,51] for the above mentioned gas jet conditions. Using that formulation, deuterium clusters with an average diameter of 190 nm are expected with our conical nozzle. Even the modified empirical formula in Ref. [23] overestimates the cluster size as 80 nm. These deviations from the widely used Hagena scaling law have been reported in recent studies [29,30], where degradation of the nozzle performance was observed using conical nozzles with large d_{eq} at high backing pressure. This emphasizes the importance of measuring the average size of deuterium clusters directly from experiments.

VI. Conclusions

We measured the average size of deuterium clusters within a mixture of deuterium clusters and helium gas, and compared it with that within a pure deuterium cluster gas jet. When the total backing pressure and temperature of a gas mixture were nearly the same as those of deuterium gas, we observed close agreement between the two measured cluster sizes. In addition to the size measurements with Rayleigh scattering, we used ion TOF data to determine the average cluster size assuming a perfect Coulomb explosion. The average cluster size determined by this method agreed with the measured size from Rayleigh scattering. That the presence of helium atoms does not significantly alter the average size and explosion dynamics of deuterium clusters facilitates the use of a mixture of deuterium clusters and ^{3}He for beam-target-fusion experiments.

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Figures

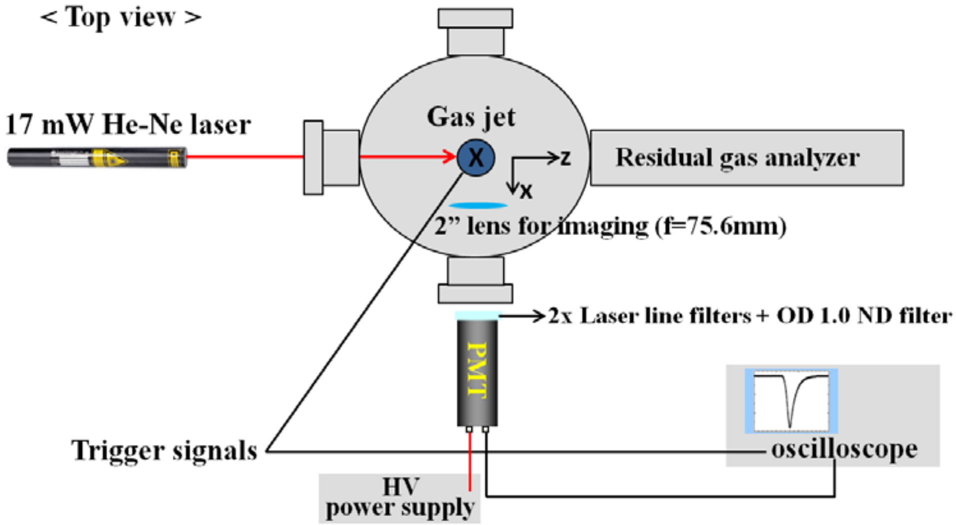

FIG. 1. (Color online) Schematic diagram of the 90° Rayleigh scattering setup for the cluster size measurements.

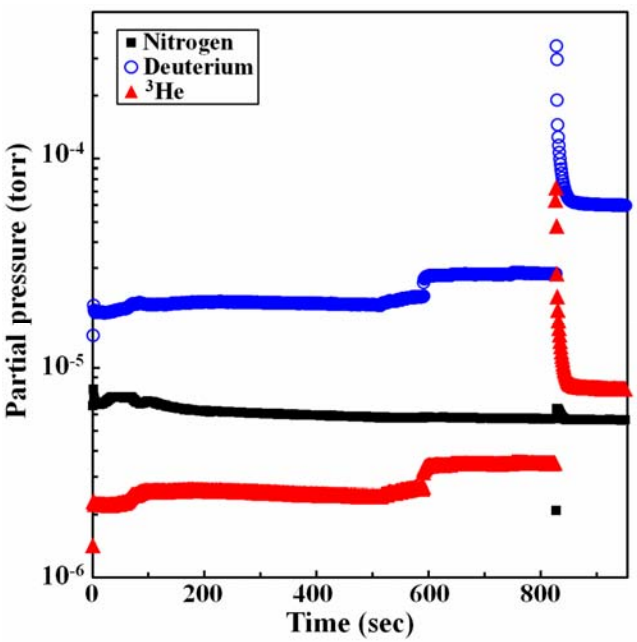

FIG. 2. (Color online) The RGA measured partial pressures of nitrogen (solid black square), deuterium (hollow blue circle), and ^{3}He (solid red triangle) as a function of time. The gas jet fired at t= 827 s, and partial pressures of deuterium and ^{3}He peaked at that time. Note that the partial pressure of the nitrogen gas inside the chamber remained largely unchanged.

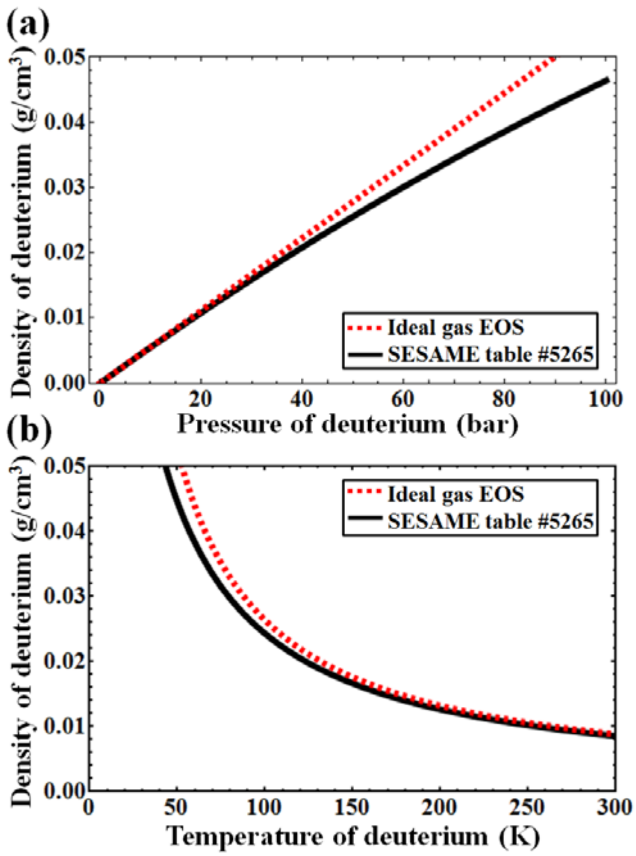

FIG. 3. (Color online) (a) Density of deuterium as a function of pressure using SESAME table #5265 (solid black line) and the ideal gas EOS (dashed red line) at 87 K, (b) density of deuterium as a function of temperature using SESAME table #5265 (solid black line) and an ideal gas EOS (dashed red line) at a gas jet backing pressure of 54 bar.

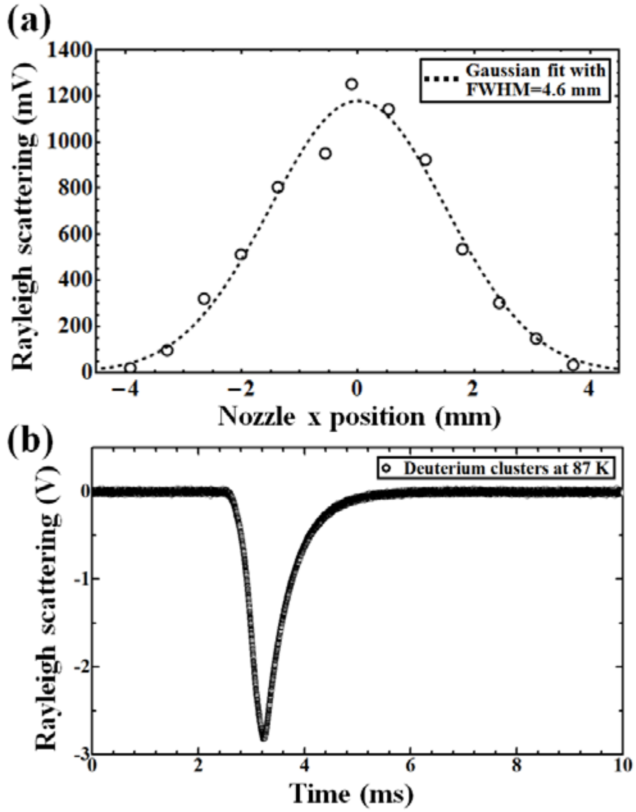

FIG. 4. (a) Rayleigh scattering signal as a function of the position of the nozzle with a Gaussian fit with a FWHM of 4.6 mm (dashed line), (b) an oscilloscope trace of the Rayleigh scattering signal from deuterium clusters with a backing pressure of 54 bar at 87 K. The pulse valve opened for 1 ms.

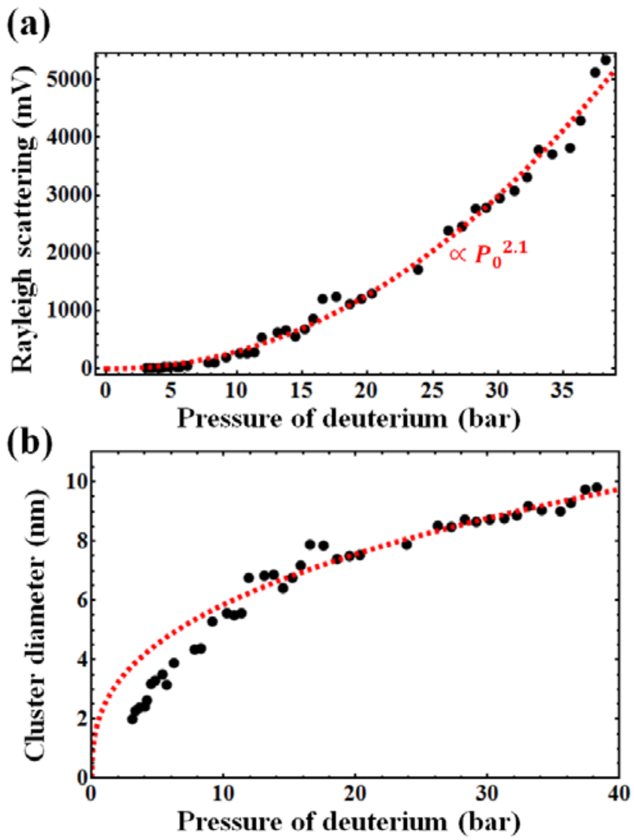

FIG. 5. (Color online) (a) Rayleigh scattering signal as a function of the backing pressure of the deuterium gas jet at 87 K, shown with a power law fit (dashed red line), $P_0^{2.1}$, (b) average diameter of deuterium clusters at different backing pressures, also shown with a fit calculated using $P_0^{2.1}$ dependence (dashed red line).

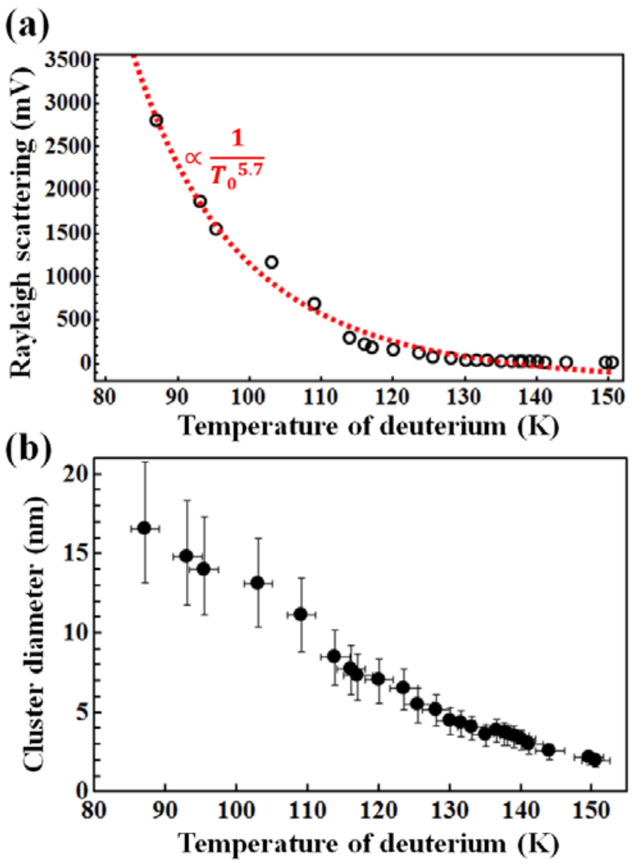

FIG. 6. (Color online) (a) Rayleigh scattering signal as a function of the deuterium gas jet temperature at a constant backing pressure of 54 bar, shown with a power law fit (dashed red line), $1/T_0^{5.7}$, (b) average diameter of deuterium clusters, with error bars, for different gas jet temperatures at a backing pressure of 54 bar.

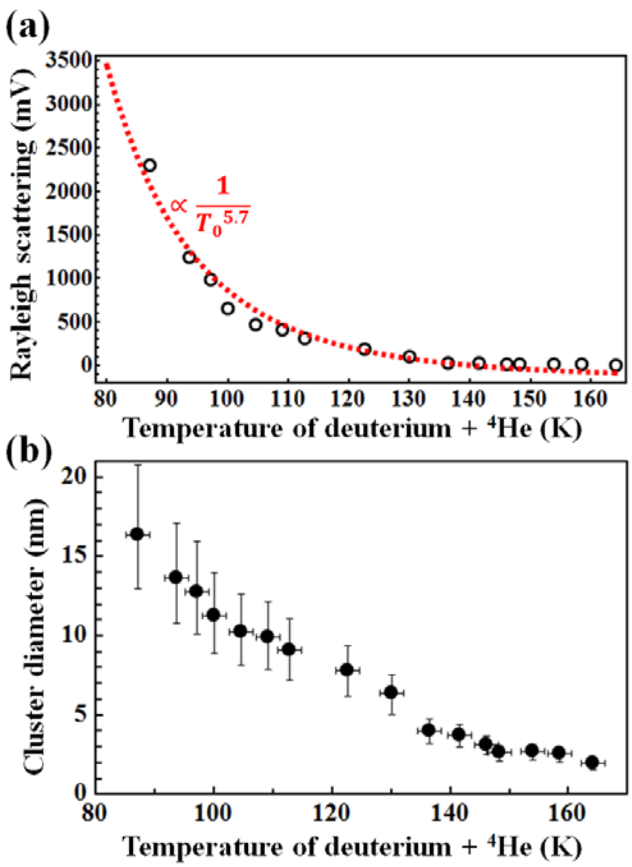

FIG. 7. (Color online) (a) Rayleigh scattering signal as a function of the temperature of deuterium + ^{4}He gas mixture at a constant backing pressure of 54 bar, shown with a power law fit (dashed red line), $1/T_0^{5.7}$, (b) average diameter of deuterium clusters in the mixture for different gas jet temperatures at a backing pressure of 54 bar, shown with error bars.

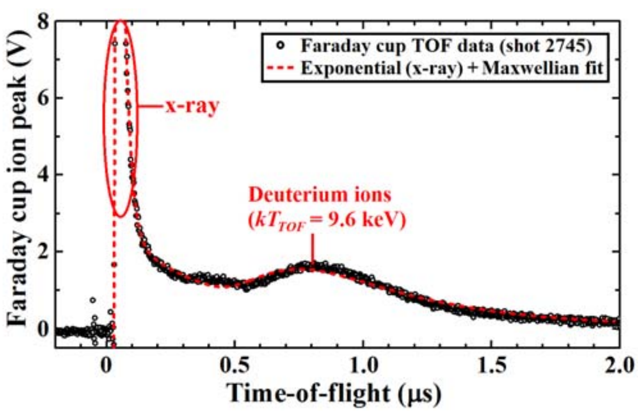

FIG. 8. (Color online) Faraday cup ion TOF data with a mixture target at an incident laser intensity of 2.2×10^{16} W/cm^2. The RGA measured the target composition and indicated (partial pressure of deuterium):(partial pressure of ^{3}He)=2:1. The average kinetic energy of deuterium ions was 14.5 ±1.5 keV on this shot (kT_{TOF}= 9.6 keV), comparable to the average ion energy reported in Ref. [16] at a similar laser intensity.