Deuterium cluster jet produced at moderate backing pressures

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A deuterium cluster jet produced in the supersonic expansion into vacuum of deuterium gas at liquid nitrogen temperature and moderate backing pressures is studied by Rayleigh scattering techniques. The experimental results show that deuterium clusters can be created at moderate gas backing pressures ranging from 8 to 23 bar, and a maximum average cluster size of 350 atoms per cluster is estimated. The temporal evolution of the cluster jet generated at the backing pressure of 20 bar demonstrates a two-plateau structure. The possible mechanism responsible for this structure is discussed. The former plateau with higher average atom and cluster densities is more suitable for the general laser-cluster interaction experiments.

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Triggered by the advent of ultrashort high-intensity lasers, interactions between this kind of lasers and clusters became a hot topic in the past decade[1−8]. Laser beams with intensities of $10^{15} - 10^{20}$ W/cm^2 can create extremely hot plasmas with ion temperatures around 10—50 keV or even 1 MeV[1,2]. Table-top laser driven deuterium-deuterium (D-D) fusion with a neutron yield of about 10^5 J^{-1} is therefore observed due to the large deuterium cluster size and the high laser energy absorption near 90% by the cluster plume[3,4].

The formation and temporal evolution of clusters in a gas jet critically affect the physical processes in the laser-cluster interaction. The increase of several orders of magnitude in ion energy in the laser-created plasmas was observed when the xenon cluster size reaching thousands of atoms[3]. Therefore, the estimation of cluster size is necessary for the laser-cluster interaction processes. Hagena's empirical scaling parameter is a good guide to estimate the cluster size, however, may be not exact enough to provide a reliable cluster size scaling for some specific experiments[9,10]. Various methods, such as time-of-flight spectroscopy[11], Rayleigh scattering[12−14], fluorescence excitation[15], and atom scattering[16], were used to measure the cluster size. Most previous experiments were restricted to rare gas clusters formed at room temperature. In this paper we investigate the formation and temporal evolution of a deuterium cluster jet which was produced at low temperature and moderate gas backing pressures using Rayleigh scattering techniques. The experimental results show that the deuterium clusters can be formed with a maximum size as large as about 350 atoms per cluster at a gas backing pressure P_0 of 23 bar. The time-resolved Rayleigh scattering measurement illustrates a two-plateau structure of the deuterium cluster jet evolving with time.

The deuterium clusters were generated during the expansion of a high pressure deuterium gas of 8 to 23 bar into vacuum through a pulsed valve and a 300-μm conical nozzle with a half opening angle of 5°. The cylindrical valve was surrounded by a close fitting liquid nitrogen reservoir. The temperature of the cluster source was cooled to about 80 K during the experiments.

The Rayleigh scattering method was employed to measure the deuterium cluster size. Figure 1 is the experimental setup of the Rayleigh scattering measurement. A 532-nm pulsed laser beam with energy of about 2 μJ was focused by a lens and introduced into the vacuum chamber to intersect the deuterium plume at right angles about 3 mm from the nozzle exit. A photomultiplier perpendicular to both the cluster jet and the incident laser beam was used to detect the scattered

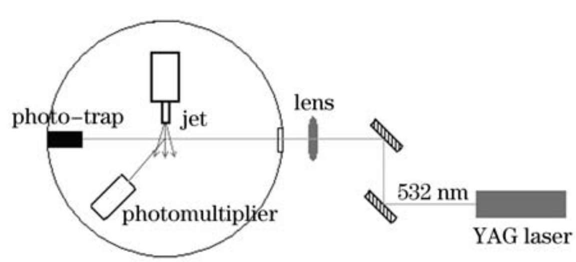

Fig. 1. Experimental layout for the size measurement of clusters in a gas jet by a Rayleigh scattering method.

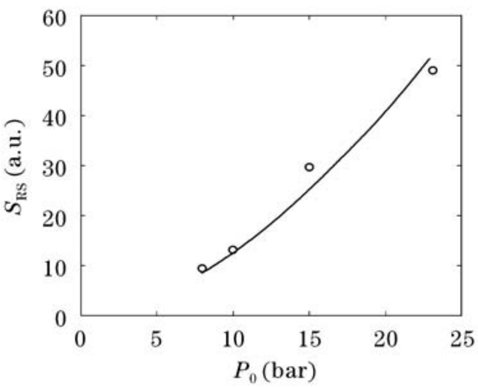

Fig. 2. Rayleigh scattering light signal S_{RS} as a function of the gas backing pressure P_0 with $S_{RS} \propto {P_0}^{1.7}$ scaling.

light from the deuterium clusters. The signal from the photomultiplier was then fed to a digital oscilloscope (LeCroy 9350AL). The data were obtained after averaging over more than 20 shots for every datum. Under the assumption that all the atoms in the plume are condensed into clusters, the classical Rayleigh scattering theory shows that the Rayleigh scattered light signal S_{RS} varies with P_0 and the average cluster size $\bar{N}_c$, given as $S_{RS} \propto P_0\bar{N}_c$. In the experiments, to suppress the noise induced by the background light reflected from chamber walls and other items in the chamber, a laser beam collimation system and a blackbody-like photo-trap were adopted.

Figure 2 shows the dependence of S_{RS} on P_0 varing from 8 to 23 bar, with a scaling of $S_{RS} \propto {P_0}^{1.7}$ being obtained. Based on the $S_{RS} \propto P_0\bar{N}_c$ relation, $\bar{N}_c$ varies with $\bar{N}_c \propto {P_0}^{0.7}$, deviating essentially from the scaling of $N_c \propto {P_0}^{2.0-2.5}$[9−11] for rare gas clusters. Moreover, unlike the results in Ref. [12] where clustering for H_2 gas began from about 33 bar. Figure 2 shows that the onset of D_2 clustering starts from the backing pressure of 8 bar. In fact, according to the rather high signal-to-noise ratio (SNR) of 2.3 observed at 8 bar, and to a separate experiment in which the onsets of D_2 clustering began at 6 bar were recorded with a SNR of 1.6, an evidently clear onset of clustering should be recognized at 5 bar in this experiment.

The present scaling of $\bar{N}_c \propto {P_0}^{0.7}$ is indeed anomalous as compared with the usual results for Ar, Kr, and Xe clusters[9−11,14,17], and even with H_2 cluster generated at gas backing pressures from 33 to 67 bar[12]. In the experiment, the gas puffed into the vacuum chamber strongly so that the working circle of the pulsed valve was kept to be 0.2—1.0 Hz in order to maintain the vacuum. It means that the opening of the pulsed valve should be long enough (several milliseconds) to support clustering of deuterium gas at moderate backing pressures. This unusual scaling of $\bar{N}_c \propto {P_0}^{0.7}$ may indicate that the H_2 gas was condensed into clusters more gradually, and the clusters grew up more slowly at these moderate backing pressures than the higher ones. At the moderate backing pressures, perhaps, only a limited percentage η of the deuterium atoms in the gas plume was condensed into clusters. If this would be true, then we will have $S_{RS} \propto \eta P_0\bar{N}_c$, resulting in a weaker scattered light signal. The criterion of the onset of clustering would be modified correspondingly from $N_c \approx 100$ to $N_c \approx 100/\eta$, compared with the conditions under which all the atoms in a gas plume are clustered, i.e., $\eta = 1$. However, it is impossible to give a quantitative estimation of the η value at present. Moreover, considering the smaller interatomic spacing of 0.36 nm for H_2 clusters (liquid hydrogen atom density is 4.22×10^{22} cm^{-3}[18]), compared with 0.38, 0.45, and 0.49 nm for Ar, Kr, and Xe clusters respectively[17], the cluster size at the onset of clustering for H_2 could be $N_c > 100$. So we take an estimated cluster size at the onset of clustering at 5 bar to be $N_c \approx 120$. Then, the largest deuterium cluster size at 23 bar is calculated to be about 350 atoms per cluster through $\bar{N}_c \propto {P_0}^{0.7}$. The cluster size in this experiment is fairly small, however, the experimental results have demonstrated that the clustering of deuterium gas can take place at liquid nitrogen temperature, especially, at the moderate gas backing pressure which is much lower than that reported in Ref. [12].

A time-resolved Rayleigh scattering experiment was conducted to examine the deuterium cluster formation process and the evolution of the cluster jet with time. By varying the delay time t_d of the laser beam with respect to the rise time of the electrical pulse which triggers the pulsed valve, the time-resolved S_{RS} as a function of t_d is illustrated in Fig. 3. In the experiment, the 300 μm nozzle was used and P_0 was 20 bar. Shown in Fig. 3 is a two-plateau structure. Starting from the delay time of 1 ms, the scattered signal increases very sharply, indicating the rapid formation of the clusters. From the delay time of about 3 ms, the signal begins to decline. The declination, which lasts not too long, is followed by a second increase of the scattered light signal. This phenomenon was reported previously only on large sizes of Kr and Xe clusters[14], never on H_2 and D_2 gases even at very high gas backing pressures[12].

The second plateau lasts very long, even 9 ms after the valve's trigger. It might be due to a second gas puffing induced by the bounce of the valve plug from the teflon O-ring when the plug is forced to close the valve under the electromagnetic force[14]. This slight plug bounce makes a dramatic effect on the cluster formation. After the main puffing gas expands into vacuum through the conical nozzle, a small quantity of gaseous clusters may remain in the nozzle room. These residual clusters may play a role as the condensation nuclei in the second gas puffing, resulting in an efficient clustering in the second plateau with the cluster sizes larger than those in the

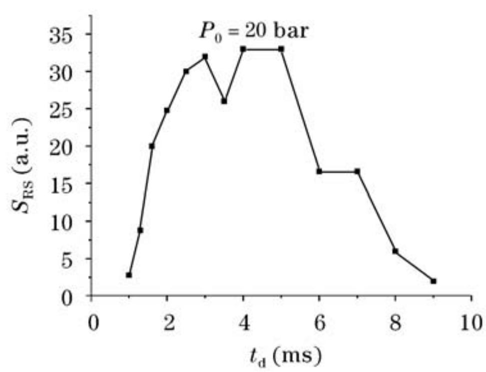

Fig. 3. The time-resolved scatted light signal S_{RS} as a function of the delay time t_d with a two-plateau structure.

first plateau. Therefore, the average cluster density $\bar{N}_c$ in the second plateau drops down substantially. Taking into account the fact that the second gas injection is much weaker than the first one, the clusters in the first plateau with higher average atomic and cluster densities are more suitable to the laser-cluster interactions in general. The time width (full-width at half-maximum, FWHM) of the first major plateau is about 2 ms.

In conclusion, the formation and temporal evolution of deuterium clusters at the moderate gas backing pressure and low temperature are experimentally studied by Rayleigh scattering techniques. The results show that clusters with a size as large as 350 atoms per cluster were formed at a deuterium gas pressure of 23 bar. The time-resolved Rayleigh scattering experiment reveals that there are two plateaus in the time evolution of the cluster jet. The first plateau is generated by the main gas puffing and has higher average atomic and cluster densities, compared with the second plateau induced by the leakage of the gas due to the bounce of the valve plug from the teflon O-ring. Due to the complexity of the clustering process revealed by many experiments including that reported here, the further work remains necessary in this regard.

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