D-D fusion induced by oxygen clusters impacting deuterated ice targets

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Deuterated ice targets were bombarded by oxygen clusters at incident energies of 115 and 172.5 keV per oxygen atom. The fusion yields were measured by detecting the 3-MeV protons from the $D(D,p)^3H$ channel. Comparisons of the fusion yields from clusters with those from single atoms at the same energy per oxygen atom show no evidence of collective enhancement, in disagreement with a recent report [Bae, Beuhler, Chu, Friedlander, and Friedman, Phys. Rev A **48**, 4461 (1993)].

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Molecular-dynamics simulations demonstrated that when a solid surface is bombarded by large clusters, sizes of hundreds of atoms, at energies of a few keV per atom, the local energy density of the bombarded region on the target surface can be higher than when it is bombarded by single atoms at these bombarding energies [1,2]. The cluster atoms lose most of their energy by nuclear collisions. Nuclear physics can provide a unique probe of this transient environment as nuclear reaction rates in this energy domain usually depend experimentally on the local temperature. Some experimental studies were reported in the past on D-D fusion induced by molecular clusters incident on deuterated polyethylene [3–7], ice [8], and TiD [9,10] targets. Although some groups claimed observing an enhancement in the fusion yields [3,9], in at least one case, it was later discovered to be an artifact due to beam contaminants [8,11].

In an early study of cluster induced fusion it had been remarked that nondeuterated clusters resulted in a small fusion rate. A later study demonstrated that fusion could be induced by a secondary reaction [5] where a projectile atom scatters off a target deuteron whose recoil energy is sufficient to induce a D-D fusion reaction with another atom deuteron. No collective enhancement was found in this study.

Recently, a new claim for cluster enhancement of the D-D fusion reaction was reported, in this case for clusters not containing deuterons [8]. The D-D fusion reaction was studied by impacting water clusters on deuterated ice targets. The enhancement increases as the cluster size changes from 2 to 4 and saturates at a value of about 2 for cluster sizes of 5 to 11. The reason for an enhancement for such small clusters is not understood. Here, we report our measurement of the D-D fusion induced by oxygen clusters impacting deuterated ice targets.

The experiment was carried out at the Nuclear Physics Laboratory in the University of Washington. An overview of the experimental apparatus is shown in Ref. [4]. 115 keV/oxygen O^-, $O_2{}^-$, and $O_3{}^-$ and 172.5 keV/oxygen O^- and $O_2{}^-$, respectively, beams were produced by a direct extraction ion source. The beam stability was monitored by an upstream beam scanner. The deuterated ice target was made in the target chamber on a thick 2.5×2.5 cm^2 copper backing. The target was kept cold throughout the experiment. The cooling of the target was achieved by attaching the target on a copper rod which extended out of the vacuum chamber into a liquid-nitrogen Dewar mounted on the top. The target uniformity was checked by using 172.5 keV deuteron beams. The variation in the target thickness was negligible. A 5.6 mm aperture was used to collimate the beam. The beam size was about 2 mm. In order to avoid melting the target, the beam current was limited to 20 nA on the target. Additionally, the target position was changed every 10 min. by 3.2 mm to vary the spot irradiated. The vacuum was better than 1×10^{-6} Torr, measured 40 cm from the target. In order to verify the integrity of the clusters at the target position, a separate experiment was performed by sending an $O_2{}^-$ cluster beam to a pair of electrostatic deflectors, located 230 cm further downstream with respect to the target position. In this experiment, the vacuum measured near the target position was $(2–3)\times10^{-6}$ Torr, several times higher than during data runs in order to establish a worst scenario. With proper bias voltages on the deflectors, more than 95% of the beam was bent 90° to the exit of the deflectors. The loss of clusters in the beam due to a breakup is very rare. Therefore breakup of the incident clusters prior to reaching the ice target can be ignored.

The fusion events were measured by detecting 3-MeV protons from the $D(D,p)^3H$ nuclear reaction using a 300 mm^2 surface barrier detector. Figure 1 is an example of the measured energy spectrum of the 3-MeV protons.

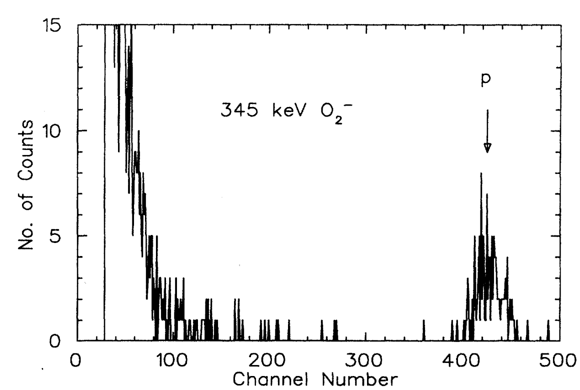

FIG. 1. Energy spectrum of the $D(D,p)^3H$ fusion reaction induced by 345 keV $O_2{}^-$ clusters bombarding a deuterated ice target. The 3-MeV proton peak appears at the right side of the spectrum.

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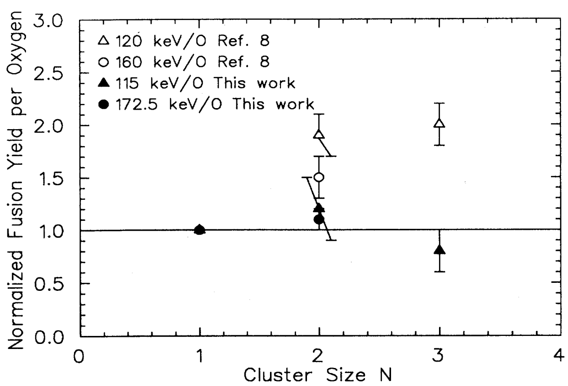

FIG. 2. Fusion yields/oxygen atom of O clusters normalized to the yields of single O atoms as a function of the cluster size. The solid symbols are from this measurement and the unfilled symbols are from Ref. [8].

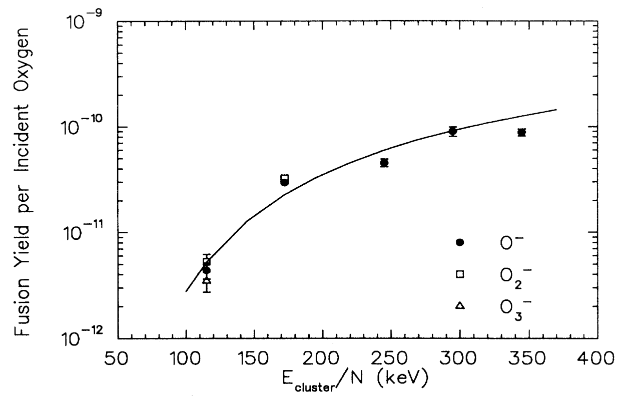

FIG. 3. Fusion yields as a function of energy. The full curve is from a knock-on calculation arbitrarily normalized to the data.

As can be seen, the region of interest is well above the detector noise level. The fusion yields, measured protons/incident oxygen atom, are compared among different incident cluster sizes in Table I. The number of incident particles in the beam was calculated from integrating the beam current on the target. Since the target ice is an insulator, a direct integration of the beam current on the target is somewhat difficult, particularly when the charge was built up in the target after a short bombardment time. To solve this problem, the beam was first tuned on the bare metal of the target where the beam current could be read directly from the target. By comparing the current on the target and the beam collimator, the sum of both made up the total current measured at an upstream Faraday cup which is 90 cm from the target. The Faraday cup, collimator, and target were biased +90 V to suppress secondary electron emission; a guard ring was biased −90 V to prevent cross talks between aperture and target. The uncertainty of the current measurement is estimated to be at most 5%. At the beginning and the end of a run, the beam current was measured at the upstream Faraday cup. During a run, the beam current was measured at the collimator and monitored by an upstream scanner. The variation in the beam intensity was insignificant throughout a run. The beam current on the target was obtained by subtracting the current measured in the collimator from the current measured in the Faraday cup. The fusion yields are of the order of 10^{-13} and 10^{-14} measured protons/incident oxygen atom for beam energies of 172.5 keV/oxygen and 115 keV/oxygen, respectively. The errors quoted here consist of statistical and systematic errors. The fusion yield for the cluster size of two, $Y(O_2)$, and three, $Y(O_3)$, normalized to the yield for a single oxygen atom, $Y(O_1)$, as a function of the cluster size, is shown in Fig. 2. The ratios $Y(O_2)/Y(O_1)$ and $Y(O_3)/Y(O_1)$ are 1 within the experimental uncertainty at those two energies. As a comparison, the results from Ref. [8] at comparable energies, 120 and 160 keV/oxygen are also shown in the figure. The ratio $Y(O_2)/Y(O_1)$ and $Y(O_3)/Y(O_1)$, from their measurement, varies between 1.5 and 2.

In this experiment, since there is no deuteron in the beam, the D-D fusion is ascribed to a knock-on mechanism. The incident oxygen cluster collides with a deuteron and transfers its energy to the deuteron. When the recoiling deuteron runs into another deuteron in the target, fusion can take place if the recoiling deuteron has enough energy. The knock-on yield is given by [12]

$$Y_{KO} = n_D N \int_0^{E_0} dE \frac{1}{|dE/dx|} \int_0^{U_{max}} dU Y(U) \frac{d\sigma(U,E)}{dU} ,$$

where n_D is the number density of D in the target ice; N is the number of atoms in a cluster; $\frac{1}{|dE/dx|}$ is the stopping power of O in the ice; $Y(U)$ is the thick target yield; $\frac{d\sigma(U,E)}{dU}$ is the differential cross section for energy transfer from O to D; $E_0 = E_{in}/N$; $U_{max} = \frac{4m_D m_O}{(m_D+m_O)^2}E_0$. Calculations were performed to estimate the knock-on yield as a function of the beam energy. The stopping power of oxygen in the ice target was obtained from Ziegler's TRIM [13] calculations. The Rutherford cross section was used as the energy-transfer cross section $\frac{d\sigma(U,E)}{dU}$ [5]. Shown in Fig. 3 is the result of the knock-on calculations compared with the data. The calculation, shown by the solid curve, was arbitrarily normalized to the data. The calculation overpredicts the fusion yield by an order of magnitude. This may be due to the parametrization of the energy-transfer cross section by the Rutherford cross section and to uncertainties in the stopping powers. However, the measured energy dependence of the fusion yield is reasonably well described by the calculation. Moreover, the

TABLE I. Measured protons per incident oxygen atom.

E/N (keV)	$Y(O^-)$	$Y(O_2{}^-)$	$Y(O_3{}^-)$
172.5	$(3.9 \pm 0.1) \times 10^{-13}$	$(4.3 \pm 0.2) \times 10^{-13}$	
115	$(5.8 \pm 1.0) \times 10^{-14}$	$(7.0 \pm 1.2) \times 10^{-14}$	$(4.6 \pm 1.0) \times 10^{-14}$

measured fusion yields are comparable to those measured in Ref. [5].

To summarize, the D-D fusion yields for deuterated ice targets impacted by oxygen clusters were measured. The results were compared at the same incident energy per oxygen atom for different cluster sizes. In contrast to the results of Ref. [8], no collective effect, defined as an enhancement in fusion yields for clusters as compared to single atoms, was observed. The energy dependence of the fusion yields are consistent with a knock-on mechanism. Further study using larger clusters is underway.

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