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Neutron enhancement from laser interaction with a critical fluid

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ABSTRACT

We discuss experimentally and theoretically neutron production from the laser driven explosion of gas clusters prepared near the liquid-gas critical point. We let deuterated methane that was prepared very close to its critical temperature and pressure expand through a conical nozzle to create clusters, and then irradiated those clusters with a high intensity pulse from the Texas Petawatt Laser. After ionization, the clusters explode producing energetic ions, some of which fuse with resultant neutron emission. We show that the critical fluctuations present in the nozzle before the expansion influence the dynamics of neutron production. Neutron production near the critical point follows a power law, which is a signature of a second order phase transition and it is consistent with the Fisher model. This result might be relevant for energy production from fusion reactions.

An intense, ultrashort pulse laser can ionize atomic and molecular clusters within a gas, creating conditions for nuclear fusion in the resulting plasma [1–14]. The laser-driven explosion of cryogenically cooled deuterium (D_2) clusters or near-room-temperature deuterated methane (CD_4) clusters, are two such examples. In our experiments, 100 J laser pulses of around 150 fs duration produced explosions of the clusters resulting in tens of keV ion plasma temperature. DD fusion occurring within this high temperature plasma (commonly referred as beam–beam fusion mechanism), along with beam-target fusion between the ejected ions of the clusters and surrounding cold cluster gas, leads to a burst of fusion neutrons and protons. Following these experiments, we prepared our CD_4 gas cluster source close to its critical pressure ($P_c = 4660$ kPa) and temperature ($T_c = 189.2$ K) for the liquid-gas phase transition. For D_2, the critical point ($T_c = 38.34$ K, $P_c = 1665$ kPa) is much lower than we could reach with our experimental setup; thus, we only used it for comparison [15]. We would like to stress here that one of the goals of these experiments is to measure fusion cross sections in plasmas [13] in the region of tens of KeV (Gamow peak) which are relevant for astrophysical considerations.

We addressed three main questions in our experiment:

1) Are nuclear processes influenced by fluctuations in a system prepared near a critical point?
2) What are the signatures, if any, of the critical behavior?
3) Does the expansion of the critical fluid modify its properties?

The number of neutrons (or fusions in general) N_f from the hot plasma is given by:

$$N_f = \rho_1 \rho_2 \frac{V}{1+\delta_{12}} \int \frac{dN}{dE} \sigma(E) \xi(E) dE. \quad (1)$$

In eq. (1), ρ_1 and ρ_2 are the densities of the colliding ions of species 1 and 2 respectively. For identical particles (i.e. DD fusions) the Kronecker delta δ_{12} is equal to one. We have conveniently singled out the volume V, which is fixed by the laser focus creating the plasma. The hot plasma kinetic energy distribution dN/dE is normalized to one. The symbols $\sigma(E)$ and $\xi(E)$ are the fusion cross section and the ion range for such reaction in the hot plasma.

For a fluid prepared near the critical point, the density is an order parameter [16]:

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$$\Delta\rho \equiv \rho_l - \rho_g \sim \left|\frac{T - T_c}{T_c}\right|^{\beta} \equiv |t|^{\beta}. \quad (2)$$

T and T_c are the temperature and the critical temperature of the fluid, respectively. The $\sim$ implies that the density has a singular part proportional to the distance from the reduced critical temperature [16]: $\beta = 0.32$–0.39 is one critical exponent [16].

We can tentatively associate the range of the ions with the correlation length in a critical fluid:

$$\xi \sim |t|^{-\nu}. \quad (3)$$

$\nu = 0.6$–0.7 is another critical exponent [16]. Near the critical point, eq. (3) diverges [15,16]. Already from these simple considerations it is clear that the initial correlations might influence the neutron production with a singular part $N_f \sim |t|^{2\beta-\nu}$; i.e. with a critical exponent $\eta = 2\beta - \nu = 0.05$, the Rushbrooke law [16]. In our case, the system can at most reach the finite dimension of the order of R, the radius of the nozzle, thus:

$$\xi \le R. \quad (4)$$

We assume that the range is a constant for given initial T and critical pressure P and it can be taken out of the integral in eq. (1). Recall that, for finite systems, divergences become maxima.

There are other experimental features that influence the ion range in the plasma and in particular the laser pulse duration based on our previous measurements [15]. Essentially the laser beam ionizes the clusters or drops formed during the expansion from the nozzle. The 'naked' ions are now subject to an intense Coulomb repulsion and they acquire kinetic energy [1–14]. Ions coming from different clusters (drops) can collide and fuse in a quantity governed by eq. (1). There are two important durations relevant to our considerations [17,18]. The first one, τ_{cl}, is the time of an ion to cross the cluster of size R_{cl} [17,18]:

$$\tau_{\mathrm{cl}} \approx \frac{R_{\mathrm{cl}}}{v_D} = 7.7\ \mathrm{fs}, \quad (5)$$

where $R_{\mathrm{cl}} = r_0 M^{1/3} = 1.7 M^{1/3} A^0$, M is the number of ions in a cluster (drop). v_D is the average ion velocity which can be obtained from the average Coulomb energy V_c per ion:

$$\frac{V_c}{M} = 5.1 M^{\frac{2}{3}}\ (\mathrm{eV}) = E_D = \frac{1}{2} m_D v_D^2, \quad (6)$$

with m_D representing the ion mass.

This time is usually shorter than the laser pulse duration (about 150 fs for the Texas Petawatt laser). That means that a cluster will disassemble before all the laser energy is deposited onto the gas. Energetic ions could reach another cluster before the remaining laser pulse ionizes it. The crossing time τ_{IC} needed for an ion to reach another cluster is defined as [17]:

$$\tau_{IC} = \frac{R_{IC}}{v_D} = \frac{(\frac{\rho}{M})^{-\frac{1}{3}}}{v_D} \approx 450\ \mathrm{fs}, \quad (7)$$

where we have assumed $\rho = 10^{18}\ \mathrm{cm}^{-3}$ and define R_{IC} as the average distance among clusters. Under our normal conditions, the laser pulse duration is much shorter than the ion inter-cluster crossing time. We therefore assume that neutron production in the laser-gas interaction region occurs mostly between ions coming from the disassembly of two different clusters. This mechanism is referred to as beam–beam (BB) fusion reactions [10–14]. In these conditions we expect the ion range in the hot plasma to be of the order of the nozzle radius. However, we can increase the laser pulse duration time to study its effects when it becomes comparable or larger than the τ_{IC} estimated above. For much longer times we expect that energetic ions might collide with clusters in the same laser beam direction, which have not been ionized yet by the laser ionization wave. In this case the fusion mechanism is referred to as beam-target (BT) mechanism since one of the two ions is practically at rest. Eq. (1) must be modified and in particular the ion range might scale like eq. (3) in the case of a critical fluid [15]. If these considerations are correct we expect that increasing the laser pulse duration time will decrease the number of neutrons [18] produced from systems prepared in similar conditions, i.e. similar chemical composition, temperature and pressure at the nozzle, focusing etc. Within this scenario we expect the number of neutrons $\#n$ to be approximately given by:

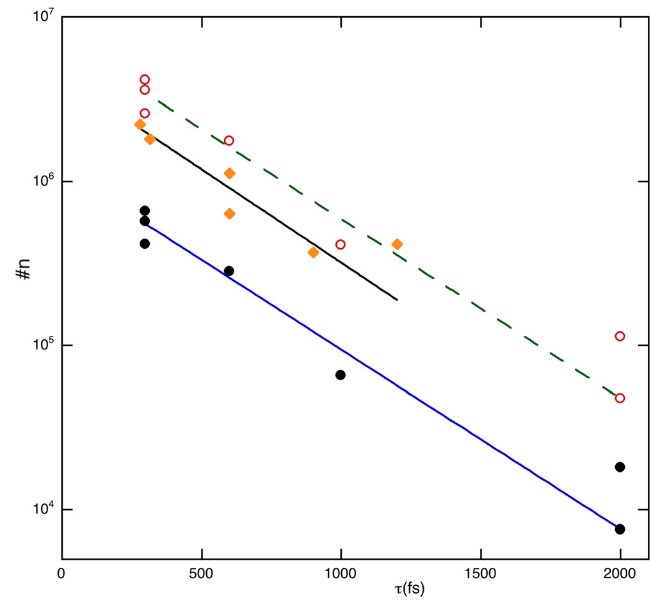

Fig. 1. Number of produced neutrons in D_2 (full diamonds) and CD_4 (full circles) as function of the laser pulse duration. The fitting lines are exponential decays according to eq. (8). The open circles are the CD_4 results multiplied by a factor 6.25 (see text).

$$\#n = \#n_0 e^{-\tau/\tau_{IC}}, \quad (8)$$

$\#n_0$ is the number of neutrons obtained in the limit of zero pulse duration. We have verified eq. (8) by preparing either D_2 or CD_4 gases in similar initial physical conditions and changing the laser pulse duration up to 2000 fs. In Fig. 1 we plot the number of detected neutrons vs the laser pulse duration together with the fit according to eq. (8).

The fits give the following values for $\#n_0 = 4.4 \pm 0.8 \cdot 10^6$ ($1.2 \pm 0.3 \cdot 10^6$) and $\tau_{IC} = 382 \pm 71$ fs (397 ± 127 fs) for D_2 (CD_4) gases. In our experiment we found a maximum number of $\#n$ for the two systems in agreement with $\#n_0$ and laser pulse duration around 150 fs. The lower neutron yield obtained from the CD_4 system respect to D_2 should not surprise. It is mostly due to the D concentration, for CD_4 the concentration reduces the neutron yield by a factor 1/6.25 for a similar ion current. Thus we predict that if a D_2 gas is prepared near the critical point, the neutron yield should be at least a factor 6.25 larger than the CD_4 gas prepared near its critical point, open circles in Fig. 1.

The values of τ_{IC} suggest slightly larger average deuterium densities than given above, eq. (7), and in particular, $1.60 \cdot 10^{18}\ \mathrm{cm}^{-3}$ and $1.46 \cdot 10^{18}\ \mathrm{cm}^{-3}$ for D_2 and CD_4 respectively [15]. The above considerations support the possibility of change of the fusion mechanism in the hot region from BB to BT [17] and in particular the possibility that the ions range might be given either by eq. (3) or eq. (4), thus with a critical exponent between 0 and $-\nu$.

To complete our analysis of eq. (1) we need to estimate the quantity inside the integral. The range can be assumed indepen-