Ion Heating and Thermonuclear Neutron Production from High-Intensity Subpicosecond Laser Pulses Interacting with Underdense Plasmas

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Thermonuclear fusion neutrons produced by $D(d,n)^3He$ reactions have been measured from the interaction of a high-intensity laser with underdense deuterium plasmas. For an input laser energy of 62 J, more than $(1.0 \pm 0.2) \times 10^6$ neutrons with a mean kinetic energy of (2.5 ± 0.2) MeV were detected. These neutrons were observed to have an isotropic angular emission profile. By comparing these measurements with those using a secondary solid CD_2 target it was determined that neutrons are produced from direct ion heating during this interaction.

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The generation of energetic particles and radiation from intense laser-plasma interactions is a new and rapidly evolving branch of physics and of particular interest for two important reasons. First, these plasmas are efficient sources of bright, energetic, and strongly collimated electron [1], proton [2], and γ ray beams [3] which may have a wide range of applications. Second, measurements of these beams provide a useful plasma diagnostic technique and can elucidate much of the fundamental physics which occurs in these interactions.

Recently, there have been important observations and simulations of neutron generation during the interaction of high-intensity lasers with matter at solid or near-solid densities [4]. These neutrons are generated by laser produced ion beams in solid deuterated targets via $D(d,n)^3He$ reactions and can provide information on the spectrum of the accelerated deuterons as well as heating processes which occur during these interactions.

In contrast, the study of ion dynamics in the interaction of intense lasers with underdense plasmas has received less attention, even though it is well known that such interactions can produce energetic ions. For example, an intense laser pulse passing through a plasma causes the radial displacement of electrons due to its ponderomotive force, $\mathbf{F}_p = -m_e c^2 \nabla(1 + a^2/2)^{1/2}$, where a is the normalized vector potential of the laser. This results in an impulsive acceleration of the ions, often called a "Coulomb explosion." The maximum ion energy that can be produced by this process is equal to their ponderomotive energy, $U = Zm_e c^2(\gamma - 1)$, where γ is the relativistic quiver velocity of electrons in the laser field given by $\gamma = (1 + a^2/2)^{1/2}$. For modern laser systems which reach relativistic intensities ($a > 1$), the energy of Coulomb explosion ions can reach several MeV [5]. Thus this process may trigger nuclear reactions within the laser focus [6].

Furthermore, the interaction of intense laser pulses with underdense plasmas can generate extremely high current electron beams [7]. It is well known that their beam particle density, n_b, is comparable to the ambient plasma density, n_e, which hence leads to a stopping power in plasmas, which is several orders of magnitude greater than the classical stopping power due to binary Coulomb collisions. Much of this enhanced stopping can be attributed to ion heating either by the beam or by the self-generated return current. This can result in significantly higher ion plasma temperatures [8].

In this Letter we present the first experimental evidence of neutron generation due to the interaction of an intense laser pulse with an underdense deuterium plasma. This confirms that it is possible for the ions in these interactions to reach keV energies required for $D(d,n)^3He$ reactions. Moreover, since neutrons have little interaction with the ambient matter, one can obtain information concerning the ion kinetics by studying the yield, spectrum, and angular distribution of the emitted neutrons. From these studies, we find that the measured neutron yield cannot be explained solely by the propagation of the Coulomb explosion ions through the ambient D_2 gas. It is deduced that plasma ions are heated to thermonuclear fusion temperatures by a noncollisional heating mechanism.

The experiment was performed on the Vulcan:CPA laser. The laser produced pulses with a duration of 0.8 to 1 ps and an energy, E_l, of up to 62 J on target, at a wavelength of 1.05 μm. Using a $f/4$ off-axis parabolic mirror, the laser beam was focused onto the edge of a D_2 gas jet produced by a 1 mm diameter sonic nozzle, which was located 1 mm below the focus. The waist of the focal spot, w_0, was 20 μm, resulting in a peak intensity of up to 2×10^{19} W/cm^2. Interferometric studies were used to characterize the atomic density profile [9]. In addition, the plasma density, n_d, which was selected to be in the range 1×10^{19} to 1×10^{20} cm^{-3}, was verified on each shot by forward Raman scattering measurements.

The time-of-flight (TOF) technique was used to obtain the neutron energy spectrum and angular distribution [10]. For this measurement, the detectors used were 5 cm diameter cylindrical NE102 scintillators, which had a rise time of 1.5 ns. These were coupled to the windows of photomultiplier (PM) tubes. The output of the PM tubes was read out on oscilloscopes, with a 500 ps sampling rate. Up to five of these detectors were used simultaneously at various distances from 1.9 to 5.5 m from the interaction region and at angles, θ, of 0 to 180° relative to the direction of propagation of the laser beam, z, in the horizontal (x, z) plane. To suppress background signals due to scattered neutrons and those generated elsewhere, up to 53 cm long tapered collimators of polyethylene and lead were used. These pointed directly towards the interaction region.

A typical TOF trace is shown in the inset of Fig. 1. This is representative of the TOF signal for detectors at all angles θ for these shots. The prompt signal is the γ flash due to bremsstrahlung generated by the energetic electrons that are produced in this interaction [7]. The peak at 187 ns is produced by neutron events having an energy E_n of (2.5 ± 0.2) MeV. This energy is characteristic for neutrons produced by thermonuclear $D(d, n)^3$He fusion reactions. The short neutron pulse confirms that these neutrons are not due to the (γ, n) or $(e, e'n)$ processes, which would produce a broader spectrum. To ensure that the peak was due to the $D(d, n)^3$He reaction, additional shots with helium as a target gas were performed. In this case, no neutron peak was observed.

The TOF signals were converted to an energy spectrum. An example spectrum for a detector at θ of 67° is

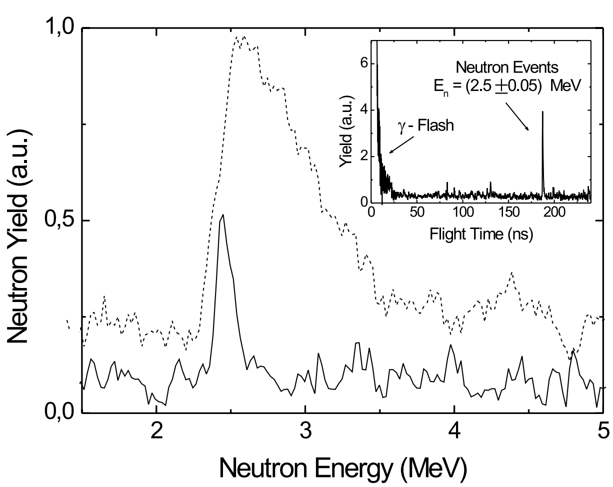

FIG. 1. Neutron spectrum for detector at θ of 67° with (dashed line) and without the secondary CD_2 target (solid line). The inset shows the corresponding TOF signal, which is typical for detectors at all θ for shots without the secondary target. For both shots, $n_d = 5 \times 10^{19}$ cm^{-3} and $E_l = 62$ J.

shown by the solid line in Fig. 1. Simulations with the Monte Carlo neutron transportation code MCNP [11] confirmed that no significant broadening of the signal occurred once the neutrons passed the target chamber. Thus, the spectrum of the emitted neutrons is simply determined by the kinematics of the original $D(d, n)^3$He reaction [12]. The isotropy and approximate Gaussian profile of the neutron spectrum suggests an initially Maxwellian deuteron distribution. With this assumption one can obtain the deuteron temperature required to produce the measured neutron energy spectrum [13]. The ion temperature implied by the solid line in Fig. 1 is (1 ± 0.2) keV.

Special attention was paid to a precise determination of the neutron yield. These additional measurements were made by nuclear activation of ^{115}In, by the process $^{115}\text{In} + n \rightarrow {}^{116}\text{In}^* \rightarrow {}^{116}\text{Sn} + e^- + \overline{\nu}_e$, where the metastable $^{116}\text{In}^*$ decays with a half-life of 54 min to ^{116}Sn, by β^- decay. The thickness of the activation target must be chosen to increase the efficiency of neutron capture, but not significantly affect the emitted electrons. The thickness used was 100 mg/cm^2, which is close to the optimum of 90 mg/cm^2 (see Ref. [14] and references therein). The total cross section, σ_t, of ^{115}In is several hundred mb for thermal neutrons [15]. Therefore, the indium foils were stacked at different distances, $\tilde{x}$, within a polyethylene brick, which acted as a moderator. This brick was placed at closest 9 cm from the interaction, and at θ of 90°. To reduce measurement of scattered neutrons and those generated by other processes, the bricks were shielded by extra layers of polyethylene.

Since this activation can also be due to a resonance of the ^{115}In nucleus from epithermal neutrons of 1.46 eV, the foils were shielded with cadmium, which has an approximately 100 times higher cross section for thermal neutrons. The difference in activity between shielded and unshielded indium foils gives the activation due to thermal neutrons. The β^- decay was measured using a Geiger-Müller counter which had a very low background due to the special low-activity lead shielding used. The number of neutrons on the activation detector was then calculated from the activity, $\dot{\phi}$, as a function of distance, $\sim \int_0^\infty \dot{\phi}(\tilde{x})\tilde{x}^2 d\tilde{x}$ [14]. Since the angular distribution was also measured by the TOF detectors and found to be almost isotropic for these shots, the total yield of neutrons can be estimated. A maximum of $(1.0 \pm 0.2) \times 10^6$ neutrons per shot was observed.

To assess if the observed neutron yield could be due to the Coulomb explosion accelerated ions, the spectrum of these ions was measured using a Thomson parabola ion spectrometer at an angle θ of 90°. CR-39 nuclear track detectors recorded the dispersed ions. As has been previously measured, the energetic ion emission was sharply peaked in this direction [5]. In these experiments about 2×10^{11} deuterons accelerated above 100 keV and up to a maximum energy of (1.2 ± 0.2) MeV were observed as can be seen in Fig. 2. Equating this to the ponderomotive potential energy U indicates that the averaged intensities in the focal spot were as expected of the order 10^{19} W/cm^2. Calculating the likely yield that these ions produce as they travel through the ambient gas surrounding the plasma, one finds that no more than 10^4 neutrons could have been produced in this way.

To demonstrate this more clearly, a 200 μm thick and 5 mm wide solid deuterated plastic (CD_2) target was placed 2.5 mm away from the interaction at the same angle as the Thomson parabola. The purpose of this target is to simulate the beam-target interaction of the expelled ions as they pass through the stationary ambient gas, but obviously with a much higher reaction rate due to the higher density of deuterons in the solid. This resulted in a significant enhancement of the neutron signal, as expected. The increase in yield is more than 1 order of magnitude, as shown by the dashed line in Fig. 1. As can be seen in Fig. 3, the energy of the emitted neutron from a beam-target $D(d, n)^3He$ reaction is a function of the relative angle, α, of observation to the deuteron momentum. The broad neutron spectrum, when the deuterated target is present, reflects that there is a continuous deuteron distribution for the $D(d, n)^3He$ reaction up to an energy of (1.0 ± 0.1) MeV. Furthermore, the distribution of the deuterons incident on the target can be calculated by

$$N_n(E_d, \theta) = n_D \int_0^\infty \frac{dN_d}{dE_d} dE_d \int_0^{E_d} \frac{\sigma(E, \theta)}{\varepsilon(E)} dE, \qquad (1)$$

where N_n is the neutron yield for $N_d(E_d)$ deuterons expelled from the plasma, n_D is the deuteron density inside the solid target, σ is the differential cross section for the $D(d, n)^3He$ reaction [10], and ε is the stopping cross section within the solid CD_2. This calculation reveals that the neutrons were produced by a Maxwellian distribution of deuterons with temperature T^{calc} of (186 ± 39) keV. This compares with the ion temperature measured by the Thomson parabola T^{exp} of (216 ± 36) keV, as shown in Fig. 2. Therefore, it is clear that the broad neutron spectrum with the solid target is the result of the radial beam of deuterons expelled from the plasma from the Coulomb explosion. However, it is also clear that the interaction of this distribution with the ambient deuterium gas cannot account for the narrow neutron spectrum obtained without the external target.

This is further emphasized by the angular dependence of the neutron emission with and without the external CD_2 target, as presented in Fig. 4. In the case of (d, n) reactions with the secondary target, an angular variation in the distribution can be observed with a minimum in the laser propagation direction, since this direction is orthogonal to the motion of all of the accelerated ions [10]. In contrast, the thermonuclear fusion neutrons generated directly in the plasma have a more isotropic emission profile in yield and temperature.

From these measurements it is clear that the neutron production without an external target cannot be ascribed to a beam-target reaction but is the result of a much more isotropic thermal distribution of ions. Surprisingly neither the neutron yield nor the plasma temperature as implied by the width of the neutron spectra exhibit a very strong dependence with the deuteron density.

A simplified estimate for the expected yield for a thermal plasma can be made from $N_n = \frac{1}{2} \cdot \langle \sigma v \rangle \cdot n_d^2 \cdot V \cdot \tau$, where $\langle \sigma v \rangle$ is the velocity-averaged fusion cross section for a Maxwellian velocity distribution [16]. Assuming that the confinement duration, τ, is about the plasma disassembly time, i.e., $\tau = w_0/C_s$, where C_s is the ion sound speed, and that the volume V is given by the original laser volume, this expression would require a plasma temperature of 40 keV for the observed yield.

The discrepancy between the temperature measured from the neutron spectra and that implied by the yield

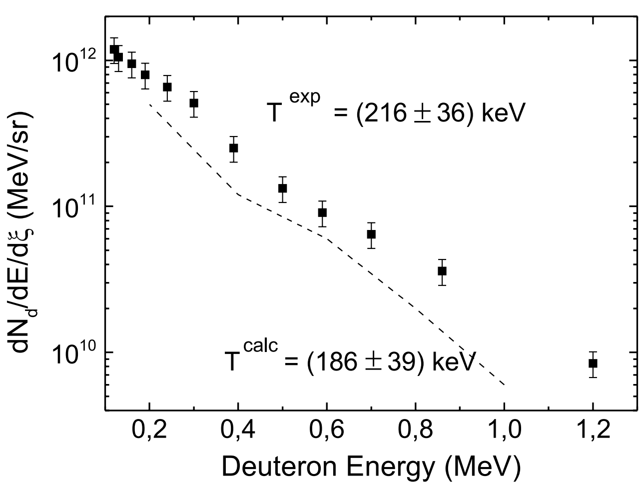

FIG. 2. Deuteron spectrum from Coulomb explosion as measured by the Thomson parabola (squares) and as calculated from the TOF signal using Eq. (1) (dashed line).

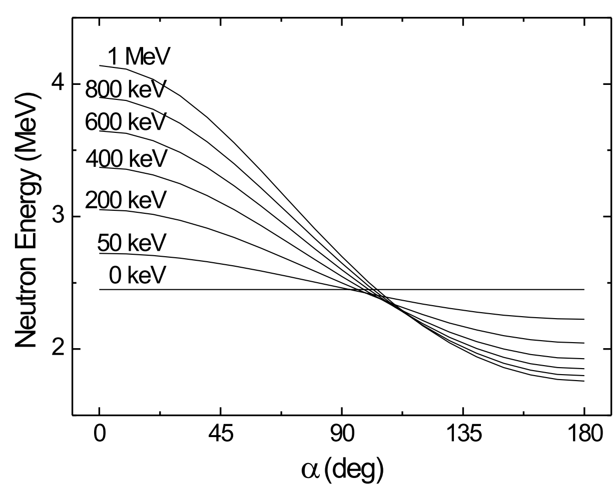

FIG. 3. Neutron energy as a function of the relative angle, α, of observation between incident deuteron and expelled neutron for $D(d, n)^3He$ reactions.

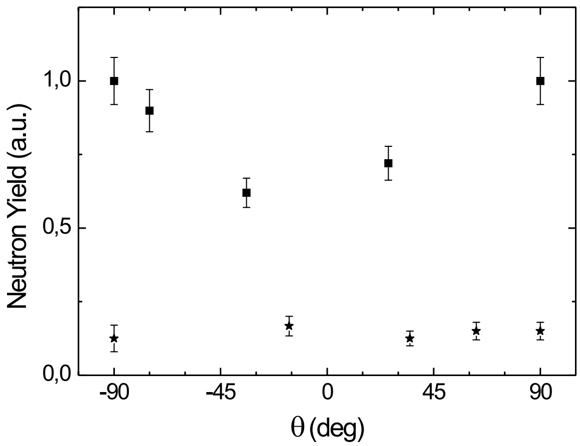

FIG. 4. Angular distribution of neutrons with (squares) and without (stars) the solid CD_2 target for two typical shots.

suggests that our assumption of a Maxwellian distribution is not adequate. In particular, it suggests the existence of a hotter tail of deuterons which are colliding with small center-of-mass momentum, which results in less broadening than expected. The yield may also be increased due to a heating over a larger volume over time greater than the disassembly time due to shock heating, as recently demonstrated in numerical simulations [6].

It is well known that the interaction of an intense laser pulse with underdense plasmas can result in efficient absorption of the laser pulse. This can lead to the production of not only beams of energetic electrons but also to a hot thermal bulk of electrons [17]. However, for the range of densities explored in this study, the time for the electrons to equilibrate with the ions is well in excess of the disassembly time for the plasma. For our conditions, τ_{eq} is more than 1 ns. Hence this ion heating must be the result of direct noncollisional heating mechanisms that occur on the time scale of the laser pulse. The simplest explanation for the ion heating is due to variations in the Coulomb potential caused by the ponderomotive expulsion of charge by the laser pulse. This is quite likely due to the presence of self-focusing and other propagation instabilities under these conditions. However, it is also noted that by systematically varying the plasma density, a correlation was observed between the neutron yield and the generation of energetic electrons. The electrons are generated by wave breaking [1] and result in a hot electron tail in the distribution with a total current approaching the Alfvén limit [7]. At densities n_{WB} below the wave breaking limit of about 1.5×10^{19} cm^{-3}, both neutron and hot electron yields dropped dramatically. However, above this deuteron density, the neutron yield showed no great variation with density. Recent simulations have shown that the filamentation and propagation instabilities of such high current electron beams in a plasma can result in collisionless heating of the ions [18].

In summary, we have observed the generation of $(1.0 \pm 0.2) \times 10^6$ thermonuclear fusion neutrons from the interaction of an intense laser pulse with an underdense plasma. These neutrons are generated by $D(d, n)^3He$ reactions in the plasma which is heated to thermonuclear fusion temperatures. It is therefore possible to measure the ion temperature of the underdense plasma, which was found to be 1 keV.

Finally it is noted that no special attention was given to maximizing the neutron yield in this experiment. It is expected that using a pulse guided over a longer distance can increase the efficiency of energy transfer to deuterons [6]. Moreover, it has been demonstrated that a small CD_2 target can increase the neutron yield by over an order of magnitude. It is thought that a longer interaction length coupled to a solid CD_2 target, which stops all the radially ejected deuterons, can significantly enhance the neutron production. This may make this interaction an attractive source for applications that require bright and short duration pulses of neutrons.

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