can make an *order-of-magnitude* estimate of Γ using a classical hard-sphere model for the collisions where the rotons are assumed to be stationary, and the He^3 quasiparticles move with a mean speed $\langle v\rangle = (3kT/m_3{}^*)^{1/2}$. Then

$$\Gamma(^\circ\mathrm{K}) = \hbar/2k\tau = (\hbar/k)\sigma n\langle v\rangle(2/3\pi)^{1/2}X,$$

where τ^{-1} is the mean collision frequency, n is the number density of atoms, and $m_3{}^* \approx 2.3m_3$ is the effective mass of the He^3 quasiparticle. Using a value of $\sigma = 1.6\times10^{-14}$ cm^2 measured by Herzlinger and King,[5] this expression becomes $\Gamma(^\circ\mathrm{K}) = 5.7X$, in satisfactory agreement with our results.

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†Alfred P. Sloan Research Fellow.

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[8] The Boltzman factor which skews the line shapes of the neutron-scattering results of Dietrich *et al.* (Ref. 1) differs from 1 by $\sim 10^{-6}$ for $T = 0.6$°K and $\hbar\omega/k_B = 8.7$°K, and therefore has a negligible effect on these results.

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Neutron Emission from Laser-Produced Plasmas*

G. H. McCall, F. Young, A. W. Ehler, J. F. Kephart, and R. P. Godwin
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87544

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Neutron emission from laser-produced plasmas is shown, experimentally, to be adequately explained by electron heating and electrostatic ion acceleration. The absence of anomalous ion-heating mechanisms is not proved, but these mechanisms, if they exist, may be unimportant in reported experiments. It is concluded that no neutrons of thermonuclear origin are necessary to explain the results obtained thus far.

Because of the possible application of lasers for the production of thermonuclear fusion, much attention has focused on the generation of neutrons in laser-produced plasmas of deuterium or deuterated polyethylene (CD_2). Inverse bremsstrahlung and other mechanisms which selectively heat only electrons are discounted as ways of heating ions to thermonuclear temperatures because of the long electron-ion equilibration time in these plasmas.[1-4] Various anomalous ion-heating mechanisms are invoked to explain the neutron emission.[5-8] In the work described below, we show that anomalous ion heating is unnecessary and possibly incorrect as a description of the neutron-generation mechanism.

It is well known that neutrons are observed in plasmas heated with 2- to 10-nsec pulse lengths,[9-12] but not to any great extent in plasmas heated with picosecond pulses.[10,13,14] We have investigated the problem experimentally using a mode-locked Nd:YAlG (yttrium aluminum garnet), Nd:glass laser capable of delivering up to 17 J, in a bandwidth-limited pulse approximately 25 psec in length, to a solid target. These experiments em-

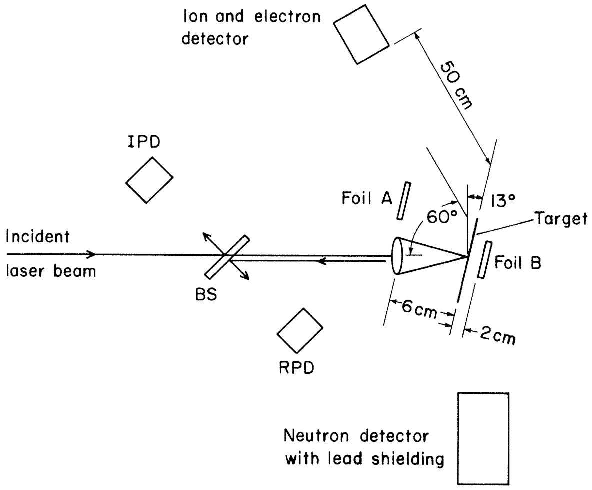

FIG. 1. Experimental setup. IPD and RPD are photodiodes for measuring incident and reflected laser energy, respectively. BS is a beam splitter.

ployed an $f/3.5$ aspheric lens which produced a spot diameter of 50 μm or less on a 125-μm-thick target of CH_2 or CD_2, giving a peak intensity of approximately 3×10^{16} W/cm^2 at the target. The experimental setup is indicated in Fig. 1. No attempt has been made to show all of the extensive set of diagnostics, but the relevant ones are indicated.

The neutron detector was a cylindrical Pilot-F scintillator 15 cm in diameter and 12.5 cm in length viewed by an RCA 4522 photomultiplier. The detector was calibrated using a known flux of 2.45-MeV neutrons from an accelerator, so its sensitivity and efficiency were known. One count would appear in the detector with 50% probability for isotropic emission by the plasma of 100 neutrons. Typical signals encountered corresponded to 1 to 20 neutrons detected. The rise time of the output pulse was approximately 5 nsec with a full width at half-maximum of 14 nsec. The neutron time of arrival was calibrated by removing the 3-cm-thick lead shielding between the detector and the target and observing the >100-keV x rays passing through the brass target chamber. Time was measured from an incident-light photodiode signal used to trigger the scope. This signal was also displayed on the Tektronix type-454 oscilloscope. A target of CH_2 was used to confirm the effectiveness of the lead shielding used to eliminate x rays in the detector.

Initially, no neutrons were observed. X rays having energies above 100 keV were detected, and a fast-ion component as shown in Fig. 2 was observed. This is identical to the x-ray and ion results for nanosecond plasmas except that for longer pulses the fast ions are accompanied by neutrons. To confirm that the fast ions were deuterons, a CD_2 foil (2 cm$\times$2.5 cm) was placed 6 cm from the target in the position indicated as foil A in Fig. 1. A neutron signal was then observed with a delay time corresponding to the velocity of the fast-ion component ($\sim 2\times10^8$ cm/sec) observed at the ion detector. Assuming an ion energy of 65 keV and a d-d cross section given by the Gamow formula,[15] with a range over which significant neutron production occurs of 2.5×10^{-5} g/cm^2, one obtains approximately 2×10^{12} ions striking foil A. No neutrons were detected from foil B of Fig. 1, which was placed 3 cm behind the target (although for some shots a factor of 5 lower yield would have been undetectable), so the fast ions are assumed uniformly distributed in the forward hemisphere. This assumption gives agreement between the foil and ion detector measurements and yields a total fast-ion number of 1×10^{14}. It is interesting that before foils A and B were inserted, a few neutrons were observed after approximately ten shots had been fired, with a delay time corresponding to generation at the chamber walls. Because of the short interaction range of a 65-keV deuteron, only a few monolayers of deuterium on the chamber walls are required to give the same result as a solid foil. This problem should be especially troublesome in experiments with solid deuterium targets. For example, the assumption of wall generation for at least part of the neutrons is not inconsistent with the data shown in Fig. 10 of Ref. 10. Thus, it is possible to observe fast ions in the absence of neutron production.

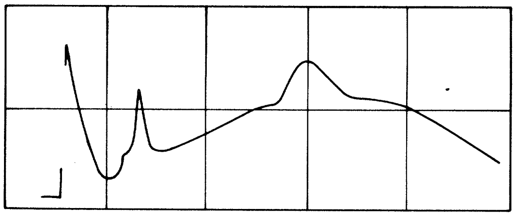

FIG. 2. Typical ion detector signal. Distance to target is 50 cm. Horizontal scale 200 nsec/div. Vertical scale 100 mV/div. Initial pulse is produced by x-ray emission from target. The second pulse is the fast-deuteron peak.

The fast-electron theory of Morse and Nielson[16] provides a possible explanation of the observed phenomena. X-ray spectral measurements[17] indicate a fast-electron component which gives a slope of 30 keV on an intensity-versus-energy plot. According to the calculation of Morse and Nielson, one should observe ion energies of the order of or, perhaps, twice that of the fast electrons. The calculation of the electron energy is based on flux balance between the laser input and the electron conduction out of the absorption region and is insensitive to the details of the electron heating mechanism. Using only flux balance, one obtains an electron energy which is in agreement with the x-ray spectral measurements. It should be noted that the ions are accelerated away from the target only, and no neutrons were observed from ion collisions in the target region. This is in agreement with a fast-electron model which predicts that the electric field on the target side of the absorption region should be canceled by the flow of cold electrons from the dense region into the absorption region; it also is in agreement with the absence of anomalous ion heating. Recent measurements with an ion spectrometer indicate that the ratio of the maximum fast-ion energy to the ion charge is a constant independent of the ion species. These measurements will be reported in detail later.

The differences in neutron-emission results for nanosecond and picosecond pulses can now be understood. The ion expansion, reflected-light threshold, and x-ray emission are similar for the two cases. This indicates, at least, a nonthermal mechanism for electron heating which may be only resonance absorption,[1,2] with the enhanced reflectivity being due to stimulated Brillouin scattering.[7] For nanosecond pulses, however, a low-density, low-temperature plasma is generated in front of the target before significant fast-electron production occurs, and when electrostatic acceleration occurs near the critical surface (where the plasma frequency and laser frequency are equal), the fast ions pass through the cold plasma generating neutrons. For picosecond pulses, no low-density region exists and the fast ions produce no neutrons. The neutron yield then depends on the time characteristics of the pulse, and this mechanism may explain the difference in results obtained by different investigators.

To test this hypothesis, the CD_2 target was irradiated by two pulses of approximately 6 J each separated in time by about 4 nsec. Neutrons were produced in the target region at a time corresponding to the second pulse on each of two shots. The ion energies and x-ray spectrum were the same as for the single pulse case. (No further data were taken.)

Thus, we believe that electrostatic acceleration of a relatively small number of ions is the dominant mechanism responsible for neutrons which have been observed in laser-produced plasmas. This is not to say that the proposed instabilities are entirely absent or that they will be unimportant as laser energies are increased.

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