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Observation of Neutrons Produced by Laser Irradiation of Lithium Deuteride†

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The observation of neutrons produced by irradiation of polycrystalline LiD targets with a high-power laser is reported. Single pulses from a mode-locked Nd^{+3}-doped glass laser were amplified up to energies of 25 J. Pulse widths were 2–3 psec as measured by the two-photon fluorescence technique. The analyses of these experiments yield a somewhat higher rate of neutron production than the similar experiments recently reported by Basov *et al.*

There has been considerable interest concerning the possibility of laser-induced thermonuclear reactions since high-temperature plasmas have been produced by focused laser irradiation of solids in vacuum.[1] Recently, Basov *et al.*[2] have reported the observation of neutron production in a lithium deuteride sample when subjected to focused radiation from a high-power laser pulse. We report in this paper the results and interpretations of a similar investigation using a large 1.06-μ Nd^{+3}-doped glass laser. In our experiments, the laser pulse was focused onto the surface of polycrystalline LiD in vacuum and incident energies up to 25 J in a single pulse of duration of the order of 3 psec were used. A large pilot B scintillation counter encased in $\frac{1}{16}$-in. aluminum was time gated in order to look for counting events immediately following the laser pulse arrival at the target.

The single optical pulse was selectively gated from the train of pulses produced by a mode-locked oscillator and subsequently amplified to multijoule energy. The oscillator consisted of a 1-cm-diam $\times$ 15-cm-long double Brewster Nd^{+3}-doped glass rod pumped in close-coupled configuration. Maximum reflectivity (> 99.8%) and 55% reflectivity plano mirrors formed the optical cavity, and Eastman Kodak 9860 bleachable dye was used as the passive mode-locking Q-switching element. The optical cavity was 2.2 m long, giving an interpulse spacing in the output train of ~15 nsec. Very clean optical pulse trains having a total duration of 400 nsec were obtained when the laser was properly aligned. Care was taken to slightly tilt all reflective surfaces both inside and outside the cavity to prevent feedback to the oscillator, since such feedback was found to degrade the quality of mode locking. The time duration of the optical pulses are estimated by the use of two-photon fluorescence (TPF) in rhodamine 6 G.[3] "Properly" mode-locked pulses exhibited a single bright line with full width at half-maximum above the background of 1.0–1.3 psec and contrast ratio of approximately 2. No shoulders or low intensity blurring of the patterns were found in such cases. Subject to clarification of the interpretation of TPF data,[4–6] the pulse width delivered by this laser when properly mode locked, will be designated in terms of the TPF patterns and is nominally 2–3 psec.

The external gate was formed by a KD^+P Pockels cell between crossed Glan polarizers. The Pockels cell was activated by a 12-kV voltage pulse (total duration 15 nsec) obtained from a charged coaxial line capacitor which was switched by a laser-triggered spark gap. Rise time of the voltage pulse with the Pockels cell load was approximately 3–4 nsec, and time jitter was of the order of 2 nsec. Approximately 60% of a given optical pulse was switched out, and the energy input to the first amplifier stage was nominally 1 mJ. The amplitude of the gated pulse was normally > 100 times the amplitude of any other pulse in the output. Amplitude ratios of ~1000 have been attained by very careful alignment of the pulse-gating apparatus.

Specifications for the four amplifier stages are given in Table I. The gains given for the final stages apply for energy outputs of the order of 5 J. Clear evidences for gain saturation effects are apparent for outputs of 10–30 J. All flash lamps were timed such that the peaks of spontaneous laser emission for each amplifier occur simultaneously, the the single pulse was gated within 50 μsec of peak spontaneous emission. A beam-expanding telescope was employed between amplifiers #2 and #3 to change the beam diameter from 1.3 to 3.8 cm. A passive optical isolater consisting of a Glan polarizer and a $\frac{1}{4}\lambda$ plate was placed between amplifiers #1 and #2 in order to reduce the prelasing discussed below.

The major problem encountered thus far in operation has been prelasing (spontaneous lasing in long pulse mode before injection of the gated pulse). At the gain levels employed here, minor feedback from the target and sundry other surfaces in the laser system produced the prelasing. The detrimental results of prelasing are at least threefold: (i) The target surface is heavily eroded, and the evaporated material covers the entrance window of the sample chamber before the picosecond pulse arrives. All experiments in which prelasing was observed were discarded and included in the background statistics obtained during laser operation. In such cases, the window had to be changed and a new target spot selected before the next shot. (ii) The induced population inversion of the lasing medium is degraded by the time the picosecond pulse is amplified and the energy in the pulse is small. (iii) Total circulating energy is approximately equal throughout the amplifier units and the small diameter rods become damaged by the high-energy long-duration pulses; in our case, amplifier rod # 2 has been damaged severely several times. The nonspecular targets used here always gave severe prelasing difficulties for over-all gains in excess of 20 000. Therefore, we report here on energy depositions only to 20–25 J.

It is to be noted that this difficulty did not exist for other experiments and test measurements performed in this laboratory: (a) Energies > 75 J in a single pulse have been delivered to a *Hohlraum* calorimeter with no evidence of prelasing. (b) Energies > 40 J have been delivered to a 2-cm^2 quartz-gage transducer in experiments on fast rise-time shock waves. (c) Energies > 35 J have been delivered to the focus of the laser beam in air in experiments on air breakdown.

To prevent prelasing, a Faraday isolator system was placed between the output rod of the laser and the target. This isolator had a clear aperture of only 2.8 cm which, together with the imperfect polarizers on hand, still limited maximum energy delivered to the target to 20–25 J.

The neutron counter consisted of a cylinder of pilot B scintillator (8 in. high × 16 in. diam), which subtended a solid angle of $0.16 \times 4\pi$ sr at the target, viewed by 4 photomultiplier tubes with parallel outputs. In addition to the single counting event produced by a burst of high-energy neutrons due to proton recoil, the thermalized neutrons yield counting events from the neutron capture reaction $p(n,\gamma)d$, due to the ~2-MeV γ rays. The half-life for capture is a few hundred μsec, and the counter was gated for 1000 μsec upon delivery of the laser pulse to the target. The discriminator level of the counter was set to accept counting events from γ rays of 1.3 MeV. Under these conditions the average number of background counts per 1000-μsec interval was 0.47 counts, established over more than 1000 events. However, 64 background frames were recorded during actual operation of the laser in calibration, alignment, and "null" shots at targets; and the average background for these series is 0.72 counts. Of the 64

TABLE I. Sandia pulsed laser specifications.

Component	Rod dimension (cm diam × cm length)	Pump energy (Maximum kJ)	Maximum gain (psec pulses)
Amplifier #1	1.3 × 61	8	35
Amplifier #2	1.3 × 61	6	30
Amplifier #3	3.8 × 106	48	30
Amplifier #4	3.8 × 55	16	4.5
Total amplifier length = 283 cm	78	78	140 000

events, only one frame with 3 counts was recorded, and that frame occurred on one of the prelasing shots at a LiD target. The reason for the discrepancy in "active" and "passive" background counts has not been resolved at this time.

Several diagnostic measurements were made on the laser output in order to verify proper performance. A ballistic thermopile established the total energy delivered from the laser. An integrating photodiode examined the energy on a time scale of 10–1000 μsec and hence differentiated between prelasing and single-pulse output. A fast photodiode (TRG-104A) was used to look for multiple pulse gating and for background energy on the 1-100-nsec time scale. The TPF measurement was usually usurped to photograph the beam cross section in order to determine beam homogeneity and to check on over-all laser alignment. Table II lists the results of 15 laser pulses delivered to several LiD targets. *All* shots delivered to the target are included in the table *except* those which exhibited prelasing and/or those which delivered less than 0.5 J to the target due to malfunction of the oscillator-gating system. All such shots are included as active background shots, i.e., background counts determined during activation of the full laser system electronics.

The probability that 29 counts in 15 shots are purely statistical is 4×10^{-6} based on a summed Poisson probability distribution assuming 0.72 background counts per event, i.e., the probability that neutrons have been observed is 0.999996. Assuming the "nonactive" background counts of 0.47 per event, the corresponding probability is 7×10^{-10}.

The LiD targets employed were quite rough and irregular in surface contour, so that verification that the laser pulse was precisely focused on the surface was difficult. It is felt that this fact might largely account for the results being nonreproducible with respect to counts observed versus energy delivered. Future experiments with high-quality single LiD crystal samples as well as solid deuterium targets will be reported in a more complete form.

TABLE II. Results of LiD irradiations.

Incident energy (J)	Counts recorded (1 msec interval)	Probability events are other than statistical
1.3	2	0.999996 based on summed Poisson probability distribution and 0.72 background counts per shot.
3.0	1	
4.6	2	
5.6	2	
6.0	2	
6.3	3	
7.4	2	
7.8	1	
8.5	1	
9.4	2	
9.8	2	
9.9	1	
12.5	2	
13.9	3	
23.2	3	
15 shots	29 total counts	

We interpret these results as full confirmation of the results reported by Basov *et al.* and as an illustration that thermonuclear temperatures can be attained for (very) brief times in plasmas created by small volume irradiations of solids with ultrahigh power lasers.

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