TABLE I. The ionization cross sections for He^0 in the triplet metastable state incident on gas-target atoms.

			σ_{t+} (10^{-17} cm^2/molecule)				
He energy (keV)	Xenon	Krypton	Hydrogen	Nitrogen	Argon	Neon	Helium
10	130 ± 60	14 ± 8	23 ± 12	5.6 ± 3.7	21 ± 10	1.8 ± 1.8	3.6 ± 3.6
15	100 ± 50	19 ± 9	60 ± 29	28 ± 16	23 ± 11	12 ± 9	5.7 ± 5.7
20	160 ± 70	13 ± 7	43 ± 21	48 ± 20	25 ± 12	9 ± 6	34 ± 17
25	180 ± 80	32 ± 12	130 ± 63	53 ± 27	74 ± 38	16 ± 9	57 ± 27
30	110 ± 40	37 ± 17	122 ± 58	71 ± 34	86 ± 42	18 ± 12	65 ± 31

the graphs of the data.

In general, σ_{t+} seems to be about as large as $\sigma_{t+} + \sigma_{ts}$, and it seems reasonable to assume that at these energies σ_{t+} provides a major contribution to the total cross section for destruction of fast He^0 in the triplet metastable state.

Unfortunately, although the values for the sum $\sigma_{t+} + \sigma_{ts}$ and for σ_{t+} have been measured in separate experiments, a value for σ_{ts} cannot be determined. This is because the value for σ_{t+} is almost as large as $\sigma_{t+} + \sigma_{ts}$, and because the combination of the uncertainties for the individual measurements of σ_{t+} and of $\sigma_{t+} + \sigma_{ts}$ is too large to ascertain a meaningful difference between these two values.

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Nuclear Fusion Reactions in Solid-Deuterium Laser-Produced Plasma

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When focusing a 4-GW, fast-rise-time, nsec-range laser onto a solid deuterium target, neutron production is observed. We give evidence for nuclear fusion reactions, measure the electronic temperature, and estimate the number of neutrons for each laser shot.

Nanosecond laser pulse heating of solid-state deuterium targets has been carried on in our laboratory for three years. Evidence for electron temperatures of up to 500 eV was reported earlier.[1–3]

In order to deal with experimental results, a tractable theoretical model was devised.[4] It predicts a plasma temperature proportional to the two-thirds power of the incoming light flux, which is in fair agreement with electron-temperature measurements. Since 500 eV were found with only 1 GW, it was expected that a higher power would lead to plasmas in which a significant amount of nuclear DD reactions would occur.

Our approach to the problem of kilovolt plasmas produced by laser irradiation of a solid target is then quite different from that of Basov's and his coworkers, who focus powerful picosecond pulses onto DLi targets.[5] Another important feature of the interaction process is the coupling between the plasma dynamics and the laser pulse itself: The beam is focused inside the ice (0.7 cm in depth, say), and, indeed, one has to manage in order that the deflagration front reaches the focal volume when the laser pulse is at its peak value.[4] The increase of the maximum power should be completed by a suitable tailoring of the pulse shape.

In the previous experiment,[3] the Nd glass laser's maximum output power was 1 GW, and the main limitation to the increase of temperature was the too-long rise time of the pulse. Then the following trick was used. A Pockels's cell, made of a potassium dihydrogen phosphate crystal inserted between two Glan prisms, was located after the first amplifier rod. Triggering is provided by part of the 30-nsec pulse deviated towards an 8-atm argon-filled spark gap. By applying to the cell a voltage pulse of 12-kV amplitude and a rise time of 2 nsec, the laser pulse half-width is reduced to 15 nsec, and its energy is about 2 J. It is then amplified by four rods up to 80 J; diameter of the end rod is 45 mm. Figure 1 shows a typical pulse. The rise time is less than 5 nsec. An average output energy of 40 J was used, and the peak power varied from 3–5 GW, depending on each shot. The beam is focused by a 50-mm focal length f/1 aspherical lens.[6] The target is a solid deuterium stick, 1 mm square in cross section. Optimum focusing conditions range from 100–300 μm inside the ice. Light is partly reflected from the target, is amplified backwards through the cascade, and is eventually shuttered by the Glan prism, thus preventing the first stages of the laser from being broken down. The system is now operating well, and can sustain about 3 or 4 J of reflected energy, measured at the Glan-prism level, without any damage.

Electron-temperature recording and neutron detection are used as diagnostics. The "plasma thermometer" uses nickel and beryllium foils. The setup and results were extensively described in Ref. 2 and Ref. 3. Neutron detection is secured by two large, plastic phosphors connected through light pipes with XP 1040 Radiotechnique photomultipliers. Each phosphor is 450 mm in diam. From calibration measurements made by means of a DD pulsed neutron source, the efficiency of detection was found to be one pulse for about 40 neutrons emitted in a solid angle of 4π sr by a source located 50 cm from the center of the phosphor external boundary. The quantum efficiency of the phosphor is about 50%. The detectors are completely shielded by lead sheets 5 mm thick. They are located 50 cm from the plasma in opposite directions. One of them can be moved from 50 to 150 cm in order to make time-of-flight measurements. X rays and neutron signals are recorded by Tektronics 585 cathode-ray oscilloscopes. A time recorder, whose steps are registered with each track to be analyzed, provides a standard time scale. Then, by taking into account the photomultiplier time delay – which turned out to be close to 36 nsec – a chronology of laser pulse, x rays, and neutron signals can be made with an accuracy better than 10 nsec. More than 150 shots have been performed. Energy varies from shot to shot in the range 30–50 J, and the peak power ranges from 3 to 5 GW. Since the focal-spot diameter inside the ice is about 100 μm, the maximum flux density is a few times 10^{13} W/cm.[2] Shots are carried on in series of 15 and, within each series, signals were recorded from neutron detectors 10 times over. After improving the focusing accuracy, 90% of the shots yielded signals from neutron detectors.

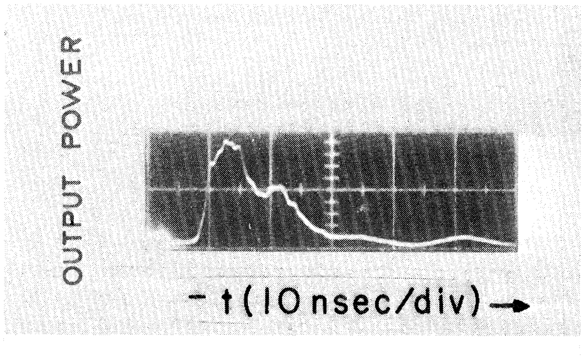

FIG. 1. Typical oscillogram of output laser pulse recorded on a Tektronix 519 oscilloscope. Signal is given by an ITT fast-rise-time photodiode.

To determine the origin of these signals, tests were made under the following conditions.

(a) The lead shield also protects the detector against the laser flash lamp light. When several shots were made without target, no signals were detected. Thus, our neutron detectors are not sensitive to spurious electromagnetic noise. (b) To determine if these signals could be caused by hard x rays (>120-keV energy), the lead shield was taken off one of the detectors. The signals recorded on the two detectors were of the same amplitude.

(c) Our experimental setup allows us to use, alternatively, deuterium and hydrogen targets; this is quickly effected by merely changing the gas entering the cryogenic device. Thus, other experimental conditions remain identical. When shining on hydrogen targets, the electron temperature was recorded and was found to be the same as those recorded in deuterium plasmas, within the experimental uncertainties.

In all tests, signals from neutron detectors were recorded with deuterium targets: No signal occurred when replacing deuterium by hydrogen; and signals were recorded again when returning to the deuterium ice. Thus, we got evidence for believing that the recorded signals coming from the plasma were due to the presence of deuterium atoms inside the target. Further information is derived from signal chronology. It was checked that within a 10-nsec accuracy: (a) Soft x rays are contemporary to the laser peak power; (b) shots were made, locating one of the phosphors at 50 cm and the other one at 150 cm from the plasma. Typical signals are displayed in Figs. 2(a) and 2(b).

Taking into account the first spikes, these are found to be about 45 nsec apart, which is consistent with the time of flight of 2.45-MeV neutrons produced by DD reaction (46 nsec). Further spikes occur randomly up to 120 to 150 nsec after the first: They are due to scattering, as will be shown later. Figures 2(c) and 2(d) correspond to a less efficient laser shot; with both detectors 150 cm apart from the target, no further spikes occurred. With respect to the laser peak power, the first neutron spikes occur 20 or 25 nsec later, when detectors are located at 50 cm from the target. When this distance is varied to 75, 100, and 150 cm, the signals appear 35, 50, and 70 nsec after the laser peak value. For these measurements, the measured photomultiplier time delay of 36 nsec has been taken into account. Now if one subtracts the time of flight of DD neutrons from the experimentally recorded chronology, and compares it with the laser pulse time history, it is found that most of the detected signals are consistent with neutrons emitted when the laser power is maximum, as shown in Fig. 3. The number of neutrons for each shot is estimated on the oscillogram by studying the maximum amplitude of signals and by counting the different pile-up spikes. For one laser shot, the number of neutrons varies from 100–500 emitted in the total solid angle. This number strongly depends on the laser power and the focusing conditions. The tail observed for later times is consistent with neutron paths larger than direct trajectories by about 1 m, which is most likely due to scattering on nearby items, such as the helium bath, gas pipes and tanks, and iron structures. In another test, the most sensitive detector was entirely shielded by a 3-mm-thick cadmium foil and by 25 cm of paraffin. In this case, no signal occurred, whereas, for the same shot, a signal was recorded from the bare detector. Taking off the shield, signals occurred again on the two detectors. Finally a BF$_3$ detector, using three counters inserted into paraffin with an over-all efficiency of one pulse for 100 neutrons emitted at 15 cm in 4π sr, was set up and one to five pulses were recorded for each laser shot. Connected with these measurements, electron temperatures were derived from x-ray signals. Since we concentrated on neutron detection, the results are not at this time very accurate. However, average electron temperatures range between 500–700 eV. For these values, provided ions are at the same temperature as electrons, rough calculations show that some DD fusion reactions are likely to occur.

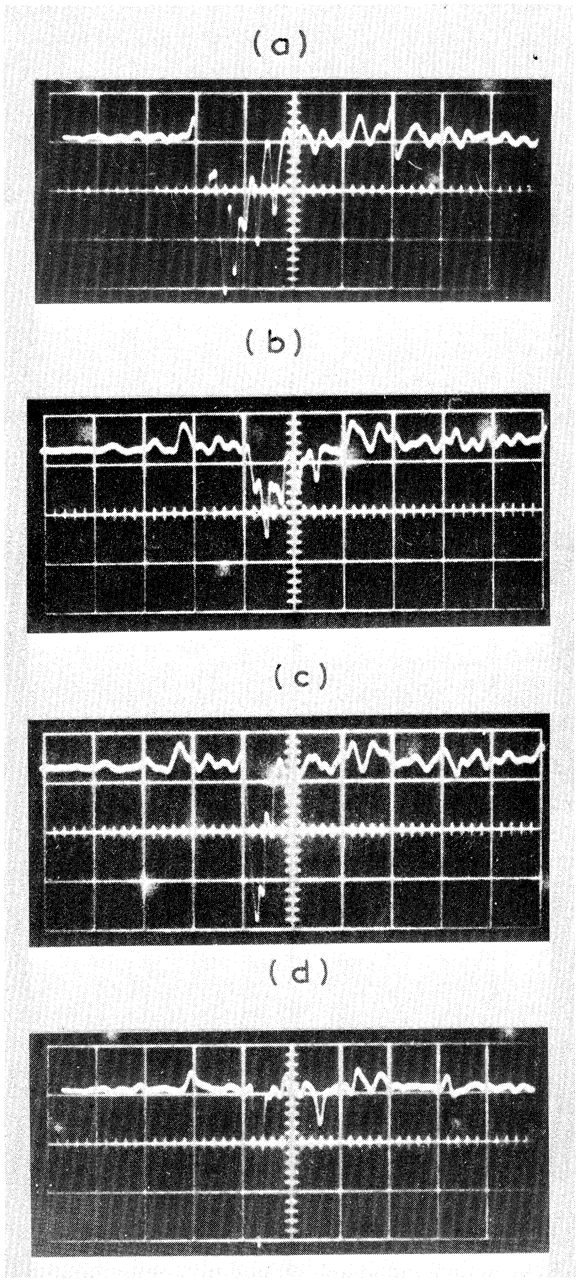

FIG. 2. Typical oscillograms of neutron signals. Detectors are located, respectively, at (a) 50 cm and (b) 150 cm from the target. The recording is made with 200 mV/div and 40 nsec/div. Cases (c) and (d) correspond to a less efficient laser shot, with the two detectors located at 150 cm from the target.

We seem to have gotten definite evidence for a neutron yield from a laser-produced deuterium plasma. These neutrons are most likely due to DD

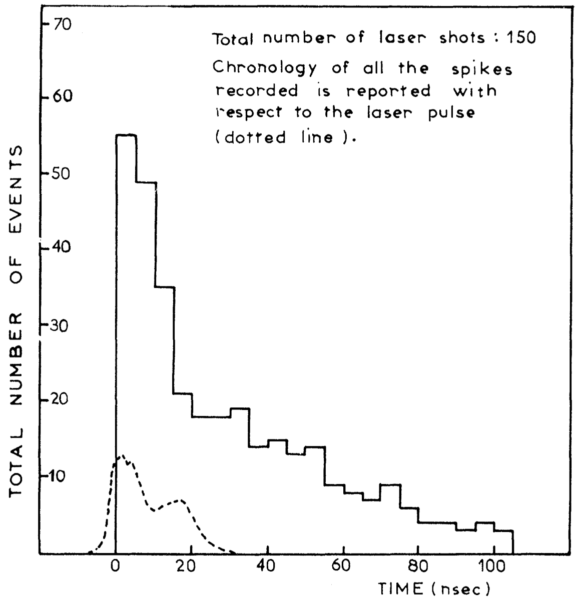

FIG. 3. Histogram of up-to-date results. Neutron spikes are numbered with amplitude and time for each laser shot. The total number of so-recorded events is plotted in a time scale given by laser pulse. Chronology takes account of times of flight corresponding to distances between plasma and phosphors.

fusion reactions. This result, which was obtained by carefully tailoring the pulse shape of an otherwise-classical, nanosecond giant pulse laser, appears promising for the quest of very-high-temperature plasmas. In this respect, nanosecond lasers are expected to be very convenient and efficient tools, since neutrons were obtained with a peak power of only 4 GW.

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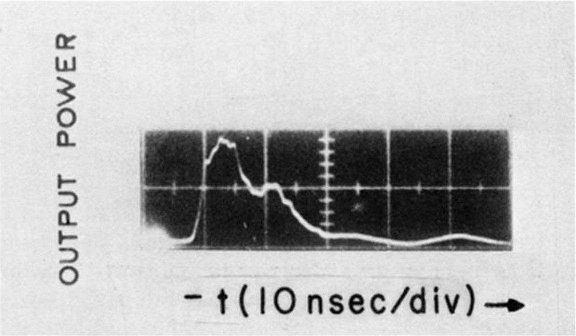

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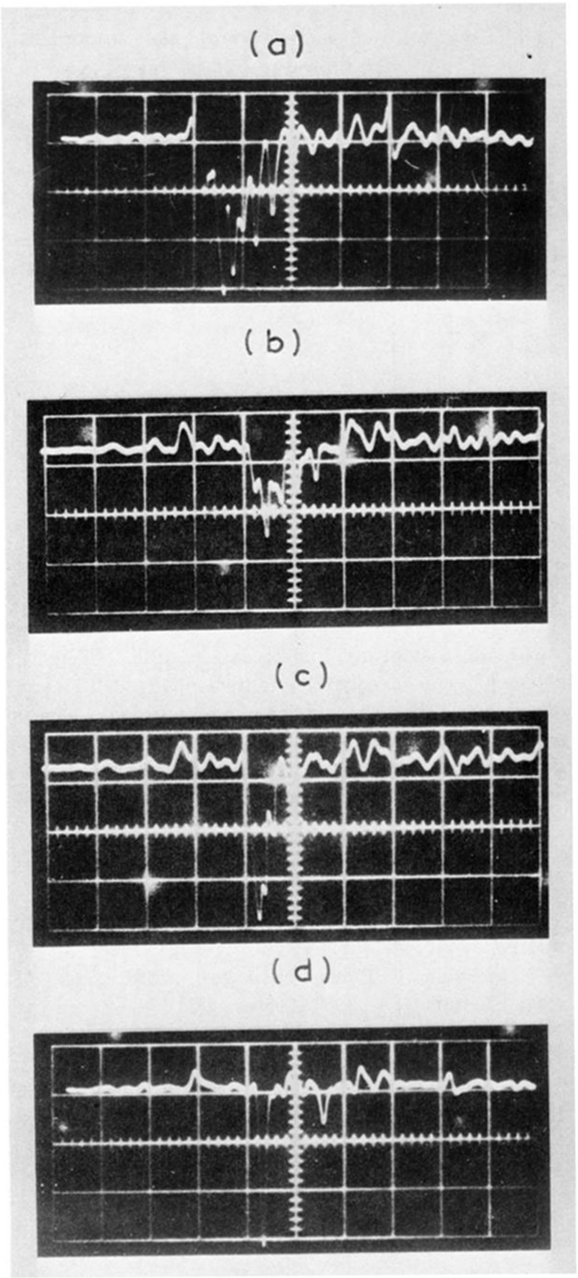

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