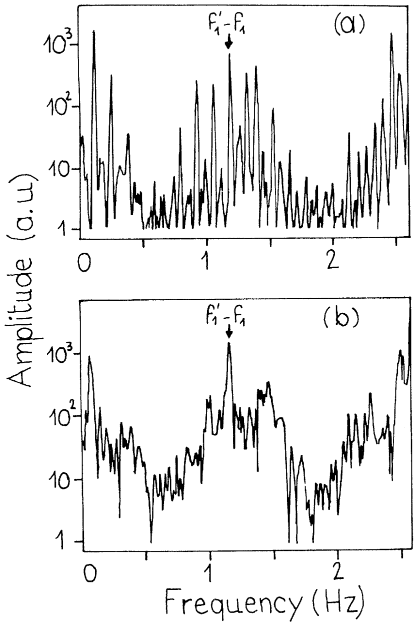

FIG. 6. Fourier analysis of the output voltage at B_0 = 1.2 T. (a) $\epsilon = 12\times 10^{-3}$, (b) $\epsilon = 18\times 10^{-3}$.

stand. One is tempted to relate the onset of turbulence to the nonlinear dynamics of three coupled oscillators, in accordance with the general scheme of Ruelle and Takens.[8] However, an observer moving with the phase velocity $2\pi f_1/m$ detects only two independent frequencies so that this type of interpretation is questionable.

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[3]In the range $0.3 < B_0 < 0.93$ T, the flow is turbulent at the first threshold: Slow aperiodic fluctuations of the velocity, weakly correlated in space, appear as the first dynamical event at the output of the probes. This phenomenon is probably due to continuous chaotic changes in the structure of stationary cells. More detailed investigation is clearly required.

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Direct Measurement of the Fuel Density-Radius Product in Laser-Fusion Experiments

S. Kacenjar, S. Skupsky, A. Entenberg, L. Goldman, and M. Richardson

Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14627

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The first *direct* measurement of fuel density-radius product ρR in laser-fusion experiments is obtained by measuring the number of deuterium and tritium ions elastically scattered out of the fuel by 14-MeV fusion neutrons. They were recorded with the solid-state track detector CR-39. The energy spectrum of these particles is found to agree well with the theoretical result. This diagnostic was used in low- and high-compression experiments and gave measured ρR values of 1.3×10^{-4} and 1.2×10^{-3} g/cm^2, with an uncertainty of $\sim 20\%$.

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The first *direct* measurement of fuel density-radius product ρR in laser-fusion experiments has been obtained for the implosion of deuterium-tritium (DT) filled, glass-shell targets. (The quantity ρR characterizes the proximity to energy breakeven in inertial fusion[1] and is analogous to $n\tau$ used for the Lawson criterion in magnetic fusion.) The measurement involved counting the number of energetic deuterons and tritons produced from elastic scattering with the 14-MeV DT fusion neutrons as they traversed the fuel (Fig. 1). These hydrogen isotopes can be recorded by the solid-state track detector CR-39.[2] The total number of "knockon" particles, Q, is related to

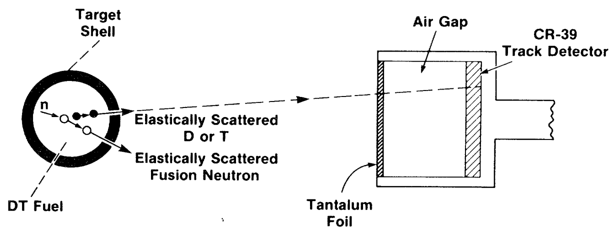

FIG. 1. The production of knockon particles. Energy loss in the shell is negligible when $\rho\Delta R \lesssim 5\times10^{-3}$ g/cm^2.

the fuel conditions by[3]

$$Q=[\sigma_T\langle n_T R\rangle+\sigma_D\langle n_D R\rangle]Y, \quad (1)$$

where $\langle nR\rangle$ is the average product of number-density and distance along the neutron trajectories, Y is the number of neutrons, and σ is the cross section for neutron elastic scattering (0.92 and 0.62 b for D and T, respectively). The actual number of knockons detected, Q^*, will be determined by the detection solid angle $\Delta\Omega$ and the fraction of particles ϵ that can produce a signal in CR-39. In terms of these parameters, the fuel ρR for equimolar DT is given by

$$\langle\rho R\rangle=5.4(4\pi/\Delta\Omega)(1/\epsilon)Q^*/Y \text{ g/cm}^2. \quad (2)$$

To confirm that the track-detector signal was indeed the result of knockons, the energy spectrum of these particles was sampled in selected intervals, and was found to agree well with the unique spectrum for D and T ions elastically scattered by 14-MeV neutrons.

This diagnostic was used for two experiments in which ρR was found to span almost 1 order of magnitude (Table I). In a short-pulse, high-intensity experiment, the target shell was exploded, and the resulting ρR was 1.3×10^{-4} g/cm$^2\pm20\%$. For a long-pulse, low-intensity experiment in which the target was expected to be more ablatively driven, the fuel ρR was measured to be 1.2×10^{-3} g/cm$^2\pm20\%$. The uncertainty in both cases was estimated to be about 15% systematic and 15% statistical, and the results were within 25% of those from computer simulations of the experiments. The values of ρR are well defined by the diagnostic and do not rely on computer simulations for guidance.

These experiments[4] were performed with the 24-beam, Nd:glass laser (OMEGA) at the University of Rochester. For high-compression shots, two CR-39 track detectors, 90° apart (~150 μm thick), were used, each subtending a solid angle of 0.5% of 4π, at 7.0 cm from the target. Each detector was enclosed in a sealed, air-filled environment to avoid desensitization due to lack of oxygen, and a tantalum foil was used to protect the CR-39 from x rays and low-energy charged particles from the target. The signals from both detectors were added to reduce the statistical uncertainty, and this produced a ρR geometrically averaged over two orthogonal directions. In fact, the two signals were statistically consistent, suggesting that the fuel was still spherical at the time of thermonuclear burn.

Before a value of ρR could be determined, it was necessary to examine the energy spectrum of the charged particles incident on the track detector, to determine that the tracks were caused by knockons and not another source of energetic particles. The energy spectrum for the superposition of deuteron and triton knockons has well-defined peaks and valleys (Fig. 2) determined by the differential cross sections for neutron elastic scattering.[5] In Fig. 2, it was convenient to plot the spectrum as a function of energy per nucleon, as this parameter determines the initial track diameter in CR-39.[2] The two peaks shown are at 10.6 and 12.5 MeV and are produced by neutron "head-on" collisions with deuterons and tritons, respectively. Particles in this region are above

TABLE I. Experimental conditions and results.

	High Compression	Low Compression
SHOT NUMBER	7038	6037/6038
LASER:		
Energy (J)	1982	693/778
Pulse Width (psec)	921	89/92
Intensity (W/cm^2)	4×10^{14}	$2\times10^{16}/2\times10^{16}$
TARGET (SiO_2 shell):		
Thickness (μm)	0.91	1.01/1.11
Radius (μm)	209	103/99
Fill Pressure (atm)	20	16/20
YIELDS:		
Neutrons (Y)	5.5×10^8	$1\times10^{10}/1\times10^{10}$
Knock-On Tracks (Q*)	91	49
Total Number of Knock-Ons (Q)	9.4×10^4 [a]	5.0×10^5 [b]
INFERRED ρR (g/cm^2)	1.2×10^{-3}	1.3×10^{-4}

[a] Based on a solid angle of 0.92% of 4π and a detection efficiency of 8.2% of the total knockon spectrum.

[b] Obtained with the five-foil configuration discussed in the text at 10.6 cm from the target. The total configuration had an effective solid angle of 0.055% of 4π and detected 18% of the knockon spectrum. The signal was accumulated over two similar shots.

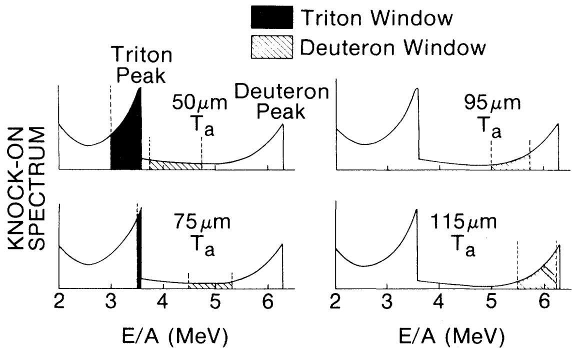

FIG. 2. Different regions of the knockon spectrum can be detected using different thicknesses of Ta foil in front of the CR-39 track detector.

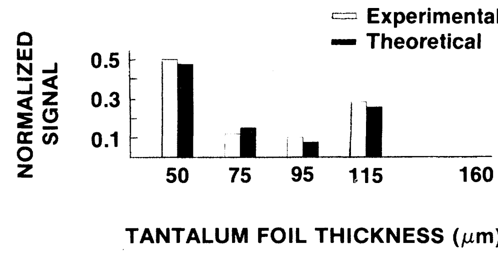

FIG. 3. Comparison between the experimental and theoretical results for the knockon spectrum in the energy intervals shown in Fig. 2 using different thicknesses of Ta. A fifth detector, with a Ta thickness of 160 μm, searched for particles above the maximum energy permitted for knockons, and found none. (The data consisted of 49 tracks accumulated over shots 6037 and 6038.)

the energy-sensitive range for detection by CR-39 which is 2–3 MeV/nucleon; however, they can be brought into the energy window by slowing them down through thin tantalum foils placed in front of the detector. The portion of the spectrum that will be detected for different thicknesses of Ta is shown in Fig. 2. (The amounts of Ta indicated are based on energy-loss data from Williamson, Boujot, and Picard.[6])

To sample the energy spectrum of knockons in different intervals, a track detector was divided into five regions, each with a different thickness of Ta. Four of the Ta foils were as indicated in Fig. 2; the fifth was 160 μm thick to search for particles beyond the maximum energy for knockons. The comparison between the predicted and measured signals is shown graphically in Fig. 3. The two peaks and the valley are easily discerned, and no signal appears beyond the deuteron peak. The close agreement between the measured and predicted signals indicates that the CR-39 tracks were indeed caused by elastically scattered deuterons and tritons.

In general, at least ~40 μm of Ta foil (or its equivalent) must be placed in front of the detector to isolate it from DT alpha particles, DD protons, and charged particles from the target debris. There are other sources of more energetic particles (in particular, protons) that can penetrate the Ta filter and produce background tracks. Some of these are (n,p) reactions in deuterium and silicon, and energetic protons created by the laser interaction with water vapor or an oil contaminant on the target surface. A technique was developed for separating a proton background from the knockon signal, based on the track diameter and particle range in CR-39. The track diameter is determined by the energy per nucleon (E/A) of the projectile,[2] and the range is proportional to the atomic number (for a given E/A)[6]; i.e., deuterons and tritons penetrate farther than protons with the same entry track diameter. This method involved choosing a thickness of CR-39 such that protons would be stopped within the track detector, but deuterons and tritons would pass through it, for a certain range of track diameters. For a CR-39 thickness of 150 μm, it was found that protons with a track diameter greater than 12.5 μm were stopped (assuming a 16-h etch time in 6N NaOH at 70 °C).[7] Thus, tracks with spatially coincident entrance and exit holes with diameters greater than 12.5 μm could only be from D or T knockons, and this defines the energy window for detection. From this analysis, we estimate that the signal-to-background ratio was 20:1 with the coincidence technique and 3:1 without it.

After it was established that the track detector signal originated from DT knockons, then only a 50-μm Ta filter was used across the whole detector, to obtain the maximum number of tracks. This placed the 10.6-MeV triton peak in the Cr-39 energy window and accounted for 8.2% of the knockon particles.[3] For the values of ρR achieved in all the present experiments ($\rho R < 10^{-2}$ g/cm^2), there should not be any significant shift of the triton peak due to energy loss in the target.[3] For a 1% solid angle and a 50-μm Ta filter, the product of ρR and neutron yield must be 3×10^5 neutrons·g/cm^2, in order to produce fifty tracks.

Two examples of experiments diagnosed by the knockon technique are the short- and long-pulse shots described in Table I. In both cases the targets are 1-μm-thick glass shells filled with ~20 atm of DT fuel. The target radii were 100 and 200 μm, respectively, giving both approximately the same specific absorbed energy, ~0.6 J/ng. In the short-pulse case, 700 J of laser energy were incident on the target in 90 psec, producing a peak intensity of $\sim 2\times 10^{16}$ W/cm^2. The laser-target interaction at such high intensities generates energetic electrons[8] (with an effective temperature of 35 keV) which penetrate and heat the whole target, precluding a high-density compression. In contrast, the long-pulse experiment had a peak intensity of $\sim 4\times 10^{14}$ W/cm^2, with 2 kJ delivered in 1 nsec. The amount of suprathermal electrons generated in this case is expected to be small, and those produced should have a relatively short mean free path and deposit their energy close to the target surface. The result would be a more ablative (and hydrodynamically efficient) implosion,[1,8] with the fuel and inner portion of the shell on a relatively low adiabat, yielding a higher compression. (The lower neutron yield, 10^8 compared to 10^{10}, is the result of a low fuel temperature.) The fuel ρR is obtained from Eq. (2) together with the measured neutron yield (Y) and the number of knockons (Q) from Table I. Indeed, the ρR for the low-intensity shots was found to be about 10 times larger than the high-intensity ρR, namely 1.2×10^{-3} g/cm^2 compared to 1.3×10^{-4} g/cm^2.

Similar values of ρR have been inferred indirectly at several laboratories. Mainly two techniques were used: (1) radiochemical analysis of ions that were transmuted in the target shell by the 14-MeV neutrons[9,10] and (2) x-ray imaging of the target, using either direct emission from the target or "backlighting" by an external source.[11] In general, both methods have required either guidance from computer simulations of the implosion or an assumption that the fuel is uniform, spherically compressed, and fully contained within the target shell. In principle, the radiochemistry technique could be used as a direct fuel diagnostic by seeding the DT with high-Z ions that could be transmuted to radioactive nuclides[10]; and this is presently under investigation. A third method of diagnosis is to measure density ρ by the x-ray line broadening of high-Z seed ions in the fuel,[12] and this has indicated values of ρR consistent with the knockon results. (ρ has usually been related to ρR by assuming a constant fuel density.) In general, fuel conditions at the times of x-ray emission and neutron production can be very different, and it will require computer simulation to demonstrate that the diagnostic signals are consistent.

To summarize, the knockon diagnostic has been successfully implemented in laser-fusion experiments. It has produced the first direct measurement of fuel ρR in a relatively simple fashion, using the number of tracks recorded in a solid-state track detector. Among its attractive features are that no special target preparation is required, and that it should be able to detect gross nonuniformities in the compressed fuel by measuring ρR from different directions. Although this diagnostic will not be applicable for breakeven targets (as the knockon particles will be stopped within the target), it should be a useful tool for understanding the near-term experiments approaching thermonuclear ignition.[3]

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