theoretical papers on this subject, based on point-defect (nontopological) models.[16,17] I am grateful to W. Paul, G. A. N. Connell, M. H. Brodsky, and S. G. Kirkpatrick for discussions and preprints. D. R. Hamann suggested several improvements in exposition.

[1]J. C. Phillips, in *Proceedings of the Fourteenth International Conference on the Physics of Semiconductors*, edited by R. A. Stradling (Plessy, Edinburgh, 1978), and to be published.

[2]J. D. Joannopoulos and F. Yndurain, Phys. Rev. B 10, 5164 (1974).

[3]R. J. Temkin, W. Paul, and G. A. N. Connell, Adv. Phys. 22, 581 (1973).

[4]W. E. Spear, Adv. Phys. 26, 811 (1977), see especially p. 819.

[5]P. A. Thomas, M. H. Brodsky, D. Kaplan, and D. Lepine, Phys. Rev. B 18, 3059 (1978).

[6]G. A. N. Connell and J. R. Pawlik, Phys. Rev. B 13, 787 (1976).

[7]D. Kaplan, N. Sol, and G. Velasco, Appl. Phys. Lett. 33, 440 (1978).

[8]J. C. Phillips, in *Physics of Semiconductors*, edited by F. Fumi (Tipografia Marves, Rome, 1976), p. 12; K. C. Pandey and J. C. Phillips, Phys. Rev. Lett. 34, 1450 (1975); J. A. Appelbaum, G. A. Baraff, and D. R. Hamann, Phys. Rev. B 14, 588 (1976); A. W. Parke, A. McKinley, and R. H. Williams, J. Phys. C 11, L993 (1978).

[9]M. H. Brodsky, R. S. Title, K. Weisner, and G. D. Pettit, Phys. Rev. B 1, 2632 (1970); R. Grigorovici and R. Manaila, Thin Solid Films 1, 343 (1967).

[10]B. L. Crowder, R. S. Title, M. H. Brodsky, and G. D. Pettit, Appl. Phys. Lett. 16, 205 (1970).

[11]R. J. Stein and P. S. Peercy (to be published) have used Si-ion bombardment and H-ion implantation of crystalline Si to examine the internal surface structure through the infrared Si-H stretching spectrum. For voids embedded in crystalline Si, about ten narrow lines are observed between 1800 and 2200 cm^{-1}. The line spectrum collapses to one broad line after amorphization. In my model this collapse is associated with the formation of a relaxed interconnected internal surface of atoms with one broken bond each (Si-H) similar to the (111) crystalline surface. Further experiments of this type are in progesss.

[12]E. C. Freeman and W. Paul, to be published.

[13]Threefold-coordinated P may be a double donor, because in chalcogenide glass alloys P is *pentavalent.* See Y. Monteil and H. Vincent, Z. Anorg. Allg. Chem. 428, 259 (1977).

[14]S. R. Ovshinsky and A. Madan, Nature (London) 276, 482 (1978).

[15]P. L. Leath, Phys. Rev. B 14, 5046 (1976).

[16]R. Fisch and D. C. Licciardello, Phys. Rev. Lett. 41, 889 (1978).

[17]D. Adler, Phys. Rev. Lett. 41, 1755 (1978).

Ultrahigh-Pressure Laser-Driven Shock-Wave Experiments in Aluminum

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We have measured the velocities of strong laser-driven shocks in aluminum. Pressures of 0.6 and 1.8 TPa were produced by incident laser intensities of 8×10^{13} and 3×10^{14} W/cm^2. This is the first time that pressures this high have been inferred in a laboratory experiment.

Present laboratory physics experiments are limited to pressures below about 0.5 TPa (1 TPa ≡ 10 Mbar). To explore higher-pressure regimes, very large-scale experimental configurations, such as those employing nuclear explosives,[1,2] have been required in the past. Few experiments of this type have ever been performed because of their scale and cost. Since present theoretical calculations are reliable only above 10–100 TPa, there exists a large range of pressures over which little is known about material properties. Along the principal Hugoniot this pressure range is of interest because temperature and pressure ionization effects, strongly controlled by atomic shell structure, may dominate many physical properties.

The capability of high-power lasers to produce ultrahigh shock pressures has been predicted for many years,[3] and the success of present laser fusion research is indirect testimony to the validity of these predictions. However, the pressures reported in previous laser-driven shock studies[4-6] have been much lower than those predicted theoretically. In this Letter we present the first direct experimental evidence that shock pressures as high as those predicted by theory can be achieved by laser ablation. These experiments consist of measuring shock propagation velocities in laser-irradiated aluminum disks. Experiments were performed with the Janus laser,[7] which produces up to 100 J in each of its two arms in 300-ps (full width at half maximum) pulses, with < 50-μJ prepulses.

The technique for measuring shock velocity is shown in Fig. 1. A fast streaking camera records the luminous history of the stepped rear surface a thin metal slab. When the shock, traveling at a velocity U_s, approaches to within a few skin depths δ of a rear surface, the camera will record a rapidly rising signal produced by the intense thermal radiation ($T \sim 5$ eV, typically) behind the shock front. The rise time of this signal should roughly equal δ/U_s, which is less than 10 ps for most metals at pressures of 1–3 TPa and optical detection frequencies. Thus, shock arrival times may be measured with a resolution comparable to the ultimate time resolution of modern streaking cameras. The shock velocity is found by measuring the shock arrival times at two different levels on the surface.

In the present experiments, the laser pulse is focused at normal incidence onto the target with an $f/1$ lens. Focal-spot diameters are varied between 300 and 700 μm. An RG695 color-glass filter is positioned between the chain output and the target to prevent visible radiation from the laser flashlamps from reaching the target imaging system. The rear surface of the target is imaged onto the slit of a streaking camera having S20 spectral response and 10 ps time resolution.[8] The target is viewed along the normal to its surface, collinear with the laser beam axis. A bandpass filter (either 500 ± 5 or 532 ± 5 nm) is positioned in front of the camera slit.

Aluminum targets for these experiments were prepared by vapor deposition, using a masking technique to produce one 10-μm-high step running along the target diameter atop a 25-μm-thick, 1-mm-diam base (see Fig. 1). Target density was about 2% below bulk density. Target dimensions were chosen to satisfy several criteria. Laser focal-spot diameter must be small enough to produce the required high intensity, yet be much greater than target thickness l to ensure a planar shock. Since a rarefaction propagates into the target after the pulse terminates, overtaking and attenuating the shock, we must choose $l \lesssim U_s \tau$, where τ is the pulse length, in order to study a steady shock. However, l must be greater than the range of suprathermal electrons to ensure that the material ahead of the shock is not significantly preheated. The LASNEX laser-fusion code[9] used to study potential target designs and was particularly useful for estimating suprathermal electron effects. For the short pulse lengths produced by Janus, it is impossible to satisfy all of the constraints. Consequently, the necessity of low preheat in these experiments meant that we would always be studying an eroding shock wave.

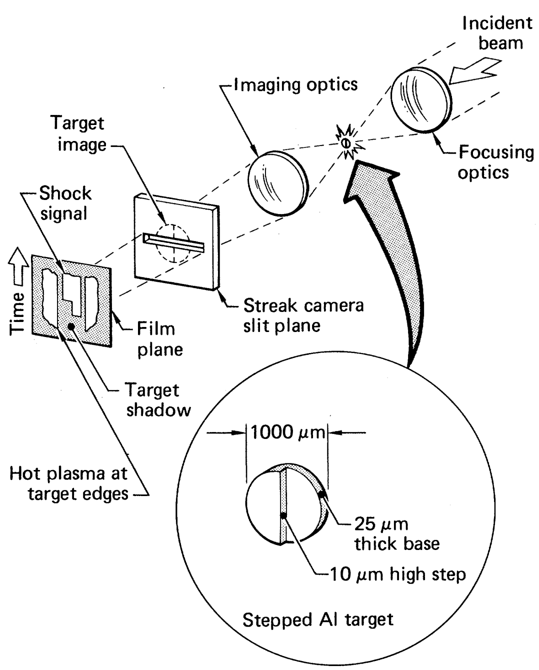

FIG. 1. Experimental configuration for measuring shock velocities. Inset depicts the targets used in these experiments.

Figure 2 shows a streak photograph of the rear surface of a target irradiated by a 8×10^{13}-W/cm^2 pulse (66-J/300-ps pulse, 600-μm-diam spot). Time is measured with respect to the arrival of the leading edge of the laser pulse at the target (known to ± 50 ps). At early times ($t < 1$ ns), the shadow of the target is clearly seen against an intense backlighting source, which we have observed in every experiment and which appears around the target edges within ~100 ps after the pulse arrival. At $t \simeq 1.1$ ns a signal ascribed to shock arrival at the thin level of the target is observed, and at $t \simeq 1.6$ ns, a second signal, due to the shock breaking through the thick level, is seen. Microdensitometry of the streak photographs shows that signal rise times are $\simeq 20$ ps,

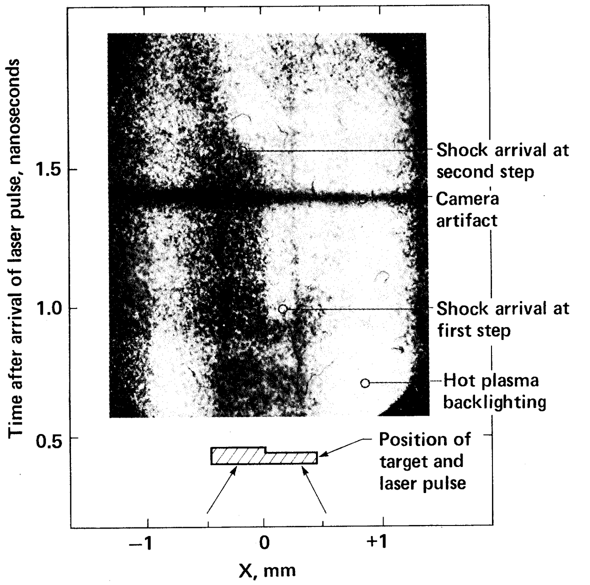

FIG. 2. Streak-camera photograph of the rear surface of an aluminum stepped-disk target irradiated by an 8×10^{13}-W/cm^2 pulse.

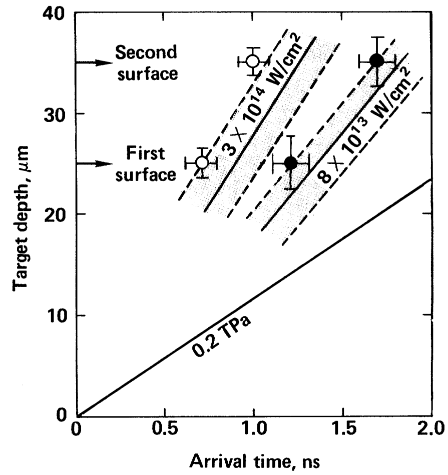

FIG. 3. Measured and calculated shock arrival times at the two free surfaces on the rear of a stepped Al target. Results are shown for intensities of 8×10^{13} (solid circles) and 3×10^{14} W/cm^2 (open circles). Calculations for these intensities are shown as the solid lines, with shaded regions representing the changes produced by 10% changes in laser focal-spot area and absorbed energy fraction. Also shown for comparison is the curve for an 0.2-TPa steady shock.

in agreement with other measurements,[6] implying shock widths of no more than 0.4 μm. This is comparable to the surface roughness of our targets. After the initial rise of the signals, a relatively slow decrease in intensity begins within 50–100 ps. This slow cooling is a consequence of the irreversible nature of the shock heating/adiabatic cooling sequence.

Figure 3 shows arrival time data for two experiments. We simulated these experiments with one-dimensional LASNEX calculations, making no post-shot adjustments other than using the me measured incident intensities and pulse lengths. We assumed that 40% of the incident laser energy was absorbed, in accordance with extensive measurements.[10] A suprathermal-electron spectrum appropriate for these intensities in aluminum was used. The calculated curves of shock position versus time are the solid lines in Fig. 3.

Table I shows the average shock velocities $\overline{U}_s$ measured across the 25-μm-thick base of the target and the 10-μm-high step. Here $\overline{U}_s=\Delta x/\Delta t$, where Δx is the thickness of material traversed in Δt. $\overline{U}_s$ measured in the base is greater than that measured in the step because the rarefaction from the released front surface overtakes the

TABLE I. Mean shock velocities $\overline{U}_s$, in aluminum, measured across the 15-μm-thick base and the 10-μm-high step atop the base for two laser intensities. $\overline{U}_s=\Delta x/\Delta t$, where Δx is the thickness of material traversed in Δt. Also listed are the average pressures in the step obtained from the measured and calculated values of Δt.

Incident intensity (W/cm)	$\overline{U}_s$ across base (mm/μs)	$\overline{U}_s$ across step (mm/μs)	P at 30 μm from meas. Δt across step (TPa)	P at 30 μm from calc. Δt across step (TPa)
8×10^{13}	22 ± 2	20 ± 2	$0.6^{+0.2}_{-0.1}$	0.7
3×10^{14}	36 ± 4	31 ± 3	$1.8^{+0.3}_{-0.4}$	1.3
Present laboratory maximum (Ref. 10)		12	0.2	

shock before it has reached the first surface on the rear of the target. Well-characterized experiments can only be performed in regions of the target where the shock temperature T_s is much greater than the preheat temperature T_p. According to our calculations this is not satisfied in the base. However, LASNEX predicts $T_p \lesssim 0.1T_s$ in the step; here shock velocities as high as 30 mm/μs have been achieved, whereas velocities no higher than 12 mm/μs have been measured in any previous laboratory shock-wave experiment.[11] The pressures corresponding to the shock velocities[12] measured in the step are also listed in Table I. It is seen that these experiments have achieved pressures as high as 1.8 TPa in a low-preheat region of the target. Other laboratory techniques cannot produce pressures higher than about 0.2 TPa in Al.[11] The pressures obtained from LASNEX-predicted values of $\overline{U}_s$ are also given in Table I, and are close to those obtained from the measurements.

The much lower pressures reported in early laser-driven shock studies have been ascribed to limitations imposed by the lower-power lasers used.[4,5] Very small focal spots were required to produce high intensities, and effects such as lateral spreading of energy in the thermal conduction zone and nonplanarity of the shock wave may have strongly influenced the results. Much lower pressures were also reported in recent experiments[6] with focal-spot diameters and intensities comparable to those used by us. The reasons for this difference are not yet understood, but may involve the different target geometries used in the two experiments.[13]

In summary, these experiments show for the first time that high-power pulsed lasers may be used to generate pressures well beyond those achievable by any conventional laboratory technique, thus making a new regime of high energy density accessible to the experimentalist. In addition, our shock velocity measurements provide the first experimental support for the theory of laser-generated shock waves.

We thank R. M. More and M. Kamegai for useful discussions and help with the numerical calculations. We are also grateful to M. Ross for showing us his pseudopotential calculations on Al prior to publication; to P. Lee and D. Phillion for collaboration on various aspects of the experiment; to G. Devine for target fabrication; and to J. Foster, III, for experimental assistance. This work was performed under the auspices of the U. S. Department of Energy under Contract No. W-7405-Eng-48.

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[1]L. V. Al'tshuler, B. N. Moiseev, L. V. Popov, G. V. Simakov, and R. F. Trunin, Zh. Eksp. Teor. Fiz. 54, 785 (1968) [Sov. Phys. JETP 27, 420 (1968)].

[2]C. E. Ragan, III, M. G. Silbert, and B. C. Diven, J. Appl. Phys. 48, 2860 (1977).

[3]R. E. Kidder, in *Physics of High Density*, edited by P. Caldirola and H. Knoepfel (Academic, New York, 1971), p. 306.

[4]C. G. M. van Kessel and R. Sigel, Phys. Rev. Lett. 33, 1020 (1974).

[5]D. Billon, D. Cognard, J. Launspach, E. Patou, D. Redon, and D. Schirmann, Opt. Commun. 15, 108 (1975).

[6]L. Veeser and J. Solem, Phys. Rev. Lett. 40, 1391 (1978).

[7]Laser Program Annual Report—1975, Lawrence Livermore Laboratory Report No. UCRL-50021-75, 1976 (unpublished), p. 64.

[8]S. W. Thomas, J. W. Houghton, G. R. Tripp, and L. W. Coleman, in *Proceedings of the Eleventh International Congress on High Speed Photography, London, 1974*, edited by P. J. Rolls (Chapman and Hall, London, 1975), p. 101.

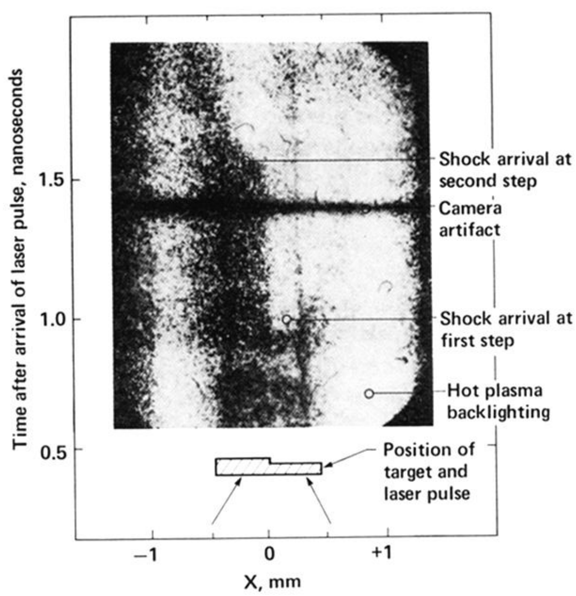
[9]G. B. Zimmerman and W. L. Kruer, Comments Plasma Phys. 2, 51 (1975).

[10]K. R. Manes, V. C. Rupert, J. M. Auerbach, P. Lee, and J. E. Swain, Phys. Rev. Lett. 39, 281 (1977), and references contained therein.

[11]M. van Thiel, Lawrence Livermore Laboratory Report No. UCRL-50108, 1977 (unpublished), Vol. 1–3, Rev. 1.

[12]The pressures corresponding to the shock velocities were calculated in three ways: from tubular equation-of-state libraries; from pseudopotential calculations by M. Ross (private communication); and from extrapolation of lower-pressure equation-of-state data. The three methods yielded pressures differing by no more than 10%.

[13]C. W. Cranfill and R. M. More, private communication; R. M. More, R. J. Trainor, M. Kamegai, and N. C. Holmes, Bull. Am. Phys. Soc. 23, 893 (1978).



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