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STRONG SHOCK WAVES*

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Shock waves traveling at speeds in excess of 10^8 cm/sec (Mach number ≥ 1000) in deuterium gas at 50 mTorr and room temperature ($n_1 = 1.3\times 10^{15}$ cm^{-3}) have been created in a 3-m-long, electromagnetically driven coaxial shock tube, and neutrons have been observed.

Strong ionizing shock waves propagating through room-temperature deuterium at shock speeds $u_s \gtrsim 10^8$ cm/sec should, according to theoretical calculations, heat the gas to kilovolt energies.[1,2] Kurtmullaev et al. previously reported[3] shock speeds of nearly 10^8 cm/sec in low-density deuterium ($n_1 \sim 10^{12}$ cm^{-3}) in which the shock wave traveled a distance of several centimeters and the wave structure was sufficiently thin to be considered as collisionless. At the Seventh International Shock Tube Symposium in June of 1969, Levine, Vitkovitsky, and Kolb reported[4] experiments with collisionless shock waves propagating several centimeters at speeds $\gtrsim 10^8$ cm/sec into low-density ($n \sim 10^{12}$ cm^{-3}) ionized argon. Both these groups employed small, fast, theta-pinch devices.

No measurements of collisional shock waves traveling faster than about 4×10^7 cm/sec have been reported.[2] High-speed collisional shock waves are of special interest for controlled fusion because such waves are expected to heat the ions, a process necessary to achieve thermonuclear reactions in the resulting plasma. We report here the operation of a new device, a coaxial electromagnetically driven shock tube, which has produced collisional shock-wave speeds $\geq 10^8$ cm/sec over distances of ~100 cm, into relatively dense ($n \sim 10^{15}$ cm^{-3}) deuterium.

A coaxial electromagnetic shock tube has been constructed at Columbia University. This device is 3 m long, has an outer diameter of 22.5 cm, and an annular gap of 5 cm. The coaxial tube, whose outer conductor is aluminum and inner conductor is copper, is pumped to approximately 10^{-7} Torr and then filled with room-temperature deuterium to a pressure p_1 between 10 and 100 mTorr. An initial azimuthal magnetic field $B_1 \approx 7200$ G is produced by the current from a 300-kJ capacitor bank whose quarter period is 100 μsec. At the time of maximum field a shock wave is driven into the cold gas by an azimuthal magnetic field (piston) produced by a current ($\sim 2\times 10^6$ A) which flows axially along the inner conductor, radially through the plasma, and returns axially along the outer conductor. For the experiments described here the inner conductor was positive with respect to the grounded outer conductor. Both the initial field and the shock-driving field had the same azimuthal direction. The shock-wave drive current was produced by a 300-kJ, 100-kV capacitor bank, which has a quarter period of 4 μsec. The shock-wave drive current is transmitted through six SF_6-gas-filled low-inductance switches, each of which is triggered by a 180-kV Blumlein pulse initiated from a single master switch. Further details of this device have been described elsewhere.[5]

Some of the initial results obtained from operation of this new electromagnetic shock tube are described below. In Table I are shown shock speeds measured in deuterium with initial pres-

Table I. Shock-wave speeds in deuterium (cm/sec) ($p_1 \approx 50$ mTorr, $T_1 = 298$°K).

		0-50 cm	0-100 cm	0-150 cm
Magnetic field probes	foot	$3.6\pm 0.5\times 10^8$	$9.2\pm 1.4\times 10^7$	
	slope	•••	$7.6\pm 0.6\times 10^7$	$4.0\pm 0.2\times 10^7$
Radiation detectors	foot	$2.5\pm 0.7\times 10^8$	$8.8\pm 0.5\times 10^7$	
	slope	$1.7\pm 0.1\times 10^8$	$6.4\pm 0.4\times 10^7$	$3.6\pm 0.5\times 10^7$

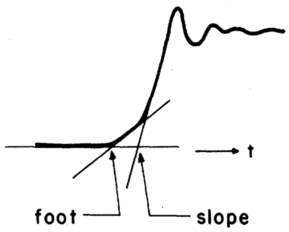

FIG. 1. A typical magnetic field, $B(t)$ trace, illustrating the terms "foot" and "slope" as used in Table I.

sure of ~50 mTorr. In Table I the word "foot" refers to the beginning of the rise of the detector signal, and "slope" refers to the time of the steep rise, as illustrated in Fig. 1. The preshock azimuthal magnetic field was 7200 G, the acoustic speed a_1 was 9.3×10^4 cm/sec, and the initial particle density $n_1 = 1.3\times10^{15}$ cm^{-3}. Emission of soft x rays from the post-shock plasma was measured. Measurements by magnetic field probes and a laser interferometer show a compression ratio of 3 to 4 across the shock wave, clearly indicating shock compression rather than any precursor effect. It is interesting to note that in the first 100 cm an average acoustic Mach number of ≈1000 was achieved, and in the first 50 cm the shock speed of 3×10^8 cm/sec was 1% of the speed of light. The equilibrium post-shock plasma temperature for these speeds is theoretically predicted to be 1 and 10 keV, respectively. Data taken at the 50-cm location, however, must be interpreted with caution as the shock wave at that point was often not yet well formed and the experimental data had appreciable scatter. Magnetic field data recorded further along the tube were highly reproducible. The average Alfvén Mach number over the first 100 cm was approximately 4. The evolution of the magnetic field profile as measured at three locations along the tube in a single firing is shown in Fig. 2. Computer simulation of the shock tube has helped in the interpretation of these magnetic field probe data.[6] In Fig. 2 the second hump in the magnetic field trace obtained at the 150-cm point is identified as drive current which follows the shock by about 1.2 μsec. This indicates a post-shock length of about 50 cm of nearly current-free plasma, or a hot-plasma volume of approximately 10^4 cm^3.

The magnetic field probe data also provide information on the structure of these strong shock waves. In Fig. 3 is shown the structure of the shock wave as determined from data taken at the 100-cm point. The shock-wave structure is

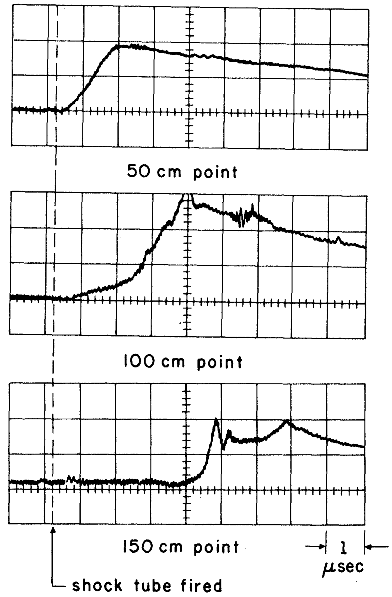

FIG. 2. Azimuthal magnetic field probe data for $p_1 = 50$ mTorr H_2, $T_1 = 298$°K. These data, taken from one shot, show clearly the shock propagation.

collisional since the molecular mean free path in the initial room-temperature deuterium is approximately 1 cm and the shock-wave thickness is approximately 20 cm. The oscillations in the plasma immediately behind the shock are of decreasing amplitude and a frequency of a few MHz. The post-shock plasma has a number density $n_2 \sim 1\times10^{16}$ cm^{-3} and is essentially collisionless. The theoretical equilibrium post-shock plasma temperature for a shock wave traveling at 100 cm/μsec in deuterium is 1 keV (10^7 K) and if the ions actually reach this temperature, thermonuclear neutrons should be produced. A relatively small change in the shock speed has a large effect upon the neutron yield because of the strong functional relationship between the fusion reaction rate and the plasma temperature.

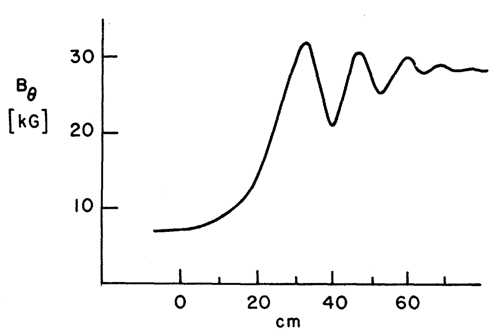

FIG. 3. Shock-wave magnetic field structure. The initial gas state was $p_1 = 50$ mTorr D_2, $T_1 = 298$°K. The average speed over the first 150 cm was 42 cm/μsec.

Theoretical estimates of the neutron production in the Columbia University shock tube, for a shock speed of 100 cm/μsec, predicted about 4×10^5 neutrons. Four 1B85 thyrode Geiger tubes, wrapped in 10-mil silver sheet and covered with a polyethylene moderator, were placed about the 50-cm point on the shock tube. For slightly slower shock speeds than shown in Table I no neutrons were observed. However, for the shock speeds indicated in Table I, neutrons have been detected, and by using a Los Alamos calibration[7] for this detector, we estimate a yield of about 5×10^5 neutrons. However, the close agreement between predictions and this measurement is thought to be more fortuitous than an indication of accuracy. A pilot *B* scintillator, shielded by 1 in. of lead, detected a burst of radiation which may be neutrons or nonthermal hard x rays. We do not know yet whether the neutrons are truly of thermonuclear origin.

The experimental data indicate that the shock-created plasma volume of $\sim 10^4$ cm^3 has an internal energy density (nkT) of about 1.2 J/cm^3, a macroscopic kinetic energy ($\frac{1}{2}\rho V^2$) of about 2.8 J/cm^3, and that about 20% of the energy originally stored in the high-voltage capacitor bank was transferred into the plasma in the first half-cycle of the current pulse.

We acknowledge the many contributions by Dr. B. Miller in the design and early development of the shock tube, and thank Mr. M. Cea, Mr. J. Osarczuk, Mr. J. Ivers, and Mr. G. Beshara for its construction. We acknowledge many enlightening discussions with Dr. C. K. Chu, Dr. R. Taussig, and Dr. B. P. Leonard.

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BRAGG REFLECTION OF LIGHT FROM SINGLE-DOMAIN CHOLESTERIC LIQUID-CRYSTAL FILMS

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Reflection measurements have been made for the first time on single-domain cholesteric liquid-crystal films. We observed spectral structure and polarization character with obliquely incident light never seen with the previously studied disordered films. We also obtained numerical solutions to Maxwell's equations for obliquely incident light in such materials by a new method. Our reflectivity measurements agree fairly well with computations based on Oseen's spiraling-dielectric-ellipsoid optical model for cholesteric systems.

Almost all previous optical studies of cholesteric liquid-crystal films were made on systems composed of cholesterol-derived molecules. The optical properties of these films were qualitatively explained by assuming a distribution in orientation of Bragg scattering domains embedded in a matrix of constant refractive index.[1] Adams and co-workers have shown that, among other difficulties, inhomogeneity in Bragg spacing makes it impractical to measure this angular distribution.[2] Because of this uncertainty in these materials no quantitative comparison can be given with the theories of Oseen,[3] De Vries,[4] and others,[5,6] who have derived optical equations for propagation and reflection in perfectly ordered samples.

We have avoided these experimental problems by studying the optical properties of a single domain of a cholesteric system in which the helicoidal axis is uniformly perpendicular to the