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[11]It can be shown that the experimentally measured quantity $S(k) \equiv \langle \delta n_e^{\,2}(k)\rangle /N$ is proportional to $(k^2\lambda_D^{\,2} - T_eZ'/2T_i)^2 2\pi^2\lambda_D^{-2}I_k/T_e$, where $Z((\omega_k - ku_0)/k\sqrt{2}c_i)$ is the plasma dispersion function.

[12]The group velocity $\partial\Delta\omega_k(n)/\partial k$ is of order $(u_0T_e/\sqrt{2}c_iT_i)[\Delta\omega_k(n)/k]$ or $\Delta\omega_k(n)/k$, according to which is largest.

Laser-Driven Implosion of Spherical DT Targets to Thermonuclear Burn Conditions*

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Calculations predict that carefully timed laser pulses can implode small DT spheres and shells to extreme densities such that thermonuclear burn ensues. We characterize the implosion quality as a function of the pulse time scale, growth law, and initial intensity. Phenomenological rules for mass scaling, input energy threshold, and yield ratio $Y_R = E_{\text{out}}/E_{\text{in}}$ are presented. We find that $Y_R = 4.7$ for only 1.9 kJ of CO_2 laser input energy to a 3-μg shell. The performance of shells is compared to spheres.

Short-pulse CO_2 and Nd lasers which deliver up to 8 kJ should soon be available.[1] Anticipating this, we discuss the possibility of initiating thermonuclear fusion in small DT targets exposed to properly timed pulses from such lasers.

Theoretical considerations.—At 8 keV the rate of thermonuclear energy production exceeds the bremsstrahlung rate in DT at equilibrium, provided the α-particle reaction products are recaptured by the plasma.[2] This temperature represents 600 J/μg. Thus, conceivably, the proposed lasers could suffice to ignite, say, a 0.75-μg sphere of DT fuel. At solid density, $n = 5\times10^{22}$ cm^{-3}, the sphere has a radius $R = 1.13\times10^{-2}$ cm. The 8-keV ions have a mean thermal speed $v_{\text{th}} = 5.6\times10^7$ cm/sec. So the sphere will disassemble by expansion on a time scale $\tau_e \simeq R/v_{\text{th}} = 1.7\times10^{-10}$ sec. Energy producing reactions occur with the characteristic time $\tau_r = 1/n\langle\sigma v\rangle = 2.9\times10^{-7}$ sec, in which the averaged cross-section term $\langle\sigma v\rangle$ increases monotonically with temperature for $T < 65$ keV.[3] Thus, $\tau_e/\tau_r \ll 1$ and any thermonuclear burn in the ambient solid is quenched long before completion. Also, the α-particle mean free path,[4] $\lambda_\alpha = 0.032T^{3/2}$ (keV) = 1 cm, far exceeds the pellet dimensions. Under compression, however, these conditions can be markedly improved since $\tau_r/\tau_e \sim \lambda_\alpha/R \sim n^{-2/3}$. With an extreme 10^4-fold increase in density, for example, $\lambda_\alpha/R = 0.7$ and $\tau_e/\tau_r = 0.27$. α particles from the center of the sphere redeposit their energy, and roughly 27% of the DT fuel is consumed. Complete burn yields 326 kJ/μg, so ~60 kJ should be produced in the sphere.

The utility of high compression is not a new concept. Early work on fission weapons at Los Alamos in 1943 by S. Neddermeyer[5] explored the possibility of improving the neutron economy and enhancing the rate of fission energy release by compressing a solid ball of fissile material to high density using a spherical implosion driven by detonating high explosives. This technique did indeed achieve high compressions and as a consequence the technique has been studied and used a great deal since. It is for this reason that the concept of using the laser energy to compress a DT pellet to improve the retention of α-particle energy and to increase the rate of thermonuclear energy release occurred naturally to workers at Los Alamos and Livermore. The maturing of this idea over the past ten years coupled with the development in laser technology and the experimental and theoretical investigation of the interaction of laser energy with matter has led to the serious consideration of this concept as an approach parallel to that of magnetic confinement for the production of electrical energy for utility use by the fusion process. The first

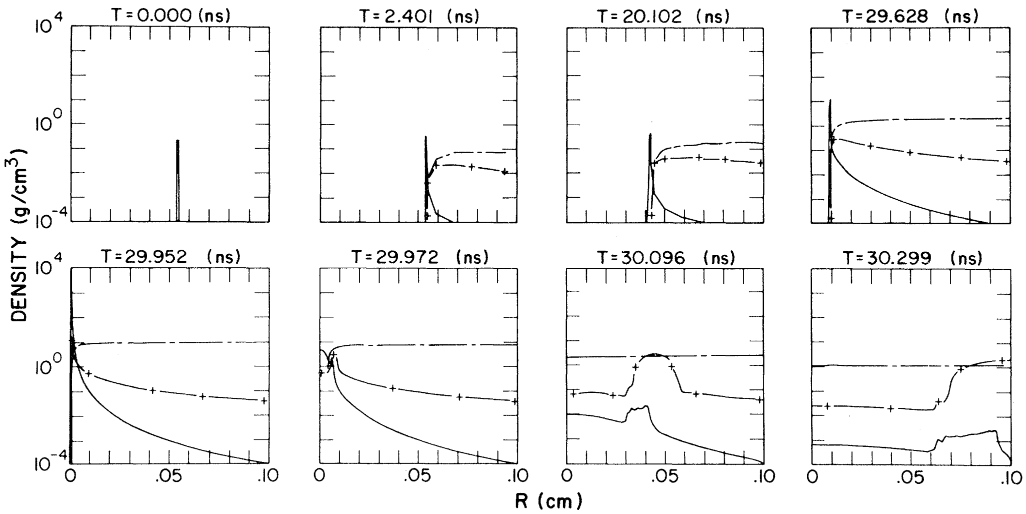

FIG. 1. Time history of the density and temperatures of a 7.5-μg DT shell subjected to 5.3 kJ of CO_2 laser energy; plusses, ion, and dashes, electron temperatures in keV.

discussion of these ideas in the journal literature appears in an article by Nuckolls *et al.*[6] This Letter presents Los Alamos work on the laser-driven ablative implosion of DT spheres and shells.

Figure 1 demonstrates this process for a shell. The laser heats electrons on the outside of the shell by inverse bremsstrahlung and anomalous mechanisms.[7-10] This heating travels inward as a thermal wave in competition with an outward-moving expansion of ablating ions.[11] The ions are thermalized by electron-ion collisions. The inner ~10% of the shell (its core) is compressed and accelerated[12] by the gradient of electron and ion pressures, and by the reactive force to the ablating ions.

Optimized timing of the laser pulse can significantly improve the quality of implosions. Compression is easiest when the DT core remains cool. In spheres some heating will derive from a first shock generated at the low initial laser intensity. Thereafter, the laser exposure profile can be tailored to keep the subsequent compression of the target core adiabatic to a maximal degree. This is accomplished when the rising laser intensity continuously generates weak, overtaking shocks which first coalesce to a strong shock just before the center. Then, only, as this shock collapses at the center are the high temperatures produced which are required for ignition.

In the adiabatic compression of a sphere or shell, the core temperature obeys $T \sim n^{\gamma-1} \sim R^{-3\gamma+3}$, where γ is the effective ratio of specific heats. The shock overtaking process keeps the mean speed of the compressed portion of the core following $v \sim T^{1/2} \sim R^{(-3\gamma+3)/2}$. Since $v \equiv -dR/dt$ with $R \to 0$ at time τ, we can therefore solve for the velocity dependence, obtaining $v \sim (1-t/\tau)^{-q}$, $q=(3\gamma-3)/(3\gamma-1)$. Finally, because work is done on the core at a total rate $\dot{W}=4\pi R^2 P v$ with $P \sim nv^2$, and since we expect this to be proportional to the energy input rate from the laser $\dot{E}(t)$, we conclude that an optimized laser exposure profile is

$$\dot{E}(t)=\begin{cases}\dot{E}_0(1-t/\tau)^{-p}, & E \leq E_{\mathrm{in}},\\ 0, & E > E_{\mathrm{in}},\end{cases} \tag{1}$$

where $p=(9\gamma-7)/(3\gamma-1)$ ($=2$ for $\gamma=\frac{5}{3}$), E_0 is some appropriate initial input power, and E_{in} is the chosen total laser input energy.

Numerical results.—We have made extensive studies of the implosion of DT spheres and shells by computer simulation. The calculations have been performed with a one-dimensional, Lagrangian hydrodynamic, three-temperature (electron, ion, and Planckian radiation) code, that includes energy exchange among the fields (Coulomb, bremsstrahlung), radiation diffusion, classical ion and electron conductivity, and time-dependent nonlocal α-particle energy deposition, with Fermi degeneracy effects included in the equations of state. For the results presented, CO_2 laser light was absorbed by inverse bremsstrahlung up to the critical density n_{crit}, with the remainder deposited at n_{crit} by assumed anomalous mechanisms.

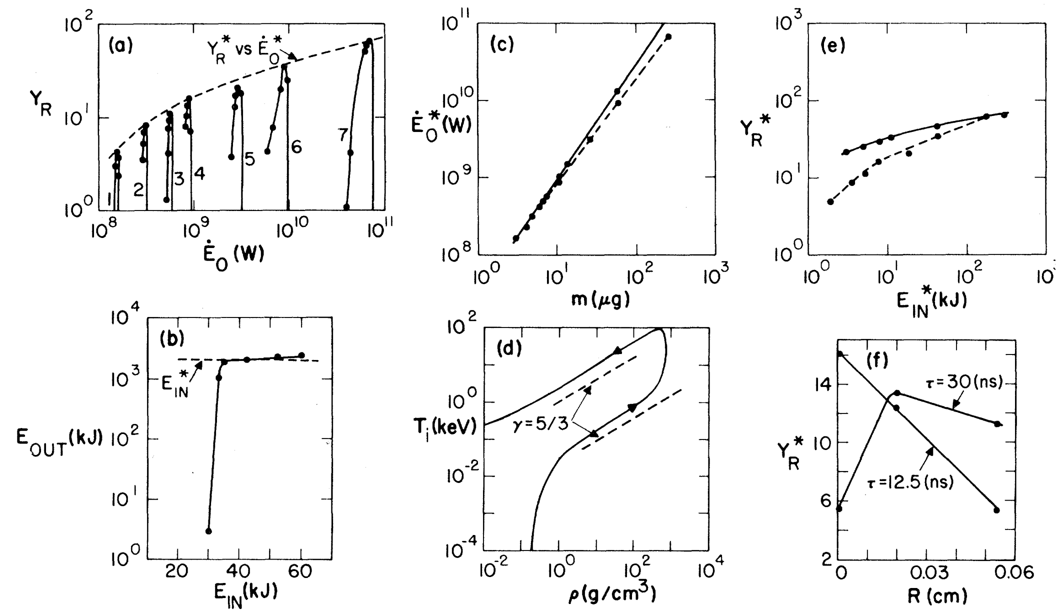

FIG. 2. DT shell and sphere performance characteristics: (a) Y_R versus $\dot{E}_0$ for (1) 3-μg, 2.2-kJ, (2) 5-μg, 3.5-kJ, (3) 7.5-μg, 5.3-kJ, (4) 10.8-μg, 7.5-kJ, (5) 26-μg, 18.2-kJ, (6) 60-μg, 43-kJ, and (7) 250-μg, 178-kJ shells of initial inner radius $R = 5.4\times 10^{-2}$ cm under profile (1) with $\tau = 30$ nsec and $p = 1.875$. (b) Input energy threshold, $\dot{E}_{\text{in}}^*$, determination. (c) Optimal $\dot{E}_0$ versus mass: solid line, for spheres ($\tau = 20$ nsec, $p = 2$); dashed curve, for the shells of (a). (d) 6-μg core trajectory, T_i versus ρ, for a 60-μg sphere during its implosion, thermonuclear burn, and expansion. (e) Optimal yield ratios versus input energy: solid curves, for the shells [in (a)]; dashed curves, for spheres. (f) Y_R^* versus inner radius for 7.5-μg shells imploded with the optimized (1) profile for $\tau = 30$ and 12.5 nsec.

Figure 1 describes the implosion of a 7.5-μg DT shell of initial inner radius $R = 5.4\times 10^{-2}$ cm and thickness $\Delta R = R/56$. The laser input energy is 5.3 kJ. The pulse parameters are $\tau = 30$ nsec, $p = 1.875$, and $E_0 = 5.7\times 10^8$ W. The peak power is 3.85×10^{13} W. With the assumed energy dump-all and classical conductivity, this raises the electron temperature at the critical density to a 10-keV maximum. A highly optimized compression results bringing the inner 0.75-μg core of the shell to 10^4 times solid density with a central peak density at 6×10^3 g/cm^3. The mean ion temperature in the core under full compression is 8 keV, although a 30-keV temperature is recorded at the pellet's center just after the shock collapse. The burn yields 58 kJ, in accordance with our theoretical considerations. Thereafter, a blast wave is seen to develop in the density coincident with a region of elevated ion temperature. The higher conductivity of the electrons rapidly flattens their temperature profile.

In Fig. 2 we have collected the data from numerous runs. We have found the quality of implosion to be relatively insensitive to the choice of p and τ in (1) over the ranges $1.5 < p < 2.5$ and $0.5\tau_0 < \tau < 3\tau_0$, where τ_0 is the transit to the center of spheres of the first shock launched with $\dot{E}(t) = \dot{E}_0$. The yield ratio, $Y_R = E_{\text{out}}/E_{\text{in}}$, is, however, quite sensitive to $\dot{E}_0$, as apparent from Fig. 2(a), which gives results for shells of differing mass. Clearly, a proper choice for $\dot{E}_0$ is more essential at smaller masses. For a given mass m a threshold energy E_{in}^* is required for good returns; more input energy than this is wasted. In general, $E_{\text{in}}^*/m = 0.7$ kJ/μg seems to apply. Figure 2(b) shows this result for a 60-μg sphere. The optimal initial intensity $\dot{E}_0^*$ has been found to obey the strict mass dependences (over 3 orders of magnitude) $\dot{E}_0^* \sim m^{1.50}$ for spheres, and $\dot{E}_0^* \sim m^{1.38}$ for the shells, as derived from Fig. 2(c). For a fixed mass, inner radius, and choice of p, the time dependence $\dot{E}_0^* \sim \tau^{-p}$ is obeyed. From this, integrating (1), we can conclude that with fixed E_{in}^* the optimal pulse closes at a fixed power level, $\dot{E}^*(t = t_{\text{in}})$, independent of the time scale.

Figure 2(d) shows the mean temperature versus mass-density behavior of the 6-μg core of a 60-μg spherical pellet under (1), employing $\tau = 20$ nsec, $p = 2$, and $\dot{E}_0^* = 1.3\times 10^{10}$ W. The DT is first shock heated to 10^{-2} keV, then rides up the $\gamma=\frac{5}{3}$ adiabat to 2 keV, where the final shock collapse and burn raises T_i to 95 keV, prior to the expansive disassembly of the core. Clearly, the expansion pursues a similar adiabat down to $\rho=0.1$ g/cm^3.

Optimal yield ratios (from pulses using $\dot{E}_0{}^*$) are given versus $\dot{E}_{\rm in}{}^*$ in Fig. 2(e). Here the calculations for spheres employed local α deposition, which artificially improves their performance at small m. For the shells with nonlocal, time-dependent deposition, the rules $Y_R{}^* \sim (E_{\rm in}{}^*)^{0.45}$, $E_{\rm in}{}^* > 8$ kJ, and $Y_R{}^* \sim (E_{\rm in})^{0.90}$, $E_{\rm in} \leq 8$ kJ, are observed. We calculate $Y_R{}^* = 4.7$ for only 1.9 kJ delivered to a 3-μg shell. Thus, breakeven with only 350 J of input energy is implied. With nonlocal deposition and parameters other than R and $\dot{E}_0{}^*$ held constant, our studies show degraded performance for shells relative to spheres under the exposure profile (1), as documented by Fig. 2(f).

Thus, within the constraints of the physical model described, our calculations imply the feasibility of controlled thermonuclear burn by inertial confinement. Scaling laws for a broad range of potential target designs have been presented. Still numerous questions remain, as to the three-dimensional stability of these designs, the details of anomalous light absorption,[13] hyperthermal electron production and deposition,[14] and the effects of spontaneously generated magnetic fields.[15]

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Superconductivity in "Amorphous" Transition-Metal Alloy Films

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The superconducting transition temperatures of "amorphous" transition-metal alloys have been measured. The variation of T_c as a function of the electron-to-atom ratio is consistent with the presence of an atomiclike parameter characterizing the systematics of T_c, with, however, an unexplained peak at the half-filled d shell. The data do not support a recent explanation based entirely on a simple averaging or smearing of the crystalline electronic density of states.

In this Letter we report measurements of the superconducting transition temperature T_c for disordered $4d$ and $5d$ transition-metal alloy films.[1] We have observed that the T_c in amorphous (or highly disordered) transition metals differs strongly from that of crystalline transition metals (see Figs. 1 and 2). The resulting behavior of the amorphous T_c is believed to be a manifestation of "the dominance of atoms and their local environment in determining supercon-