Measuring Implosion Symmetry and Core Conditions in the National Ignition Facility

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Tertiary protons with birth energies from 27 to 30.8 MeV result from the implosion of ignition-scale inertial confinement fusion targets, such as those planned for the National Ignition Facility. Measurement of the tertiaries' slowing can provide a determination of the imploded areal density of the fuel capsule, as well as information about implosion asymmetry that results from anisotropy of the areal density and plasma temperature. To determine the utility of tertiaries for all phases of ignition experiments, we analyze three representative cases: a gas capsule (0.7 kJ yield), a cryogenic fuel capsule that fails to ignite (15 kJ), and a cryogenic fuel capsule that ignites and burns (13 000 kJ). In each case, tertiaries escape from the capsule and convey critical information about implosion dynamics. [S0031-9007(96)01141-6]

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In both the U.S. [1–4] and France [5] widespread attention has focused on new initiatives in inertial fusion, the National Ignition Facility (NIF) in the U.S. and the Mega-Joule Laser Facility in France. The goal is to generate 10 times more energy from fusion than the laser energy ($\leq$1.8 MJ) used to drive capsule implosions. In such experiments, densities and areal densities will be immense ($\sim 10^3$ g/cm^3 and $\sim$1 g/cm^2, respectively). Precisely because of such extremes (see Figs. 1–3), new diagnostic methods will be required to measure critical parameters such as capsule implosion symmetry [1,6–8] and areal density [9–12]. Here we identify a solution to these particular issues based on detection of tertiary protons that have birth energies between $\sim$27 and 30.8 MeV. We concentrate on these high-energy tertiaries both because of their ability to escape the capsules envisioned for all phases of the NIF and because they convey pivotal information.

Diagnosis of tertiary protons will be useful during three phases of the approach to ignition. In the first phase, conditions for symmetric drive will be established using non-igniting DT gas-filled capsules, with small fusion yields

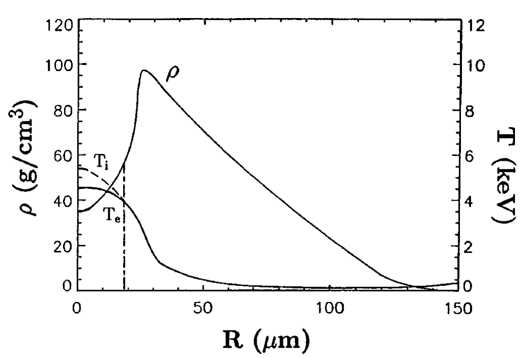

FIG. 1. Calculated density and temperature profiles, at peak burn, for a gas-capsule implosion (0.7 kJ) in the National Ignition Facility (NIF). From such profiles, estimates are made of the yield of $\sim$27 to 30.8 MeV tertiary protons, and their energy loss as they transit the capsule (case A, Table I). In this instance, they lose between 10 and 12 MeV. The dash-dotted line indicates the crossover from DT to CH-ablator plasma. For the first few years, gas-capsule implosions will be the focus of the NIF.

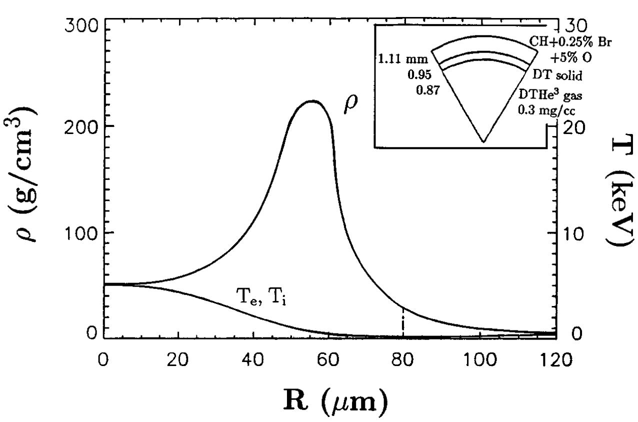

FIG. 2. Calculated density and temperature profiles, at peak burn, for a NIF cryogenic-capsule implosion (15 kJ) that fails to ignite (case B, Table I). This simulated failure was achieved by overdriving the implosion. The dash-dotted line indicates the crossover from DT to CH-ablator plasma. Inset: Typical starting capsule [1] for indirectly driven implosions of Figs. 2 and 3. Laser irradiance parameters are given in Ref. [1]. In our simulations, the initial gas mixture is typically 0.15 mg/cm^3 of He^3. (Simulations ignite even when the gas density is comprised entirely of He^3 [17].) For the gas-capsule implosion of Fig. 1, the solid cryogenic layer is removed and the CH ablator thickened to maintain constant areal density; the initial gas mixture (D:T:He^3) is then 0.5:0.25:0.25.

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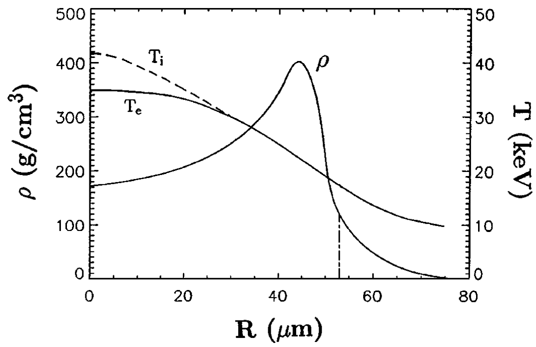

FIG. 3. Calculated density and temperature profiles, at peak burn, for a NIF cryogenic-capsule implosion (13 000 kJ) that ignites (case C, Table I). In this instance, the fusion energy is about 10 times greater than the laser energy used to drive the implosion. The dash-dotted line indicates the crossover from DT to CH-ablator plasma.

(0.7 kJ). In the second phase, the drive pulse shape for igniting cryogenic (solid fuel) capsules will be determined, as well as further fine-tuning of drive symmetry. Ignition itself will not yet be achieved, but the yields will typically be much larger (15 kJ) than for gas capsules. In the final stage, fully ignited cryogenic capsules with large yields (13 000 kJ) will be diagnosed. Below we analyze the tertiary production and spectra from each of these cases. In addition to these considerations of the NIF implosions, we briefly examine the potential utility of tertiary protons for current laser experiments such as the recently completed OMEGA.

High-energy tertiary protons are generated in a three-step process starting with the primary fusion between deuterium (D) and tritium (T) ions

$$D + T \rightarrow \alpha(3.5\ \text{MeV}) + n(14.1\ \text{MeV}), \qquad (1)$$

where the short range of the α particles propagates the fusion burn from the igniting core outwards into the dense fuel region [13,14]. The second step involves the 14.1-MeV neutron elastically scattering off a plasma deuteron:

$$n(14.1\ \text{MeV}) + D \rightarrow n' + D(11-12.5\ \text{MeV}). \qquad (2)$$

11 (12.5) MeV corresponds to a collision in which the deuteron scatters at 20 (0) degrees with respect to the incident neutron direction. The total cross section for this reaction is $\sigma_D \approx 620$ mb. Because the differential cross section is strongly peaked in the forward direction [15], about 13% of the reactions result in deuteron energies at or above 11 MeV. [This corresponds to the factor F_θ in Table I and Eq. (4).] The third and final step involves these very energetic deuterons fusing with plasma ^{3}He ions, with tertiaries being emitted within 30 [20] degrees of the forward direction:

$$D(11-12.5\ \text{MeV}) + {}^3\text{He} \rightarrow \alpha + P(27.6\ [28.5]-30.8\ \text{MeV}). \qquad (3)$$

The total cross section for this reaction is $\sigma_{He} \approx 40$ mb. Because this differential cross section [16] is also strongly forward peaked, about 17% [12%] of all tertiary protons are emitted with energies at or above 27.6 (28.5) MeV [the factor F_ϕ in Eq. (4)]. This reaction requires the presence of ^{3}He, with which the capsule is seeded during fabrication (related to the factor γ_{He}) [17,18].

To determine the energy loss of the tertiary protons in the NIF we construct, through the use of hydrodynamic-radiative codes such as HYADES [19], representative profiles of temperature and density near peak burn for a gas-capsule implosion (0.7 kJ, Fig. 1); for a cryogenic capsule that fails to ignite (15 kJ, Fig. 2); and for a fully ignited cryogenic capsule (13 000 kJ, Fig. 3) [1,2]. Combining these profiles with stopping power calculations [20], the energy loss during capsule transit is calculated for tertiaries that originate near

TABLE I. Tertiary energy loss and yield (Y_p) expected from 3 NIF capsules: (A) gas capsule, (B) cryocapsule that fails to ignite, (C) cryocapsule which ignites. And (D) expected OMEGA gas-capsule tertiary yield.

	National Ignition Facility			OMEGA
	Case A	Case B	Case C	Case D
Fusion yield (kJ)	0.7	15	13 000	0.051
Tertiary birth energies (MeV) [from near capsule center]	30.8, 27.0	30.8, 27.0	30.8, 27.0	30.8, 20
Tertiary energy loss (MeV) (after capsule transit)	10.1, 11.7	9.9, 11.4	4.5, 4.6	3.2, 4.6
Tertiary escape energy (MeV)	20.7, 15.3	20.9, 15.6	26.3, 22.4	27.6, 15.4
Y_n: Primary neutron yield	2.5×10^{14}	5.3×10^{15}	4.6×10^{18}	1.8×10^{13}
F_n: Fraction of Y_n passing thru ^{3}He-doped fuel	1.0	0.2	0.2	1.0
D:T:^{3}He ratio in the fuel and/or core (γ_D, γ_{He})	0.5:0.25:0.25	0.475:0.475:0.05	0.475:0.475:0.05	0.5:0.25:0.25
$\rho\Delta R$: "Active" part of fuel areal density [g/cm^2]	0.07	0.50	0.54	0.038
F_θ: Factor for knockon deuteron to be scattered within 20° of forward direction	0.13	0.13	0.13	0.13
F_ϕ [α]: Factor for tertiary proton to be emitted within α(deg) of forward direction	0.17 [30°]	0.17 [30°]	0.17 [30°]	0.58 [80°]
m_{eff}: Effective ion mass of fuel ($m_p = 1.67 \times 10^{-24}$ g)	$2.50m_p$	$2.52m_p$	$2.52m_p$	$2.50m_p$
Y_p: Tertiary proton yield	1.5×10^{7} [a]	2.0×10^8	2.0×10^{11}	1.0×10^{6} [a]

[a]Also includes the ^{3}He knockon component.

capsule center (Table I, Fig. 4). In the capsule interior (exterior), tertiary slowing is dominated by plasma electrons from DT (CH). Ion stopping is totally negligible, as are scattering effects [21].

Focusing first on the gas-capsule implosion (case A, Table I), 10.1 to 11.7 MeV is lost during capsule transit for tertiaries with birth energies of 30.8 and 27 MeV, respectively. Most of this loss results from electron stopping in the CH pusher-ablator plasma that encloses the fuel (Fig. 1).

For igniting cryogenic capsules (case C, Table I), only about 5 MeV is lost in capsule transit by tertiaries with birth energies of 27–30.8 MeV. Despite the immense capsule densities, the high temperatures keep the plasma relatively "transparent" (Figs. 3 and 4). Energy loss is more important for nonigniting cryogenic capsules (case B, Table I). This is a consequence of the fact that areal densities are still substantial while temperatures are relatively low (Figs. 2 and 4). The energy loss is 9.9 to 11.4 MeV for 30.8 and 27 MeV protons, respectively. (Because $\sim$0.5 MeV loss in deuteron energy occurs before fusing with ^{3}He, an additional 0.5 MeV is removed from the low-energy end of the proton spectrum.)

To estimate the magnitude of the tertiary yields, we utilize the cross sections associated with Eqs. (2) and (3) as well as the characteristic temperature-density profiles (Figs. 1–3). The yield is

$$Y_p \sim \{(\sigma_{\rm D})(F_\theta)(\gamma_{\rm D})\}\{(\sigma_{\rm He})(F_\phi)(\gamma_{\rm He})\} \times (m_{\rm eff}^{-2})(\rho\Delta R)^2(F_n Y_n), \qquad (4)$$

where Table I lists the interpretation and value of the parameters [22].

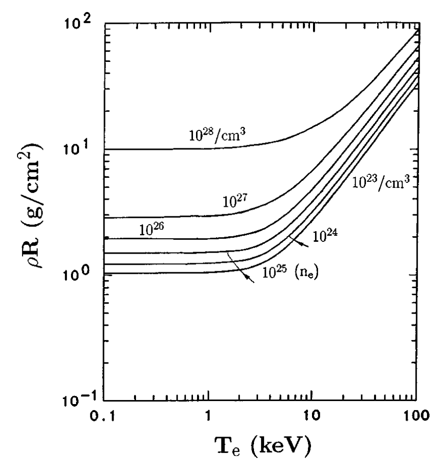

FIG. 4. Range calculations for 30.8-MeV tertiary protons in DT plasmas relevant to simulated implosions in the NIF and OMEGA. In contrast to 3.5-MeV α's, the high energy of tertiary protons results in negligible slowing with plasma ions, even for the ignited cryogenic capsule (Fig. 3) that has an ion temperature of $\sim$40 keV. Scattering effects are also inconsequential [21]. It is for closely related reasons that, by simply multiplying each ρR curve by 0.74, this same family of curves also applies to 30.8-MeV tertiaries in the CH-ablator plasma.

An additional source for tertiary protons, with maximum energy of 28.9 MeV, are those from fusion reactions of knockon ^{3}He ions with plasma deuterons. On the basis of the knockon and fusion cross sections, this contribution is important for the gas-capsule targets when the ^{3}He fraction is large. [It amounts to multiplying Eq. (4) by a factor of about 3 for the conditions of Table I.]

For the NIF gas-capsule implosion (case A, Table I), the tertiary yield is approximately 1.5×10^7 and, for a detector with fractional solid angle of $\sim 10^{-4}$, the signal would be of order 1500 counts. Since this signal is connected with the entire fuel ρR (Fig. 1), this diagnostic is similar in spirit to proposed tertiary neutron measurements [12].

At the other extreme, the ignited cryogenic implosion results in approximately 2.0×10^{11} tertiaries and, in contrast to the gas capsule, they would be largely slowed in the main fuel ρR (Fig. 3). For a detector with fractional solid angle of $\sim 10^{-6}$, the resulting signal would be of order 2×10^5 counts. Another important feature is the substantial energy of the escaping tertiaries, well in excess of the 14.1-MeV neutrons. In such instances, tertiary diagnostics might expeditiously be based on time-of-flight separation from the 14.1-MeV neutrons [23].

For more complicated implosion scenarios, the situation should be even more interesting than these illustrative cases. For example, two-dimensional hydrodynamic calculations for ignited capsules indicate that pole-to-waist [1] angular variations in the cryogenic fuel ρR can vary by as much as 40% from the one-dimensional density profiles depicted above. Such asymmetries might be discernible from measurements of the escaping proton spectrum [22,24].

The previous calculations concerned implosions in the NIF. Here we show that tertiaries might also be useful for present facilities. Utilizing LILAC hydrodynamic calculations [25] and Eq. (4), we list in column D (Table I) neutron yield and $\rho\Delta$R values expected for OMEGA direct-drive gas-capsule implosions (Fig. 5). Treating nascent tertiaries from 20 to 30.8 MeV, the calculated yield is 1.0×10^6. For OMEGA implosions, 20 MeV can be used for the low-energy end of the proton spectrum since only about 4 MeV is lost by the escaping tertiaries. In principle, these tertiaries should be detectable with a charged-particle spectrometer [26], based on charge coupled device technology, that we are building for OMEGA. (The spectrometer's main function is to detect the numerous charged particles from other implosion processes [11,27].) With a fractional solid angle of 3×10^{-5}, it should detect about 30 tertiaries [24]. Thus even for the present, new class of facilities like OMEGA, tertiaries might expeditiously be used to help diagnose implosion dynamics.

In summary, penetrating tertiary protons with birth energies from $\sim$27 to 30.8 MeV are shown to be sensitive to central fuel conditions and implosion symmetry in the National Ignition Facility, including those implosions with peak density of $\sim 10^3$ g/cm^3 and areal density of $\sim$1 g/cm^2. Because the sequence of experiments in

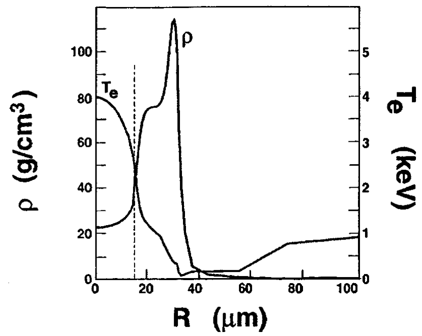

FIG. 5. Calculated density and temperature profiles, at peak burn, for a directly driven OMEGA implosion (0.051 kJ) [25]. For this particular simulation, tertiary protons may be the only charged particle species that can unambiguously convey information about the fuel ρR [23,24]. For example, knockon deuterons and tritons are ranged out, while knockon protons from (H)fuel seeding could be overwhelmed by proton knockons from the CH ablator. For this reason tertiaries could prove useful even for present-day, nonignited experiments. The dash-dotted line indicates the crossover from DT to CH-ablator plasma.

the NIF will proceed from gas to cryogenic capsules, we treated three cases that were representative of this anticipated sequence: First, a gas-capsule implosion; second, a cryogenic implosion that fails to ignite; and third, a cryogenic implosion that fully ignites. In each case, energetic tertiaries will convey useful information about fuel and core areal density and implosion symmetry. Furthermore, even for present facilities such as the newly operational OMEGA, it is possible that tertiary protons can effectively diagnose important aspects of the implosion dynamics.

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[1] S. W. Haan *et al.*, Phys. Plasmas **2**, 2480 (1995).
[2] J. D. Lindl, Phys. Plasmas **2**, 3933 (1995).
[3] *Energy & Technology Review* (Lawrence Livermore National Laboratory, Livermore, CA, 1994).
[4] M. D. Rosen, Phys. Plasmas **3**, 183 (1996).
[5] M. Andre, M. Novaro, and D. Schirmann, Chocs N#251#13, 73–84 (1995); D. Butler, Nature (London) **375**, 6 (1995); J. Maddox, Nature (London) **372**, 127 (1994); Nature (London) **371**, 7229 (1994).
[6] L. J. Suter *et al.*, Phys. Rev. Lett. **73**, 2328 (1994).
[7] A. A. Hauer *et al.*, Phys. Plasmas **2**, 2488 (1995).
[8] R. L. Kauffman *et al.*, Phys. Rev. Lett. **73**, 2320 (1994).
[9] M. D. Cable *et al.*, Phys. Rev. Lett. **73**, 2316 (1994).
[10] M. D. Cable and S. P. Hatchett, J. Appl. Phys. **72**, 2233 (1987).
[11] Y. Kitagawa *et al.*, Phys. Rev. Lett. **75**, 3130 (1995).
[12] Tertiary processes with energetic neutrons as the final product have also been reviewed [H. Azechi, M. D. Cable, and R. O. Stapf, Laser Part. Beams **9**, 119 (1991)].
[13] J. D. Lindl, R. L. McCrory, and E. M. Campbell, Physics Today **45**, No. 9, 32 (1992).
[14] S. Skupsky, Phys. Rev. A **16**, 727 (1977).
[15] National Neutron Cross Section Center, Brookhaven National Laboratory Internal Report No. 400, 1970, 3rd ed.
[16] H. Liskien and A. Paulsen, Nucl. Data Tables **11**, 569 (1973).
[17] For an imploded core ^{3}He fraction of 5%, the initial vapor-space fraction would have to be 0.5, or about 0.15 mg/cm^3. This increases the natural time constant for forming the solid layer by "beta layering" from about 25 to about 200 min (five to ten time constants are required to produce a smooth, symmetric layer). The presence of the ^{3}He will not otherwise directly affect the solid layer, but if the time constant becomes too long ^{3}He bubbles can form in the solid, leading to deleterious effects.
[18] Only for fully ignited cryogenic implosions (case C) will an important fraction of tertiary protons originate from ^{3}He generated from D-D fusion. Specifically, for the conditions of Table I and Fig. 3 (i.e., 5% ^{3}He fraction at peak burn), Monte Carlo and hydrodynamic calculations indicate that the *in situ* D-D component will be smaller by a factor of 3 [see S. Cremer *et al.* (to be published)].
[19] J. T. Larsen and S. M. Lane, J. Quant. Spectrosc. Radiat. Transfer **51**, 179 (1994).
[20] C. K. Li and R. D. Petrasso, Phys. Rev. Lett. **70**, 3059 (1993).
[21] C. K. Li and R. D. Petrasso, Phys. Plasmas **2**, 2460 (1995).
[22] There is a trade-off between the signal size and the degree to which asymmetries can be determined. Specifically the larger F_θ and F_ϕ [of Eq. (4) and Table I), the larger the signal, but the smaller the information content that can be obtained about the implosion asymmetry. In a similar vein, if the tertiary source is too extended, it can wash out short spatial scale ρR variations, of which P_2, P_4, and P_6 are of particular interest.
[23] For tertiaries it is also desirable that their escape energy exceed 14 MeV to avoid confusion with 14-MeV (and lower energy) protons that originate from neutron knockons with the (CH) ablator hydrogen.
[24] The important issue of detector noise—from neutrons, gammas, etc.—will need to be carefully assessed.
[25] J. Delettrez *et al.*, Phys. Rev. A **36**, 3926 (1987); E. B. Goldman *et al.*, Univ. of Rochester theory group (unpublished).
[26] C. K. Li *et al.*, Rev. Sci. Instrum. (to be published); D. G. Hicks *et al.*, *ibid.*; B. Burke *et al.*, *ibid.*
[27] S. Skupsky and S. Kacenjar, J. Appl. Phys. **52**, 2608 (1981).