Measurements of fuel and shell areal densities of OMEGA capsule implosions using elastically scattered protons

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Implosions of capsules filled with small quantities of deuterium–tritium (DT) were studied using up to seven proton spectrometers on the OMEGA laser system [T. R. Boehly *et al.*, Opt. Commun. **133**, 495 (1997)]. Simultaneous measurements of elastically scattered protons, i.e., ''knock-on'' protons generated from DT neutrons were obtained in several directions. The capsules, nominally 945 μm in diameter and with CD shells of $\sim$20 μm thickness, were filled to about 15 atm and irradiated with 23 kJ of UV light. The high-energy protons from these implosions were used to infer fuel areal density (6.8 ± 0.5 mg/cm^2), an average shell areal density (71 ± 3 mg/cm^2), and shell asymmetries of up to about 25 mg/cm^2. In addition to presenting new results, these measurements verify and significantly improve upon the accuracy of the fuel areal density results obtained utilizing knock-on deuterons from hydrodynamically equivalent, pure DT implosions [C. K. Li *et al.*, Phys. Plasmas **8**, 4902 (2001)]. [DOI: 10.1063/1.1511196]

I. INTRODUCTION

Maximizing fuel areal density (ρR_{fuel}) and minimizing the presence of any shell areal density (ρR_{shell}) asymmetries are important goals of the inertial confinement fusion (ICF) program.[1] Information about these parameters is therefore of importance. As reported recently and in detail by Li *et al.*,[2] ρR_{fuel} and ρR_{shell} are usually inferred in DT fuel implosions from measurements of deuterons and protons elastically scattered by 14.1 MeV neutrons (''knock-on'' deuterons and protons).[3–6] Here a different and more comprehensive approach that utilizes knock-on protons from capsules filled with hydrogen but with small quantities of deuterium–tritium (DT) is reported. There are two distinct advantages of this approach. First, the small size of new spectrometers[7,8] allows several to be fielded simultaneously. This allows for asymmetry studies and spatial averaging of the data. Second, these spectrometers can be placed at optimal distances from the capsule to maximize signal to noise (S/N).

This work brings considerable improvement over that of Nakaishi *et al.*,[9] who obtained a coarse knock-on proton spectrum in a single direction for an implosion of a thin-glass microballoon filled with equal concentrations of D, T, and H. In addition to dissimilarities in fuel composition, the work reported herein differs in several ways: First, ICF-relevant thick-walled plastic capsules were imploded;[10] second, higher-resolution proton spectra were obtained (ten times higher); third, the S/N is considerably higher (about five times); and finally, proton spectra were obtained from several directions simultaneously.

In addition to the aim of exploiting the sensitivity and comprehensiveness of this method, issues raised in Ref. 2 are revisited. In that study, the authors noted that measured deuteron yields, used to infer ρR_{fuel}, were often larger (typically 50%) than measured triton yields. In principle the tritons could also be used for an independent determination of ρR_{fuel}. However, on the basis of deuteron and triton spectra, they argued that only the deuteron spectra could reliably be used since the triton spectrum was sufficiently downshifted, a consequence of their large stopping power, that triton counts were ''lost'' as they fell below the spectrometer low-energy threshold. Alternatively, the authors posited another, less plausible, explanation: the triton deficit could result from isotopic composition imbalances of D and T that were not 50–50, but were biased towards an excess of deuterium. The method described herein will be shown to be very insensitive to the D to T ratio as long as both components are small compared to the hydrogen content.

They also noted that their measurements, obtained with a single spectrometer, are subject to a nonstatistical yield variation of about $\pm15\%$, thought to be the result of either residual B-fields or small tangential electric fields.[2,11–13] This increases the absolute error of any individual measurement well beyond the statistical error (typically $\sim3\%$). The method described herein is subject to the same yield uncertainty in any given direction but the final uncertainty is substantially reduced by spatially averaging over several simultaneous measurements (see Fig. 25 in Ref. 7, where, for nuclear lines, spatial averaging was also used).

Finally, it was determined in Ref. 2 that the measured

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fuel ρR_{fuel} for their DT implosions was ~80% of the 1D hydro calculation, while the DT yield was only ~35%. This circumstance, taken at face value, gives added impetus to independently verify the ρR_{fuel} determinations.

Section II describes the experimental conditions. Section III discusses the spectra of knock-on particles, reaction products, and their relationships to characteristics of imploded capsules. The experimental data are presented in Sec. IV, along with discussion of compressed capsule characteristics and comparisons to hydrodynamically equivalent 15 atm DT capsules. Section V summarizes the main results.

II. EXPERIMENTAL CONDITIONS

A. Capsule design

Two room temperature capsules filled with H_2 and small quantities of D and T were used in this study. The outer diameters of the capsules were about 945 μm. To achieve hydrodynamic properties similar to those of the DT implosions studied in Ref. 2, the capsule gas pressure was close to 15 atm. The capsule shells were nominally 20 μm thick and made of CD plastic. CD was chosen instead of CH plastic, as knock-on protons from a CH shell would overwhelm the proton signal from the fuel (H in CD accounts for less than 0.1% resulting in negligible number of knock-on protons produced from the shell).

To optimize the S/N ratio for these experiments, the semi-empirical results in Fig. 1(a) were used.[14] Figure 1(a) shows the primary neutron yield, the knock-on proton signal, and the yield of deuteron breakup protons (mainly from the CD-shell) as functions of hydrogen content in the fuel. The latter component, which is induced by DT neutrons, constitutes the principle noise component (further discussion of the noise is found in Sec. III B). To estimate the S/N-ratio for these experiments, the ratio between the knock-on proton yield (S) and the yield of deuteron breakup protons (N) is plotted in Fig. 1(b) as a function of the fraction of hydrogen in the fuel. This ratio becomes larger with increasing hydrogen content, although the knock-on proton yield is maximized at a H concentration of about 40%. However, since the signal decreases as H increases (above H concentration 40%), the detector should be as close as possible to the implosion (maximum number of signal events in the detector sets the limit of shortest possible detector-to-implosion distance). On the basis of these curves and for practical reasons, a H–D–T ratio of 90%–5%–5% was selected, as indicated by the vertical dashed lines in Figs. 1(a) and 1(b). The actual pressure uncertainties of H_2 and DT were 2% and 30%, respectively.

B. Laser-drive conditions

OMEGA is an Nd-doped glass laser facility with the ability to deliver 60 beams of frequency-tripled UV light (0.35 μm) at energies up to 30 kJ in a variety of pulse shapes.[15] In these experiments, the laser energy was 23–24 kJ, with a typical intensity of $\sim 1\times10^{15}$ W/cm^2. The shape of the laser pulse was approximately 1-ns square, and the beam-to-beam laser energy imbalance was <4% rms. The laser beams were smoothed by 2D-SSD, with 1.0 THz bandwidth, in addition to polarization smoothing (PS) as applied through the use of birefringent wedges.[16]

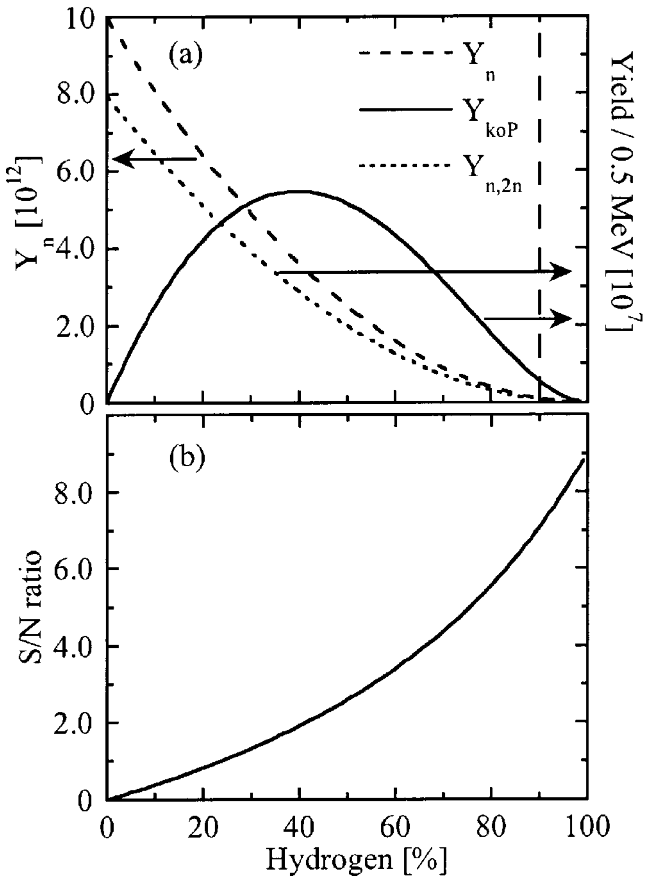

FIG. 1. (a) Using semiempirical modeling (see Ref. 14), the primary neutron yield (Y_n), knock-on proton yield (Y_{KOp}, signal), and n,2n-proton yield ($Y_{n,2n}$, noise) are estimated as functions of hydrogen content. (b) The signal to noise (S/N) ratio as a function of hydrogen content. For both (a) and (b), it is assumed that the density of H, D, and T obey the relation $n_h+2n_d=n_{\mathrm{tot}}$, where n_{tot} is held constant, and $n_d=n_t$. On the basis of these curves and for practical reasons, a H–D–T ratio of 90%–5%–5% was selected, as indicated by the vertical dashed line.

C. Experimental setup

In these experiments, seven spectrometers sensitive to protons in the range 8–18 MeV were simultaneously used for spectral measurements of the knock-on protons at different locations in the OMEGA target chamber. These spectrometers, called wedge-range-filter (WRF) spectrometers, consist of a wedge-shaped piece of aluminum (that vary in thickness from 400 to 1800 μm) positioned in front of a CR-39 track detector, which has 100% sensitivity to protons in 0.2–6 MeV energy range.[7] Detailed calibration of the transmission characteristics of each WRF, in addition to a direct mapping between the track diameter[17] and the incident proton energy for a given aluminum thickness, allow reconstruction of a continuous spectrum in the energy interval 8–18 MeV.[7] The absolute energy uncertainty in each WRF is ~ ±0.15 MeV at 15 MeV.

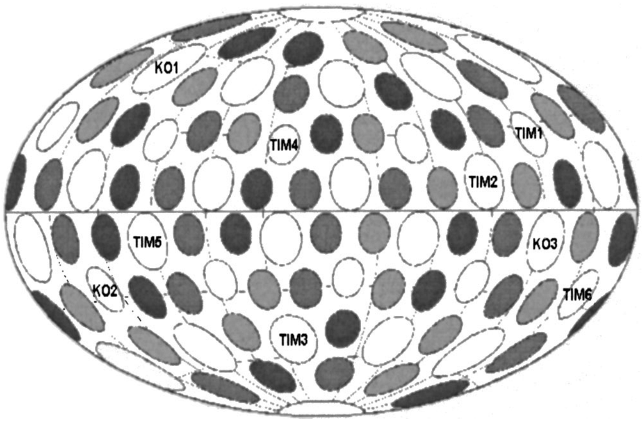

FIG. 2. OMEGA port diagram, showing the locations of TIM1 through TIM6, and KO1 through KO3, which were used for the wedge-range-filter (WRF) spectrometers.

Due to the compactness of the WRF spectrometers (about 3×3 cm^2), several can be fielded at different locations in close proximity to the implosion. For the work reported here, WRF spectrometers were positioned in the locations TIM1–TIM6, and KO1 and KO3 (see Fig. 2 for the schematic layout of the OMEGA port diagram) at distances of 12.5 cm to 40 cm from the implosion. Shorter detector-to-implosion distances were not permitted by the laser-beam configuration and the size of the WRF spectrometers.

III. SPECTRA OF KNOCK-ON PARTICLES, REACTION PRODUCTS, AND THEIR RELATIONSHIP TO CHARACTERISTICS OF IMPLODED CAPSULES

A. Signal

Knock-on protons are generated in a two-step process. First, 14.1-MeV neutrons are generated from DT fusion reactions [Eq. (1)]. A small fraction of these neutrons (of order ~0.1%) elastically scatter off the fuel hydrogen producing knock-on protons with a maximum energy of 14.1 MeV [Eq. (2)] [see also process 1 in Fig. 3(a)],

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

$$n(14.1\ \ \mathrm{MeV})+p\rightarrow n'+p(\leqslant 14.1\ \ \mathrm{MeV}). \quad (2)$$

At this neutron energy the differential cross section is practically constant in the center of mass system, corresponding to a flat energy spectrum from 0 to 14.1 MeV in the laboratory system, as shown in Fig. 3(b). This spectrum represents the birth spectrum of the knock-on protons.

The information contained in the measured knock-on proton spectrum can be used to determine the areal densities and therefore the capsule compression; the yield of the knock-on protons in the flat region provides information about the ρR_{fuel}, while information about the ρR_{shell} is contained in the energy downshift of the measured spectrum (relative to its birth spectrum). For the commonly used "uniform model" of the compressed fuel (where all primary neutrons are assumed to be produced in a uniform temperature and density plasma), ρR_{fuel} can be related to the knock-on proton yield by

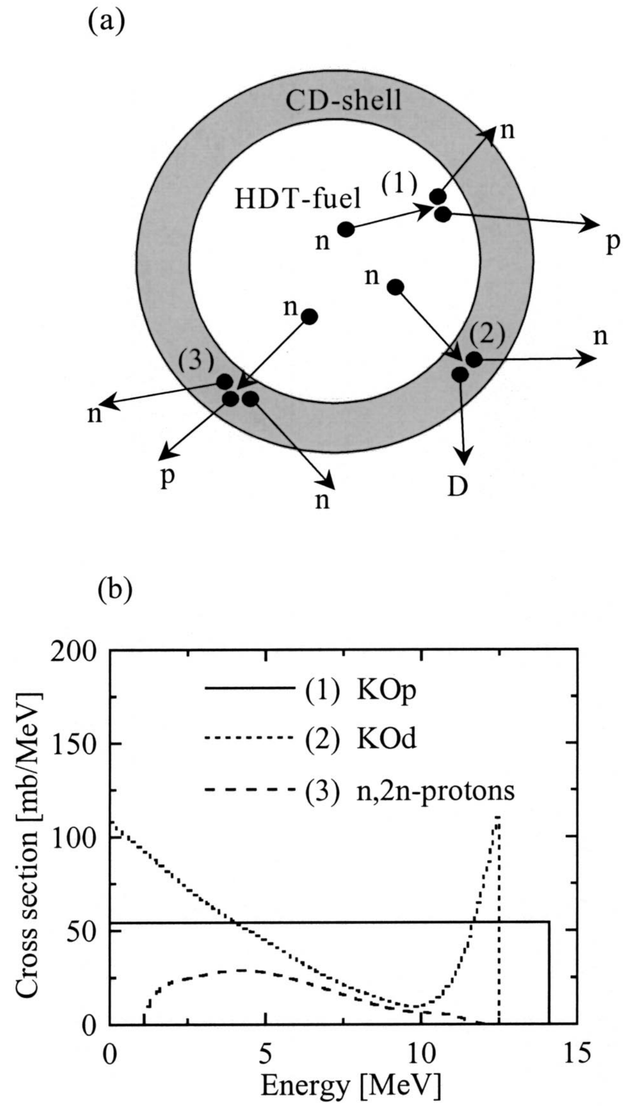

FIG. 3. (a) Nuclear processes taking place in hydrogen filled, CD-shell capsules with trace amount of DT in the gas. A small fraction of the neutrons elastically scatter off the hydrogen (process 1) producing knock-on protons; or elastically scatter off the shell deuterium (process 2) producing knock-on deuterons; or react with the shell deuterium producing deuteron-breakup protons (process 3). (b) The differential cross sections in the laboratory system for the elastic *np*- and *nD*-scattering, and deuteron breakup via the *n*,2*n* reaction.

$$\rho R_{\mathrm{fuel}}=\frac{4}{3}\,\frac{(\beta+2\gamma+3)m_p}{\beta\sigma_p^{\mathrm{eff}}}\,\frac{Y_{\mathrm{KOp}}}{Y_n}, \quad (3)$$

where $\beta=n_{\mathrm{H}}/n_{\mathrm{T}}$; $\gamma=n_d/n_t$; m_p is the proton mass; Y_{KOp} is the measured knock-on proton yield in a certain defined energy range; σ_p^{eff} is the effective cross section for the *np*-elastic scattering process producing protons in the specified energy range; and Y_n is the measured primary neutron yield. For the chosen fuel mixture, β is nominally 18 times larger than γ, showing why this method is so insensitive to the DT ratio. Using this model, the inferred ρR_{fuel} is plotted in Fig.

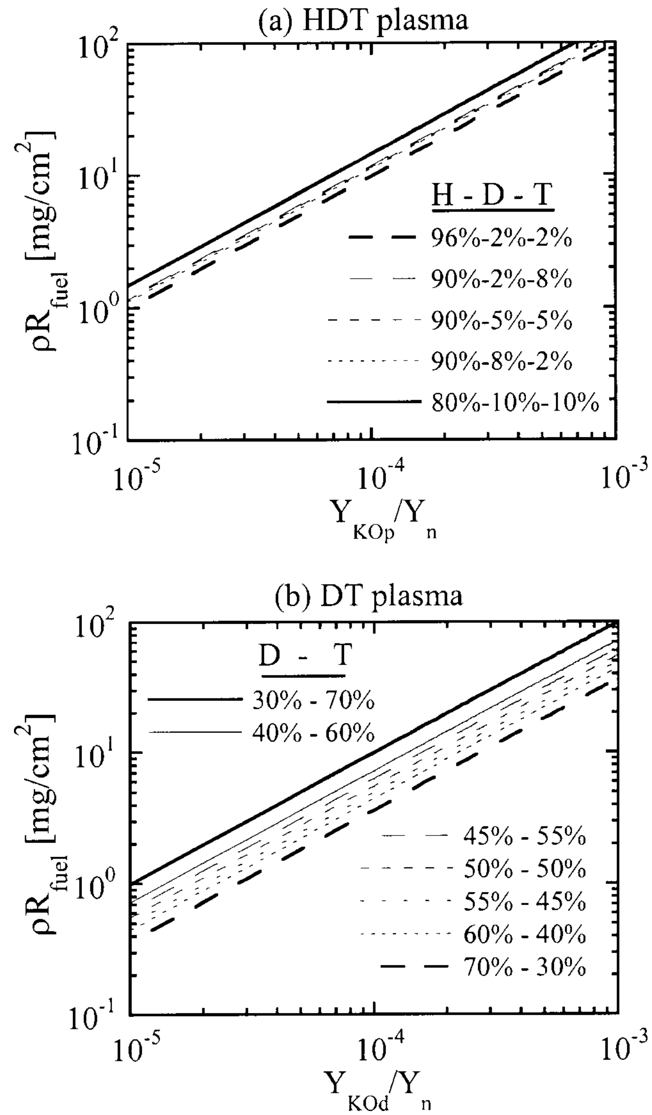

FIG. 4. (a) Inferred values of ρR_{fuel} as a function of the measured ratio of knock-on proton yield (per 0.5 MeV) to primary neutron yield for different mixtures of H, D, and T. (b) Inferred values of ρR_{fuel} as a function of the measured ratio of knock-on deuteron to primary neutron yield for different mixtures of D and T, as related to previous work (Ref. 2). In contrast to the contents of (b), (a) illustrates a weaker dependence of the ρR_{fuel} determination on the exact quantity of D and T.

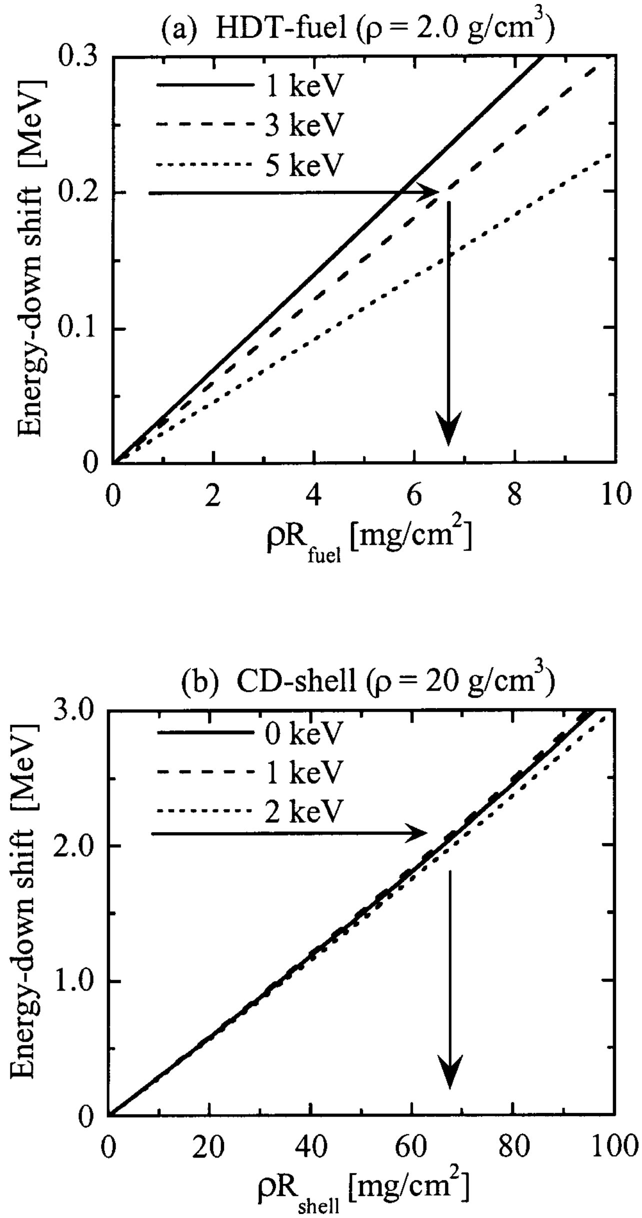

FIG. 5. Energy down shift (ΔE) of 14.1-MeV protons vs ρR_{fuel} (a) or ρR_{shell} (b).

4(a) as a function of the measured ratios of knock-on proton yield to primary neutron yield (Y_{KOp}/Y_n) for different fuel mixtures. On the basis of these dependencies, it is determined that the uncertainties in the partial fuel pressures of DT and H_2 (discussed in Sec. II C), and thus the uncertainty in the β and γ-value in Eq. (3), correspond to an uncertainty in the inferred ρR_{fuel} that is small relative to other effects discussed below. For comparison, the inferred ρR_{fuel} for DT-implosions is plotted in Fig. 4(b) as a function of the measured ratios of knock-on deuteron yield to primary neutron yield (Y_{KOd}/Y_n) for different fuel mixtures. As shown in Fig. 4(b), these dependencies illustrate a larger sensitivity to the value of the DT ratio.

The energy downshift of the measured knock-on proton spectrum, relative to the birth spectrum, provides information about the material traversed in a certain direction, or a "directional" ρR_{tot}, which is a summation of the ρR_{fuel} and the ρR_{shell} of the compressed capsule. To relate the energy downshift (ΔE) to ρR_{tot}, stopping-power calculations are required for the material traversed. The stopping-power model of Ref. 18 was used in these calculations, and the results are plotted in Figs. 5(a) and 5(b) showing ΔE for 14.1-MeV protons as a function of ρR_{fuel} and ρR_{shell} for fixed fuel and shell densities at various temperatures. In general, the contribution of ρR_{shell} is significantly larger than that of ρR_{fuel}. An estimate of ρR_{shell} is determined from ρR_{tot}, which in turn is inferred from the ΔE measured at the 50% yield level relative to the yield in the flat region of the spectrum.[19]

B. Competing background effects

Knock-on deuterons, knock-on tritons, and deuteron-breakup protons (or n,$2n$-protons) are generated in the fuel (with maximum energies of 12.5 MeV, 10.6 MeV, and 11.8 MeV, respectively), and these processes are shown in Eqs. (4)–(6),

$$n(14.1\ \text{MeV})+\text{D}\rightarrow n'+\text{D}\quad(\leqslant 12.5\ \text{MeV}),\tag{4}$$

$$n(14.1\ \text{MeV})+\text{T}\rightarrow n'+\text{T}\quad(\leqslant 10.6\ \text{MeV}),\tag{5}$$

$$n(14.1\ \text{MeV})+\text{D}'\rightarrow 2n'+p\quad(\leqslant 11.8\ \text{MeV}).\tag{6}$$

None of these products from the fuel constitute significant background sources due to the low concentrations of D and T (H–D–T=90%–5%–5%), and due to the energy discrimination of the WRF spectrometer. In contrast, the knock-on deuterons and the n,2n-protons from the CD shell constitute significant background sources. First, as the 12.5-MeV maximum energy of the knock-on deuterons from the CD shell [see process 2 in Figs. 3(a) and 3(b)] is large enough to interfere with the knock-on proton measurement for proton energies up to 9.6 MeV, ρR_{fuel} is inferred from the knock-on proton spectrum in the energy region above 9.6 MeV. Second, the n,2n-protons from the CD shell, which have energies up to 11.8 MeV [see Eq. (6) and reaction (3) in Fig. 3(a)], cannot be distinguished from the signal and will therefore interfere with the ρR_{fuel} measurement. However, as will be discussed shortly, the n,2n-protons constitute only ~15% of the measured signal above 9.6 MeV. Using the differential cross section for the n,2n-reaction in deuterium (Refs. 20–21), an expression relating the ρR_{shell} to the yield of n,2n-protons is

$$\rho R_{\text{shell}}=\frac{(\xi+6)m_d}{\xi\sigma_{n,2n}^{\text{eff}}}\,\frac{Y_{n,2n}}{Y_n},\tag{7}$$

where $\xi=n_d/n_C$; m_d is the deuteron mass; $Y_{n,2n}$, is the measured n,2n-proton yield in a certain defined energy range; $\sigma_{n,2n}^{\text{eff}}$ is the effective cross section for the deuteron breakup process in deuterium producing protons in the specified energy range; and Y_n is the measured primary neutron yield.

IV. RESULTS: EXPERIMENTAL DATA

To illustrate the various effects and advantages of this method, Fig. 6 shows a knock-on proton spectrum from shot 23471. The knock-on deuteron component from the CD shell is clearly evident, in this case, for proton-equivalent energies below 9 MeV. In the energy interval 9.0–11.8 MeV the recorded events are mainly due to both knock-on protons and n,2n-protons. Above 11.8 MeV, only the knock-on proton component contributes. Typically, the flat region in the spectrum extends from 9.6 MeV up to about 10.1 MeV (the knock-on deuteron component from the CD shell should in principle be evident at energies below 9.6 MeV). The energy region 9.6–10.1 MeV was therefore used to relate the total proton yield to ρR_{fuel} and ρR_{shell}, i.e.,

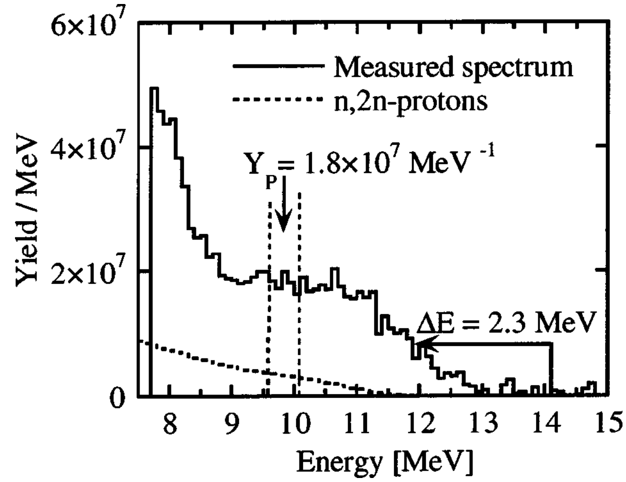

FIG. 6. Knock-on proton spectrum measured at the location of TIM1 (Fig. 2) during shot 23471. The knock-on deuteron component from the CD shell is evident for proton-equivalent energies below about 9 MeV. In the energy interval 9.6–11.8 MeV, about 15% of the recorded events, according to calculation, are due to deuteron-break-up protons (or n,2n-protons) from the CD shell (dashed curve). The rest of the events in this interval are knock-on protons from the fuel. Only the knock-on proton component contributes above 11.8 MeV.

$$\begin{aligned}Y_p&=Y_{\text{KOp}}+Y_{n,2n}\\&=\left[\frac{3}{4}\,\frac{\beta\sigma_p^{\text{eff}}}{(\beta+5)m_p}\langle\rho R\rangle_{\text{fuel}}+\frac{\xi\sigma_{n,2n}^{\text{eff}}}{(\xi+6)m_D}\langle\rho R\rangle_{\text{shell}}\right]Y_n.\end{aligned}\tag{8}$$

Using Eq. (8) in conjunction with Figs. 5(a) and 5(b), ρR_{fuel} and ρR_{shell} can be simultaneously estimated on the basis of the yield and the energy-down shift measurements (indicated in the measured spectrum shown in Fig. 6). A ρR_{fuel} and a ρR_{shell} of ~5.5 mg/cm^2 and ~70.0 mg/cm^2 were inferred from the yield and the energy-down shift measurements indicated in Fig. 6. These numbers suggest that about 83% of the recorded events, in the energy region 9.6–10.1 MeV, are knock-on protons from the fuel. In addition, several measured knock-on proton spectra were simultaneously obtained at different locations in the OMEGA target chamber (see Fig. 2) during shot 23471, and these spectra are shown in Fig. 7. The spectra were recorded at 20 cm from the implosion, except for the measurements performed at the locations TIM1 and KO1, where the WRF's were located at 12.5 cm and 40 cm from the capsule, respectively. The inferred ρR_{fuel} and ρR_{shell} values for shot 23470 and 23471 are shown in Fig. 8. For both implosions, spatial averaging of the data gives a ρR_{fuel} of 7.1±0.4 mg/cm^2 and 6.4±0.5 mg/cm^2 for shots 23470 and 23471, respectively. An average ρR_{shell} of ~71 mg/cm^2 was inferred with a ~25 mg/cm^2 range depending on an angle for both shots. More extensive studies of the shell asymmetries, based on down shifts of primary D^{3}He protons show similar results.[12]

To compare these results with the data obtained by Li *et al.*,[2] who studied pure DT implosions, a density correction must be applied and the general expression for this correction is shown in Eq. (9),

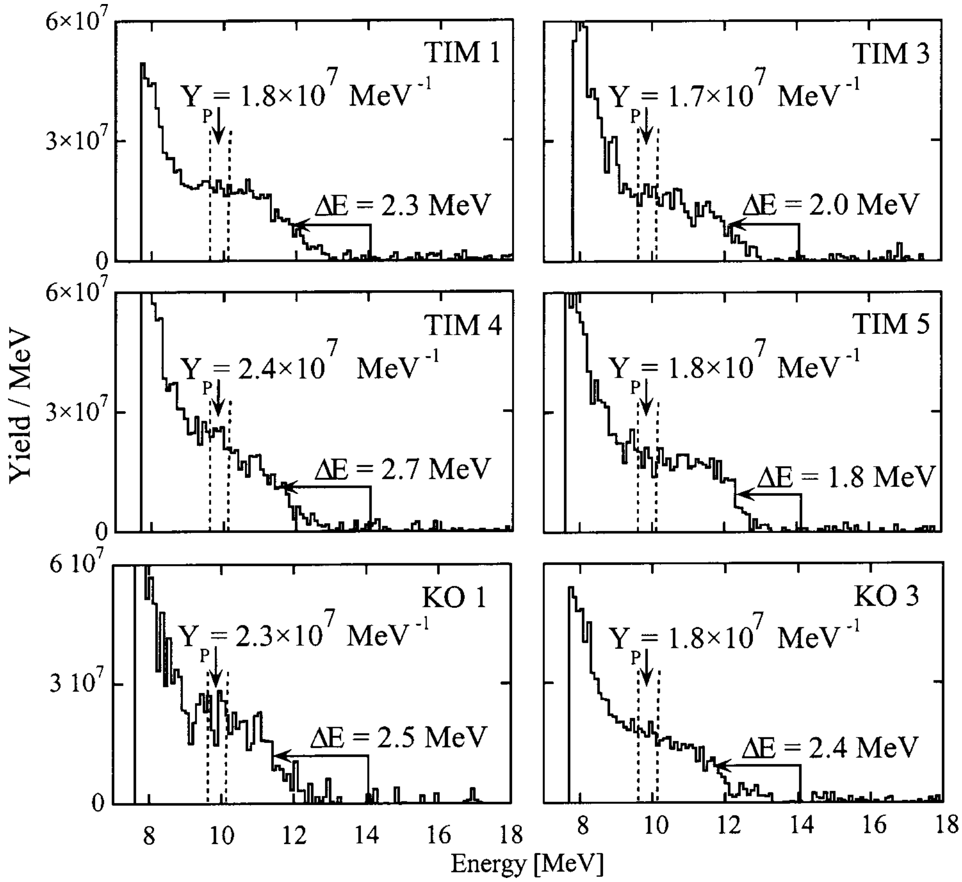

FIG. 7. Knock-on proton spectra measured at different locations (see Fig. 2) for implosion 23471. From the knock-on proton yields, an average ρR_{fuel} of $6.4\pm0.5\,\mathrm{mg/cm^2}$ was inferred. A ρR_{shell} of $70\pm4\,\mathrm{mg/cm^2}$ was inferred from the average energy downshifts of the knock-on proton spectra. The data also reveal shell asymmetries of 25 mg/cm^2.

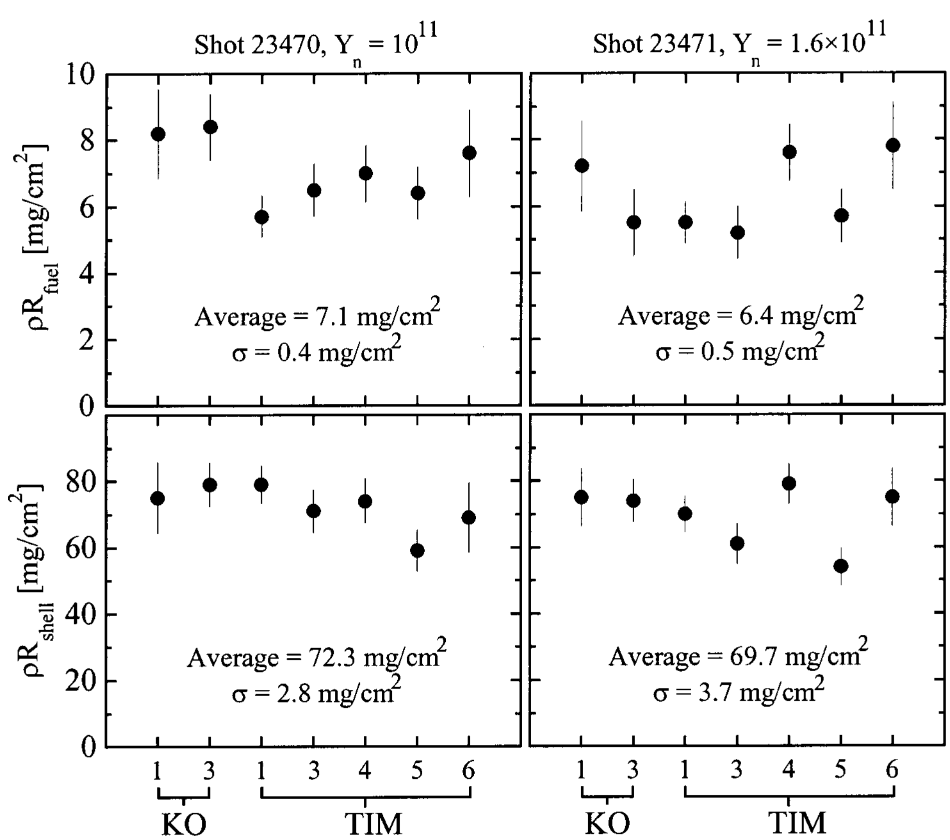

FIG. 8. For implosions 23470 and 23471, inferred ρR_{fuel} and ρR_{shell} are plotted as functions of detector location. Average values and standard deviations are indicated.

TABLE I. Comparison of implosions of capsules filled with H_2 gas doped with small quantities of DT (average value of both shots), and implosions of standard DT-gas-filled capsules with plastic shells (the DT data are from Ref. 2). Parameters shown are: initial capsule parameters (fuel pressure and shell thickness in μm); ion temperature; primary neutron yield; inferred $\rho R_{\rm fuel}$ convergence ratios (Ref. 22) (Cr) based on experiment and calculation (1D); and inferred $\rho R_{\rm shell}$.

Capsule	T_i (keV)	Y_n	$\rho R_{\rm fuel}$ (mg/cm^2)	Cr Expt	Cr 1D	$\rho R_{\rm shell}$ (mg/cm^2)
DT(2)H_2(14)CD [20]	⋯	$(1.3\pm0.6)\times10^{11}$	6.8 ± 0.5	9.8 ± 0.8	~12	54–79
DT(15)CH [20]	4.4 ± 0.5	$(1.1\pm0.3)\times10^{13}$	15 ± 3	10 ± 2	~11	50–75

$$\rho R_{\rm fuel}({\rm DT}) = \frac{\gamma m_{\rm D}+m_{\rm T}}{(\gamma+1)}\,\frac{\beta+\gamma+1}{\beta m_p+\gamma m_d+m_t}\,\rho R_{\rm fuel}({\rm HDT}). \quad (9)$$

Here, $\gamma = n_d/n_t$; $\beta = n_{\rm H}/n_{\rm T}$; m_d is the deuteron mass; m_t is the triton mass; and m_p is the proton mass. For the chosen HDT fuel mixture, a density correction of about 2.2 was applied giving a $\rho R_{\rm fuel}$ of 15.0 ± 1.0 mg/cm^2 (average value of both shots), which is well within the results of Li *et al.* who quotes a $\rho R_{\rm fuel}$ of 15 ± 3 mg/cm^2 for their pure DT implosions. The data also show that these measurements significantly improve upon the accuracy of the $\rho R_{\rm fuel}$ determination. A summary of the experimental results for the two different types of implosions is shown in Table I along with some 1D calculations.

V. SUMMARY

In summary, direct-drive implosions of hydrogen (H_2)-gas-filled capsules, doped with small quantities of DT, were studied using several proton spectrometers. Up to seven such spectrometers, positioned at different locations in the OMEGA target chamber, were simultaneously used for spectral measurements of protons elastically scattered by primary DT neutrons, i.e., ''knock-on'' protons. For the DT doped H_2-gas-filled CD capsule, a $\rho R_{\rm fuel}$ of (6.8 ± 0.5 mg/cm^2) was inferred from the knock-on proton yields; an average $\rho R_{\rm shell}$ of 71 ± 3 mg/cm^2 was inferred from energy downshifts of the knock-on proton spectra; and shell asymmetries of up to about 25 mg/cm^2 were also observed. It has been shown that these results, when reinterpreted for hydrodynamically equivalent DT implosions, imply a $\rho R_{\rm fuel}$ of 15.0 ±1.0 mg/cm^2, which verify and significantly improve upon the accuracy of the fuel areal density result reported in Ref. 2.

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