Two charged-particle spectrometers have been used to study primary and secondary fusion protons in a recent series of experiments on OMEGA involving capsules with relatively thick (15- to 24-µm) plastic shells. From capsules filled with 3 to 10 atm of D-³He, ion temperatures and total areal densities were deduced from nascent 14.7-MeV protons. Results from capsules filled with D only demonstrate that we can see secondary protons resulting from D-fusion reactions. This indicates that these secondary protons may prove useful for determining total ρR in future experiments with cryogenic DD capsules. This work was performed in part at the LLE National Laser Users’ Facility (NLUF) supported in part by the U.S. Department of Energy Contract Number DE-FG03-99SF21782, LLE subcontract number PO410025G, LLNL subcontract number B313975, and the U.S. Department of Energy Office of Inertial Confinement Fusion under Cooperative Agreement No. DE-FC03-92SF19460.
Diagnostic Use of Secondary D-$^3$He Proton Spectra for D-D OMEGA Targets

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Outline

• Why we are interested in secondary protons for studying $\rho R$
• How measured secondary spectra are related to physical quantities
• The first high-resolution secondary proton spectrum measured with the charged-particle spectrometers (CPS’s) on OMEGA
• The future: cryogenic targets and the NIF
Why are we interested in secondary protons?

• Spectra of charged, primary fusion products have been used to study yield, Ti, and $\rho R$ of OMEGA capsules with $\rho R \leq 0.1 \text{ g/cm}^2$.

• Cryogenic experiments on OMEGA and NIF will involve D fuel and higher $\rho R$. No charged, primary fusion products will escape.

• Secondary D-$^3\text{He}$ protons (12.5 to 17.4 MeV) will escape from D capsules with relatively high $\rho R$.

• Measurement of secondary proton yield and energy downshift gives information about
  
  $\rho R_{\text{total}}$

  symmetry (with multiple detectors; see P. B. Radha, this conference).
Secondary protons and their diagnostic use

\[ D + D \rightarrow n \ (2.45 \text{ MeV}) + ^3\text{He} \ (0.82 \text{ MeV}) \]
\[ ^3\text{He} \ (0.82 \text{ MeV}) + D \rightarrow \alpha \ (6.6-1.7 \text{ MeV}) + p \ (12.5-17.4 \text{ MeV}) \]

- For \( \rho R_{\text{fuel}} \leq 0.01 \text{ g/cm}^2 \):
  - yield \( \Rightarrow \rho R_{\text{fuel}}^* \)
- For \( \rho R_{\text{total}} \leq 0.5 \text{ g/cm}^2 \):
  - downshift \( \Rightarrow \rho R_{\text{total}} \)

Stopping power* for protons in D fuel or CH shell

\[ \frac{dE}{d(\rho x)} \text{ (MeV per g/cm}^2\text{)} \]

Proton energy (MeV)

1 keV

3 keV

\[ \text{D (10}^{24} \text{ ions/cm}^3\) \]

\[ \text{CH (10}^{24} \text{ ions/cm}^3\) \]

Slowing down of secondary protons by 3-keV D fuel and 1-keV CH shell

Downshifted spectrum can be characterized by

- The entire spectrum \((\rho R \leq 0.2 \text{ g/cm}^2)\)
- Mean energy \((\rho R \leq 0.2 \text{ g/cm}^2)\)
- Upper-edge energy \((\rho R < 0.4 \text{ g/cm}^2)\)
Slowing down of protons in D or CH varies with temperature.

![Graph showing the slowing down of protons in D or CH with varying temperature and proton energy. The graph includes curves for 1-keV plasma and 3-keV plasma.]
First secondary-proton spectrum measured with CPS

OMEGA shots 17663, 17664, 17665, and 17669 combined
10-atm DD fill, 19-µm CH shell, 23.7-kJ laser energy, 
\( \langle \text{primary yield} \rangle = 1.1 \times 10^{11} \)

\( \langle \text{Yield} \rangle = 4.8 \pm 0.4 \times 10^{7} \)
\( \langle E \rangle = 13.17 \pm 0.12 \text{ MeV} \)
Determination of $\rho R_{\text{total}}$ from mean energy
Comparison of data with simulation

OMEGA shots 17663, 17664, 17665, and 17669 combined

Simulation of CPS response (3-mm entrance aperture) to secondary proton spectrum ranged down by $\rho R_{\text{total}} = 0.05 \text{ g/cm}^2$

(1-keV CH shell, 3-keV D fuel)
Cryogenic targets may have higher $\rho R$, higher yield

Simulations of secondary proton spectra ranged through 3-keV DD

$\rho R = 0.4 \, \text{g/cm}^2$

$\rho R = 0.2 \, \text{g/cm}^2$

$\rho R = 0.0 \, \text{g/cm}^2$
Conclusions

- We can accurately measure the secondary proton spectrum.
- The energy downshift of the spectrum is directly related to $\rho R$.
- Yield and downshift carry information about symmetry (with multiple spectrometers).
- For cryogenic D-D capsules, secondary spectra could be usable for $\rho R$ as high as 0.4 to 0.6 g/cm$^2$ (3-keV plasma).