Nuclear Diagnostics for High-Density Implosions

The measurement of fuel compression, specifically the density-radius product (ρR), is of fundamental importance in analyzing ICF implosions. To probe the large values of ρR anticipated for OMEGA (and NIF) experiments, nuclear diagnostics must be used.

Three ρR diagnostics are being developed for OMEGA. They rely on detecting the following nuclear particles: (1) energetic D and T ions (knock-ons) produced by colliding 14-MeV neutrons;[1] (2) elastically scattered DT neutrons;[2,3] and (3) tertiary DT neutrons.[2,4] The starting point for generating each of these particles is the 14-MeV neutron produced in DT fusion, i.e.,

$$\mathrm{D}+\mathrm{T} \rightarrow \alpha + n(14.1\ \mathrm{MeV}). \tag{1}$$

A small percentage of these neutrons (typically less than 0.01% for ICF conditions) will scatter elastically from D or T ions in the fuel (a prime indicates a scattered particle):

$$n+\mathrm{D}(\mathrm{or\ T}) \rightarrow n'+\mathrm{D}'(\mathrm{or\ T}'), \tag{2}$$

where D′ will be produced in a continuous spectrum from 0 to 12.5 MeV and T′ in the range of 0 to 10.6 MeV, with the remainder of the 14.1-MeV energy going to the scattered neutron. The number of such scattering events per DT-fusion neutron is directly proportional to the ρR of the fuel. This forms the basis for two of the nuclear diagnostics under development—knock-ons and elastically scattered neutrons: (1) the techniques for detecting the D and T knock-ons that were developed on the 24-beam OMEGA system will be extended to accommodate the higher values of ρR expected in future, near-term experiments (total target $\rho R \leq 200\ \mathrm{mg/cm^2}$); and (2) techniques for detecting the elastically scattered neutrons and separating that signal from the expected neutron background will be investigated.

The third diagnostic involves reactions with the knock-on D and T ions. As these ions pass through the fuel, there is a small probability that they will undergo an in-flight fusion reaction with one of the thermal fuel ions:

$$\begin{aligned}&\mathrm{D}'(0-12.5\ \mathrm{MeV})+\mathrm{T}(\mathrm{thermal})\\&\rightarrow \alpha+n''(12-30\ \mathrm{MeV}),\end{aligned} \tag{3}$$

and similarly for the knock-on tritons, where n'' indicates a neutron scattered by an already scattered D. Because the D and T knock-ons are charged particles, they will be slowing down as they fuse. This can complicate the interpretation of the diagnostic signal, as the rate of slowing down depends on the temperature in the fuel as well as the density. The number of these high-energy neutrons from the tertiary reaction actually measures the product (ρR) ($\rho R'$), where R' is either the radius of the target or the range of the D or T knock-on ions, whichever is smaller. The first factor of ρR comes from the production of the knock-ons. Thus, for small ρR (OMEGA), the tertiary yield varies as $(\rho R)^2$, and for large ρR (NIF), it is proportional to ρR.

This article presents more details about these three diagnostics, together with comments on where further development is necessary. Two other nuclear diagnostics are under consideration but will not be discussed here, because they involve the additional complication of adding $\mathrm{He^3}$ to the target. These two diagnostics use the D-$\mathrm{He^3}$ proton: the energy loss of the 14.7-MeV proton from thermal D-$\mathrm{He^3}$ fusion can measure the target ρR up to several hundred $\mathrm{mg/cm^2}$,[1] and tertiary protons from in-flight D-$\mathrm{He^3}$ fusion, using knock-on D or $\mathrm{He^3}$ ions, can measure the ρR of the $\mathrm{He^3}$ in the target.[5] The detection of these protons from different directions can give information about gross asymmetries of the compressed core.

Knock-Ons

The knock-on diagnostic was developed at LLE for the 24-beam OMEGA laser and used to diagnose implosions with a fuel ρR up to ~30 $\mathrm{mg/cm^2}$ and with a comparable $\rho\Delta R$ for the glass shell around the fuel.[6] For values of fuel-plus-shell ρR in excess of 100 $\mathrm{mg/cm^2}$, the knock-on spectrum becomes substantially distorted due to significant slowing down of the D and T ions as they pass through the target; this can introduce some uncertainty in interpretation of the diagnostic signal. It is important to spectrally resolve the high-energy portion of this charged-particle signal, to separate the knock-ons from other sources of energetic ions, and to determine how the knock-on spectrum has been modified by slowing down in the target. Gross spectral resolution was obtained on the 24-beam OMEGA laser using stacked track detectors.[1,6] Higher resolution will be obtained in future OMEGA experiments using a charged-particle spectrometer. This will extend the applicability of the knock-on diagnostic to meet the needs of the OMEGA experimental program for the first few years of operation.

To illustrate how the diagnostic can be used, Fig. 69.35 shows the calculated spectrum of knock-on deuterons for the simple model of a hot DT core surrounded by a "cold" (0.5-keV), denser CH shell. A characteristic feature of the spectrum is a peak at high energies produced by the forward-peaked cross section for scattering with 14-MeV neutrons. (This peak contains ~16% of the deuteron knock-ons.) Figure 69.35 shows how the peak is shifted to lower energies due to increased slowing down as the $\rho\Delta R$ of the plastic shell

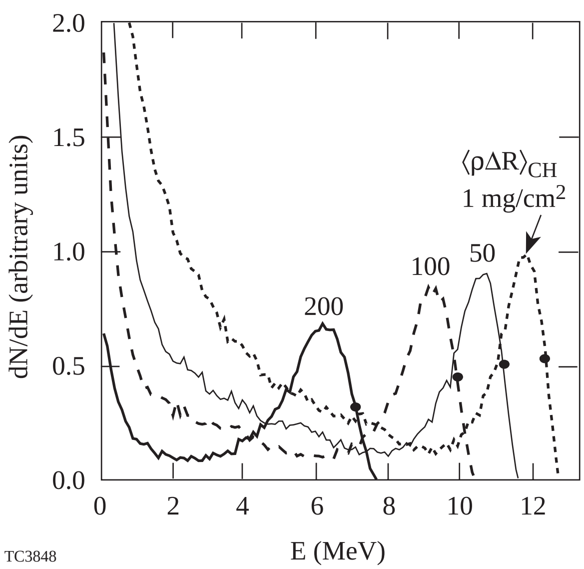

Figure 69.35
Calculated spectrum of knock-on deuterons escaping from compressed targets, with constant fuel ρR (40 mg/cm^2) and variable $\rho\Delta R$ (1 to 200 mg/cm^2) for a CH shell (of temperature 0.5 keV) surrounding the fuel. The energy shift of the high-energy peak measures the $\rho\Delta R$ of the shell, and the number of deuterons in the peak determines the ρR of the fuel.

increases. [The energy loss in the fuel is relatively small in this example because the fuel temperature is high and the ρR is small (40 mg/cm^2).] The peak changes position and shape but remains well defined. By spectrally resolving this peak, it is possible to obtain simultaneously two important pieces of information about the compressed core: the position of the peak determines the $\rho\Delta R$ of the plastic shell, and the number of knock-on deuterons in the peak determines the ρR of the fuel. The fuel ρR is related to the number of deuterons in the peak (N_D) and the DT neutron yield (Y) by the following relation:

$$\rho R = 83\ N_D / Y \quad \mathrm{g/cm^2} \tag{4}$$

for equimolar DT. A similar relation is available for knock-on tritons, but the more energetic deuterons can be used to diagnose higher values of ρR.

To facilitate measurement of the knock-on spectrum, a charged-particle spectrometer[7] is being developed at MIT for OMEGA experiments. The spectrometer uses a 7.5-kG magnet to momentum select the particles and deflect them from the straight-line path followed by neutrons and x rays. The charged-particle paths are determined from trajectory calculations. The magnet has recently been tested at MIT using protons with energies from 1 to 15 MeV. As depicted in Fig. 69.36, the particles are deflected and then impinge onto a detector plane where they are intercepted by a combination of charged-coupled devices (CCD's) and CR-39 plastic track detectors. As demonstrated in recent experimental studies at MIT, the CCD's act as high-resolution energy detectors. Through the combination of magnetic momentum selection and the energy determination of the detectors, either CCD or track, the energy and identity of each particle will be uniquely specified. From these data, the spectra of all charged particles will be constructed, and vital information about the core conditions and dynamics will be measured.

This spectrometer also forms the basis of a joint proposal between MIT, LLE, and LLNL for a NIF diagnostic that will measure both the implosion symmetry and the core ρR.[5] This makes use of very energetic tertiary protons (~31 MeV) that can easily penetrate all plasmas envisaged for the NIF. For example, the range of these protons is ~3 g/cm^2, whereas the ρR expected for a typical NIF capsule is ~1 g/cm^2. Even for some implosion scenarios simulated for OMEGA,[5] situations have been encountered where these tertiary protons could prove particularly useful for determining core conditions, beyond the range of applicability of the knock-on diagnostic.

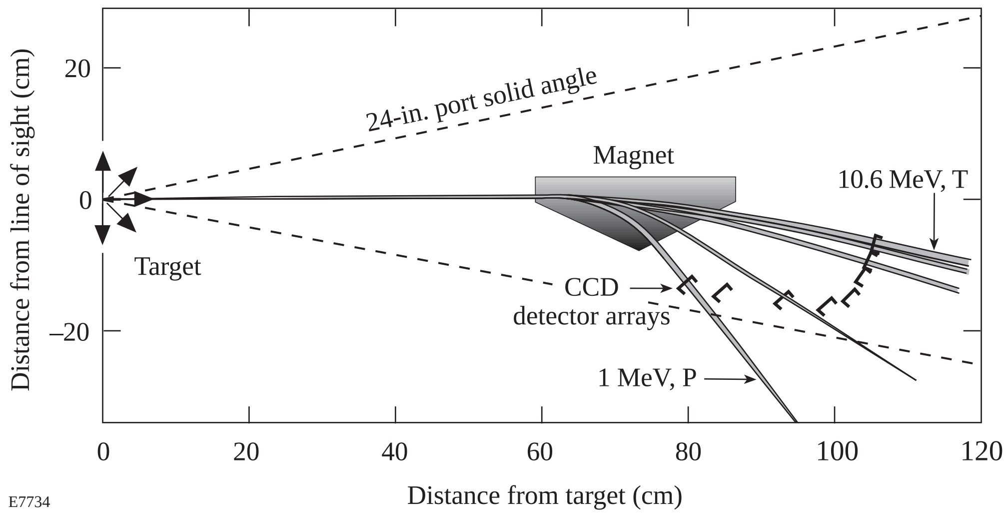

Figure 69.36
Measurement of the spectrum of charged particles escaping from the target. A spectrometer uses a magnet to momentum select the particles and CCD's or track detectors to detect the particles and provide energy resolution.

Elastically Scattered Neutrons

The second reaction product from (n,D) and (n,T) scattering, namely the elastically scattered neutron, could be used to diagnose all values of ρR of interest to ICF. Like the charged-particle knock-ons, the number of these is directly proportional to the ρR of the fuel but, since they are neutral, they do not slow down in the target, and therefore this diagnostic is not limited to small values of ρR.

To determine if the elastically scattered neutrons can be separated from other sources of neutrons produced in the target, Monte Carlo calculations have been performed to calculate the spectrum of all neutrons emerging from the target. The spectra for two values of ρR are shown in Fig. 69.37. The peak at 14 MeV is, of course, the primary source from DT fusion. The neutrons above 14 MeV are from tertiary reactions, discussed in the next section. In the range of 8 to 10 MeV, there are contributions from many sources including (n,2n) reactions with deuterium and T(T,2n)α reactions; it is not possible to separate out the contribution from elastic scattering in this region. However, in the range of 10 to 13 MeV, elastically scattered neutrons completely dominate the spectrum. The number of neutrons in this range is large enough to provide a model-independent determination of ρR for all experiments planned for OMEGA and NIF. (It should be noted that the two curves shown in Fig. 69.37 are distinguishable because they are both normalized to the primary yield.)

The main effort in neutron diagnostic development is to devise a method for shielding against the effects of the primary DT neutrons. These 14-MeV neutrons can lose energy as they scatter from structural material around the target chamber or within the diagnostic instrument itself, and they can enter the 10- to 13-MeV window that is being scanned for the elastically scattered neutrons from the target.

Tertiary Neutrons

A significant portion of the tertiary neutron spectrum lies above the 14-MeV primary source (Fig. 69.37). There are no other reactions that can produce neutrons in the range of ~15 to 30 MeV. However, because this is a tertiary reaction, the number of neutrons produced is several orders of magnitude lower than for elastic scattering. For the NIF, yields are sufficiently high that this should not be a problem. However, for OMEGA experiments, it might be difficult to collect a statistically useful number of tertiaries for targets with low neutron yields. Time-of-flight detectors with a solid angle of ~10^{-5} should be adequate for the NIF. On OMEGA, it might be necessary to use carbon activation foils that could increase the detection solid angle by an order of magnitude. The carbon foils would detect all neutrons with energy above ~18 MeV, without spectral resolution. However, since there are no other sources of neutrons in this range, spectral separation is not necessary.

For OMEGA implosions, the "cold" part of the fuel will have temperatures below ~1 keV throughout the implosion. In this range, the slowing down of the high-energy knock-on deuterons is relatively temperature independent, for the intermediate step in tertiary-neutron production. Figure 69.38 shows the expected ratio of tertiary neutrons (detected by a carbon foil) to the primary DT fusion yield as a function of ρR, assuming temperatures of 0.5 keV and 1 keV. The neutron ratio determines ρR to within ±5% for these conditions. Superim-

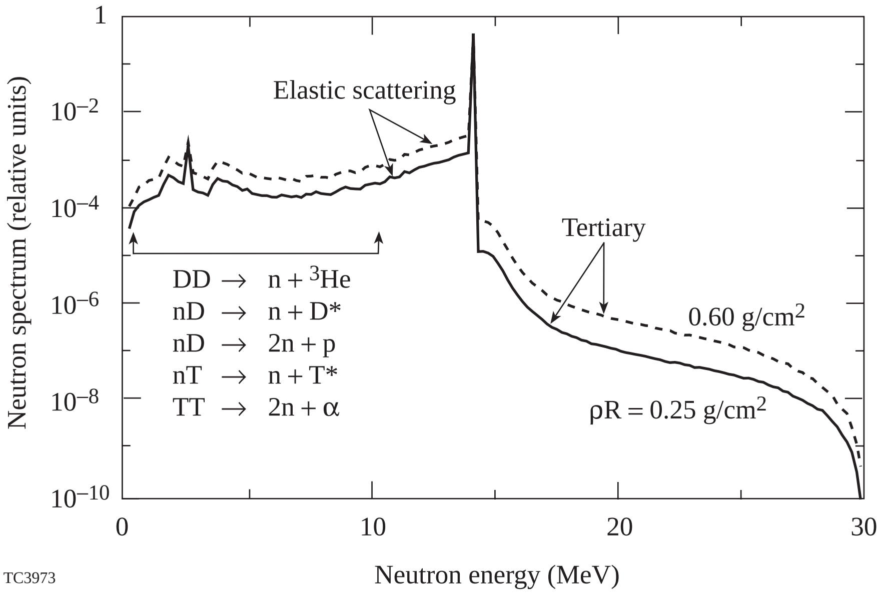

Figure 69.37
Calculated spectrum of neutrons escaping from a compressed target for two values of ρR. In the energy range between 10 MeV and 13 MeV, elastically scattered neutrons dominate; above 15 MeV, only tertiary neutrons contribute.

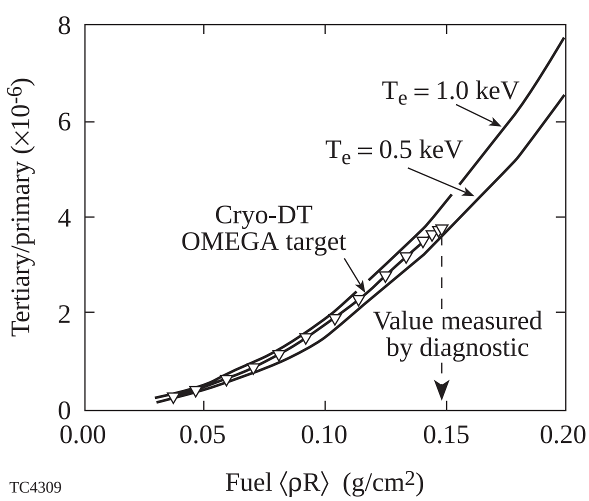

Figure 69.38
Ratio of tertiary neutrons to the primary DT fusion yield as a function of fuel ρR for two values of fuel temperature.

posed on Fig. 69.38 are results from a full hydrodynamic simulation of an OMEGA implosion showing how the neutron ratio varies with the neutron-weighted ρR at different times during the implosion. The neutron ratio varies roughly as $(\rho R)^2$, as the range of the knock-on deuterons and tritons is larger than or comparable to the radius of the target.

For a burning NIF target, the temperatures will be considerably higher and the temperature dependence of the diagnostic will be much larger. Uncertainties of interpretation due to this temperature sensitivity can be reduced by a detailed analysis of the tertiary spectrum using a neutron time-of-flight detector.

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REFERENCES

1. S. Skupsky and S. Kacenjar, J. Appl. Phys. **52**, 2608 (1981).
2. H. Azechi, M. D. Cable, and R. O. Stapf, Laser Part. Beams **9**, 119 (1991).
3. S. Cremer and S. Skupsky, "Diagnosing High-ρR Implosions Using Elastically Scattered DT Neutrons," presented at the 26th Anomalous Absorption Conference, Fairbanks, AK, 26–30 August 1996.
4. D. R. Welch, H. Kislev, and G. H. Miley, Rev. Sci. Instrum. **59**, 610 (1988).
5. R. D. Petrasso, C. K. Li, M. D. Cable, S. M. Pollaine, S. W. Haan, T. P. Bernat, J. D. Kilkenny, S. Cremer, J. P. Knauer, C. P. Verdon, and R. L. Kremens, Phys. Rev. Lett. **77**, 2718 (1996).
6. R. L. McCrory, J. M. Soures, C. P. Verdon, F. J. Marshall, S. A. Letzring, S. Skupsky, T. J. Kessler, R. L. Kremens, J. P. Knauer, H. Kim, J. Delettrez, R. L. Keck, and D. K. Bradley, Nature **335**, 225 (1988).
7. D. G. Hicks, C. K. Li, R. D. Petrasso, F. H. Seguin, B. E. Burke, J. P. Knauer, S. Cremer, R. L. Kremens, M. D. Cable, and T. W. Phillips, "Design of an Electronic Charged Particle Spectrometer to Measure (ρR) on Inertial Fusion Experiments," to be published in the Review of Scientific Instruments.