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T–T Neutron Spectrum from Inertial Confinement Implosions

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Abstract A new technique that uses inertial confinement implosions for measuring low-energy nuclear reactions important to nuclear astrophysics is described. Simultaneous measurements of n–D and n–T elastic scattering at 14.1 MeV using deuterium–tritium gas-filled capsules provide a proof of principle for this technique. Measurements have been made of D(d,p)T (dd) and T(t,2n)^{4}He (tt) reaction yields relative to the D(t,n)^{4}He (dt) reaction yield for deuterium–tritium mixtures with f_T/f_D between 0.62 and 0.75 and for a wide range of ion temperatures to test our understanding of the implosion processes. Measurements of the shape of the neutron spectrum from the T(t,2n)^{4}He reaction have been made for each of these target configurations.

1 Introduction

A new technique is being developed for measuring low-energy nuclear reactions important to nuclear astrophysics using laser-driven inertial confinement fusion (ICF) experiments at the University of Rochester's OMEGA Laser Facility [1] and Lawrence Livermore National Laboratory's National Ignition Facility (NIF) [2]. This technique produces thermal plasma environments that are very different from accelerator experiments with a beam and target. Since the reactants are ionized and the electrons are in continuum states, the plasma closely resembles the burning core in a star with negligible electron screening corrections. Neutron fluxes are extremely high and the experiments are very short (1 ps–10 ns) so radioactive backgrounds contribute less. On the other hand, the plasma environment is complex and not completely understood. And because the duration is so short, there is no possibility to measure traditional time-domain coincidence events.

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With deuterium–tritium (DT) capsules, the primary fusion reaction is D(t,n)^{4}He (or dt). A fusion reaction of special interest is T(t,2n)^{4}He (or tt), the charge symmetric reaction to the stellar ^{3}He(^{3}He,2p)^{4}He (or ^{3}He^{3}He) reaction, the dominant energy-producing step in the solar proton-proton chain. Information about the tt three-body reaction mechanism is contained in the spectral shapes of the final-state particles, neutrons and alphas. For example, the tt neutron spectrum is a broad continuum modified by the n-n and n-^{4}He final-state interactions corresponding to the di-neutron+^{4}He and n+^{5}He reaction channels.

2 Experimental Considerations

All of the measurements were carried out at the University of Rochester's OMEGA Laser System. This 60-beam, 30-kJ facility is ideal for developing new techniques since it can fire about a dozen shots each day. In these experiments, deuterium–tritium (DT) gas-filled, spherical capsules were symmetrically irradiated with powerful lasers to compress and heat the fuel to high enough temperatures and densities for significant nuclear fusion reactions to occur. To study the ICF plasma conditions, the spectral features of the reactant products were measured using magnet-based nuclear diagnostics consisting of a permanent magnet for dispersion and pieces of CR-39, a plastic polymer insensitive to the electromagnetic transients in an implosion, positioned in the focal plane to detect and identify momentum-analyzed particles. The more compact charged-particle spectrometer (CPS) [3] was used in the 14.1 MeV neutron scattering measurements and the larger magnetic recoil spectrometer (MRS) [4] was used with a recoil foil for absolute neutron spectrum measurements.

For DT capsules, the spectra of reactant particles contain both discrete lines and continua. At thermal energies the primary fusion reaction D(t,n)^{4}He produces a 14.1 MeV neutron and a 3.5 MeV ^{4}He. The position of this neutron peak is an energy calibration and its width is related to the ion temperature of the DT burn. The mid-energy (10–13 MeV) portion of the neutron spectrum is dominated by down scattering of the 14 MeV neutrons due to elastic and inelastic scattering or (n,2n) reactions on the capsule shell or on H, D or T ions in the plasma. At OMEGA, the mean-free-path for neutrons in the capsule is long enough that a neutron has about a 1 % chance of scattering before escape. The spectrum can be approximated by a single scattering model and the amount of down-scattered neutrons is a direct measure of areal density $< \rho R >$ in the capsule, a measure of implosion performance [5,6].

Simultaneous measurements of n–D and n–T elastic scattering were made using these 14.1 MeV dt fusion neutrons scattering from D and T ions in the ICF plasma to make the first nuclear cross section measurement using an ICF implosion [7]. The spectra of knock-on deuteron (d') and triton (t') ions were detected in a CPS and the ratio of the CR-39 track-identified (d') and (t') spectra has been determined. The differential cross sections were obtained by deconvolving the CPS-spectrometer response and the Doppler-broadened 14.1 MeV neutron spectrum. One can then use accurate (in this case Faddeev) calculations of the reference n–D elastic scattering at 14.1 MeV [8], to extract precise values for the n–T elastic scattering at 14.1 MeV from the ratio.

3 Experimental Results

For experiments with D–T capsules at OMEGA, the spectra of the fusion products from the three fusion reactions [D(d,p)T (dd), T(t,2n)^{4}He (tt), and D(t,n)^{4}He (dt)], carry information about the implosion core and can be used to diagnose the underlying implosion physics [9]. For the dd reaction, the reaction yield (Y_{dd}) and the absolute dd proton spectrum were measured by two charge particle spectrometers (CPSs). For the more numerous and more energetic neutrons from the dt reaction, the reaction yield (Y_{dt}), the absolute dt neutron spectrum, and the ion temperature were measured by a suite of neutron time-of-flight (nTOF) detectors. For the tt reaction [10], the reaction yield (Y_{tt}) and the absolute tt neutron spectrum were measured by the MRS by converting the neutrons incident on a CD_2 foil positioned close to the implosion into elastically scattered recoil deuterons. The CR-39 array recorded the deuteron spectrum which was then used to determine the original neutron spectrum.

This neutron spectrum is dominated by the large peak of dt neutrons near 14 MeV and their associated down scattered neutron (DSn) spectrum visible only in a narrow window just below the dt peak. In the recoil deuteron spectrum, counts from the tt reaction rise above a DSn background with a signal to noise ratio between 1.4 and 3.7. In the fitting process [10], a modeled neutron spectrum is folded with the MRS-response function and the magnitude of the DSn spectrum is used as a fit parameter, while the shape of the DSn spectrum is defined by the fuel and shell (mainly D, T, and C). The tt neutron spectrum is obtained by subtracting the best-fit contribution from DSn and then converting the recoil-deuteron energy to neutron energy through the MRS-response function. To improve the statistical accuracy, the final tt neutron spectrum is the average of six different series of implosions.

In this combined ICF spectrum at an average $E_{c.m.}$ of 23 keV, within the MRS resolution and other uncertainties, there is no sign of a peak near a neutron energy of 8.5 MeV corresponding to the tt reaction channel n + ^{5}He(g.s.). This is in sharp contrast with accelerator measurements at higher energies, $E_{c.m.}$ of 110 keV and 250 keV, where the size of the n + ^{5}He(g.s.) reaction channel is about 5 and 20 %, respectively. This indicates that the tt reaction mechanism is changing as the reaction energy is lowered. To improve upon these measurements at OMEGA, implosions of pure T_2 gas will greatly reduce the dt yield and the DSn background. Understanding the reaction mechanism is important for the tt reaction because it impacts the areal density measurement, a result of immediate relevance at NIF. For the charge symmetric ^{3}He^{3}He reaction, a changing reaction mechanism at energies near the Gamow peak in the sun is of great interest.

The extensive measurements that have been made of dd and tt reaction yields relative to the dt reaction yield for deuterium–tritium mixtures with f_T/f_D between 0.62 and 0.75 and for a wide range of ion temperatures are providing an important test of our understanding of the implosion processes [9]. Using the reaction yields described above and our measurements of the ion temperature T_i, the yield ratios $(Y_{dd})/(Y_{dt})$ and $(Y_{tt})/(Y_{dt})$ have been plotted as a function of T_i. For the measurements described here, the ion temperatures range from T_i = 9–18 keV for dd/dt and from T_i = 2–15 keV for tt/dt. For $(Y_{dd})/(Y_{dt})$, the yield ratios are suppressed relative to the expected value by a factor of 1.5–2, possibly indicating a lower deuterium fraction in the core than expected. For $(Y_{tt})/(Y_{dt})$, the yield ratios are 3–6 times higher than the expected value, also possibly indicating a lower deuterium fraction in the core than expected. It appears that these anomalous ratios could be induced by deuterium leaving the center of the implosion, an effect referred to as stratification of the fuel [9].

4 Summary and Conclusions

A new technique is reported for measuring low-energy nuclear reactions important to nuclear astrophysics. The first application measured n–D and n–T elastic scattering at a neutron energy of 14.1 MeV and the n–T results are as good as our ability to calculate the n–D reference reaction using modern techniques. In the future, the plasma environments at NIF will allow us to probe a number of new degrees of freedom in nuclear reactions and nuclear-atomic interactions.

Measurements of the shape of the neutron spectrum for the tt reaction have been used to estimate the role of the n + ^{5}He(g.s.) reaction channel in both accelerator experiments and ICF implosions. It is apparent that the tt reaction mechanism is changing as the reaction energy is lowered, but this needs to be verified by using implosions of pure T_2 gas filled capsules. Measurements of dd and tt reaction yields relative to the dt reaction yield suggest new and exciting plasma physics phenomena with direct relevance to ICF. The most important impact of this work may be the ways in which we can use known nuclear physics to help us sort out the complex behavior occurring during the ICF implosions.

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