Reaction-in-Flight neutrons as a test of stopping power in degenerate plasmas

A C Hayes1, C J Cerjan2, G Jungman1, M M Fowler1, M E Gooden1, G P Grim2, E Henry2, R S Rundberg1, S M Sepke2, D H G Schneider2, R L Singleton1, A P Tonchev2, J B Wilhelmy1 and C B Yeamans2

1Los Alamos National Laboratory, Los Alamos, NM, 87545 USA
2Lawrence Livermore National Laboratory, Livermore, CA, 94551, USA

Email: anna_hayes@lanl.gov

Abstract. Cryogenically cooled inertial confinement fusion capsule designs are suitable for studies of reaction-in-flight (RIF) neutrons. RIF neutrons occur when energetically up-scattered ions undergo DT reactions with a thermal ion in the plasma, producing neutrons in the energy range 9-30 MeV. The knock-on ions lose energy as they traverse the plasma, which directly affects the spectrum of the produced RIF neutrons. Here we present measurements from the National Ignition Facility (NIF) of RIF neutrons produced in cryogenic capsules, with energies above 15 MeV. We show that the measured RIFs probe stopping under previously unexplored degenerate plasma conditions and constrain stopping models in warm dense plasma conditions.

1. Introduction
RIF neutrons are produced in a DT plasma when a neutron or alpha particle born in the burn elastically scatters deuteron or triton ions up to MeV energies, and the energetic knock-on ion undergoes a DT reaction with a thermal ion in the plasma, producing RIF neutrons in the energy range 9.2-30 MeV. The knock-on ions lose energy as they traverse the plasma, which directly affects the number and energy spectrum of the RIF neutrons. Thus, RIF measurements can be used to extract information on the plasma stopping. In the case of cryogenic NIF capsules, RIFs probe stopping under previously unexplored plasma conditions.

2. RIF production in NIF cryogenic capsules
The knock-on ion fluence responsible for RIF production is dominantly produced in the cold fuel surrounding the hotspot of a compressed cryogenic capsule. This is because the magnitude of the knock-on fluence ($Q_0$) is determined by the 14 MeV neutron fluence ($\Phi_{14}$) and the number density of DT ions ($n_{dt}$) in the plasma, $Q_0 = \Phi_{14} n_{dt} \sigma_{ko}$, where $\sigma_{ko}$ is the neutron-ion knock-on cross section and DT density in the cold fuel is very high ($10^{25} - 10^{26}$ cm$^{-3}$). Transport of the knock-on ions through the plasma changes both the shape and magnitude of the knock-on spectrum, and hence also of the RIF spectrum. This spectrum change is determined by the stopping power, and a measurement of the RIF spectrum provides a constraint on stopping models used for the cold fuel. The detailed relationship between stopping power and the RIF spectrum is described in ref. [1].

At peak capsule compression, the outer dense DT fuel temperature is a fraction of a keV.
combined with its high density, this results in the cold fuel being degenerate, i.e., the temperature is less than the Fermi temperature, with a degeneracy parameter $\theta/\theta_F \sim 0.2-0.3$, where $\theta$ ($\theta_F$) is the electron (Fermi) temperature. The corresponding standard plasma coupling parameters $\Gamma = Ze^2/R_W\theta$ or $g= Ze^2/R_D\theta$, where $R_W$ ($R_D$) is the Wigner (Debye) radius, are approaching or exceeding unity, Fig. 1. In the present case $Z=1$. Since the cold fuel is electron degenerate, the temperature determining the stopping power is an effective temperature, $\theta_{\text{eff}} = 3/5 \theta_F F(\theta_F)$, where the function $F(\theta_F)$ is obtained by solving for the chemical potential of the system and has the property that in the zero temperature limit, $\theta_{\text{eff}} \rightarrow 3/5 \theta_F$, while in the high temperature limit $\theta_{\text{eff}} \rightarrow \theta$. Thus, a better measure of the coupling in a degenerate system is the ideality $\xi = Ze^2/R_W\theta_{\text{eff}}$, and $\xi \sim 0.05-0.2$ in cold fuel of cryogenic NIF capsules. Under these plasma conditions ($g>1$, $\xi<1$, and $\theta/\theta_F<1$), stopping powers have not been tested experimentally and existing models tend to disagree with one another. The predictions of the HYDRA code for degeneracy and the coupling parameters $g$ and $\Gamma$ as a function of the radius of the capsule are shown in the right panel of Fig.1.

3. The RIF measurements

The RIF measurements are done by assaying neutrons with energies $E_n>15$ MeV using the activation of thulium foils. Thulium is chosen because the $^{169}\text{Tm}(n,3n)$ reaction has a threshold of 15 MeV, and produces $^{167}\text{Tm}$ with a half-life $t_{1/2} = 9.25$ days by electron capture to $^{167}\text{Er}$, with the emission of a 207.8 keV gamma-ray 41% of the time. The Tm foil is part of a larger activation foil assembly that is mounted on a diagnostic instrument manipulator (DIM) at a nominal standoff of 50 cm from target chamber center, placed behind the solid debris collection diagnostic [2,3]. Activation of Zr, Al, and Au is used to characterize the neutron spectrum at and below the DT fusion primary neutron energy [4]. Activation assemblies are located both on the polar DIM, 14 degrees below the NIF north pole, and the equatorial DIM, 14 degrees below the NIF equator. Thulium samples were fielded on 14 shots with primary DT neutron yields of $1.8 \times 10^{15}$ and down-scattered ratios [5] of 2.5-4.2%. The measurement of $^{168}\text{Tm}$, produced in the $^{169}\text{Tm}(n,2n)$ reaction, provides a check of the primary 14 MeV neutron production, and is cross-compared with activation foils in the same holders.

The primary experimental challenge for the $^{167}\text{Tm}$ measurements is the huge background of $\gamma$-rays produced in the activation of the foils by the much higher fluence of primary 14 MeV neutrons, in particular those from $^{168}\text{Tm}$. To suppress this background, the activated foils are shipped to Los
Alamos, where two clover detectors are deployed to assay the $^{168}\text{Tm}$ and $^{167}\text{Tm}$ activity in the foils. The clover system consists of two high-efficiency clover germanium detectors. Each clover consists of 4 HPGe crystals, surrounded by an active NaI Compton suppressor. The $^{167}\text{Tm}$ decays to a 208 keV isomeric level in $^{167}\text{Er}$ that has a half-life of 2.28 sec. This level decays 100% of the time to the $^{167}\text{Er}$ ground state. There is nothing in coincidence with the 208 keV $\gamma$-ray, in contrast to the complex decay scheme of $^{168}\text{Tm}$. This allows us to use the clover array to identify $^{167}\text{Tm}$ above the background.

Figure 2 – (Left) Thulium activation assembly explosion drawing: The RIF neutron measurement thulium foil is held in an assembly containing materials for solid debris collection and measurement of the neutron spectrum. (Right) NIF diagnostic instrument manipulator (equatorial), showing snout-mounted Tm activation diagnostic.

4. Experimental Results and Analyses
The measured ratio of $^{167}\text{Tm}/^{168}\text{Tm}$ varies somewhat from shot to shot, but is typically measured to be on the $10^{-5}$ scale with 15% accuracy. As an example of how well the stopping power can be tested, we will restrict our discussion here to shot N140304 for which the measured $^{167}\text{Tm}/^{168}\text{Tm}$ ratio was $1.69\pm0.24\times10^{-5}$. The total RIF signal can be written as,

$$N_{\text{RIF}}^{\text{total}} = N_{14} \left\langle \rho R \right\rangle_{dI} \int \frac{d\psi}{dE} \sigma_{dI} dE_{KO}$$

where $d\psi/dE$ is the knock-on fluence per unit 14 MeV neutron. The knock-on fluence scales inversely with the stopping power, and our goal is to extract $d\psi/dE$ from the RIF measurements using full three-dimensional (3-D) simulations of the capsules for $N_{14}$ and $<\rho R>$.

In our analyses of shot N140304 we used full 3-D simulations constrained [6] by a broad range of experimental data. The constraints involve a physically consistent description of the imploded capsule at stagnation. This method attempts to validate the model of the capsule through stringent comparisons between the radiation hydrodynamic code simulations and a suite of x-ray and neutron imaging data. We carried out a second independent analysis of the RIFs using the 1-D code CPT-Implode, which also focuses on describing the stagnation properties of the capsule correctly. In both cases, we varied the stopping models and examined the change in the shape of the predicted RIF signal. The results are summarized in Table 1.

| Table 1 | 167Tm/168Tm |
|---------|-------------|
| Experiment | 1.69 +/- 0.24x $10^{-5}$ |
| Maynard-Deutsch-Zimmerman [7] | 1.59x10-5 |
| Li-Petrasso [8] | 1.16x10-5 |
| Classical Model only (Grabowski) [9] | 0.9x10$^{-5}$ |
| BPS [10] | Model breaks down- g too large |
| BPS+ effective temperature | 1.6x10$^{-5}$ |

5. Theoretical discussion
It has long been recognized [11] that quantum mechanical effects lower plasma stopping powers by about 40%, relative to classical model predictions. The situation is summarized in Fig. 3, where we compare the classical contribution to the stopping power, as predicted by Grabowski et al. [9] to the
quantum mechanical predictions from the Maynard-Deutsch-Zimmerman model (MDZ) [7]. The Li-Petrasso stopping model [8] includes quantum effects and allows for degeneracy through the use of an effective temperature. But the latter model [8] leads to a stopping power that appears [12] to be too high. The BPS model [10] is only valid when \( g<1 \). However, with the use of an effective temperature derived from the chemical potential, \( g \rightarrow g_{\text{eff}}<1 \), and the BPS results then agree with experiment. The leading dependence of the stopping power on the electron temperature and density scales as

\[
\frac{dE}{dx} \propto \frac{n}{\theta^{3/2}} \rightarrow \frac{n}{\theta_{\text{eff}}^{3/2}},
\]

where \( n \) is the electron density, and the degeneracy of the cold fuel results in an effective temperature \( (\theta_{\text{eff}} \sim 0.5 \text{ keV}) \), which is be compared to the actual temperature \( (\theta \sim 0.2 \text{ keV}) \). Thus, degeneracy further lowers the stopping power, as can be seen by comparing the red and dashed blue curve in left panel of Fig.3. The corresponding effect on the RIF spectrum is to increase the spectrum by about a factor of 2 at 15 MeV, but by less than a factor of 1.1 at 22 MeV, as seen in the right panel of Fig. 3.

A more stringent test of stopping models in degenerate plasmas would be afforded by a measurement of the shape of the RIF spectrum. For this we are developing a second RIF diagnostic, using activation of bismuth foils. The \(^{209}\text{Bi}(n,4n)\) reaction has an energy threshold of \( E_n=22.5 \text{ MeV} \) and it anchors the RIF spectrum at high energies, where degeneracy has little effect. A comparison between the bismuth and thulium RIF diagnostics would place stringent constraints on the role of degeneracy on stopping.

References
[1] Hayes A.C. et al., Physics of Plasmas 22 (8) 082703 (2015)
[2] Gostic J. M. et al. 2012 Rev. Sci. Instrum. 83 10D904.
[3] Shaughnessy D. A. et al. 2014 Rev. Sci. Instrum. 85 063508.
[4] Bleuel D. L. et al. 2012 Rev. Sci. Instrum. 83 10303.
[5] Wilson D C et al. 2002 Nucl. Instrum Meth. 488 S0168-9002(02)00474-6.
[6] Cerjan C., Springer P.T., Sepke S.M., Phys. Plasmas 20, 056319 (2013).
[7] Zimmerman G.B., Recent Developments in Monte Carlo Techniques, Lawrence Livermore National Laboratory internal report, UCRL-JC-105616, (1990).
[8] Grabowski P.E., Surh M.P., Richards D.F., Graziani F.R., and Murillo M.S., Phys. Rev. Lett. 111, 215002, (2013).
[9] Li C.K. and Petrasso R.D., Phys. Rev. Lett. 70, 3059 (1993)
[10] Brown L.S., Preston D.L., and Singleton R.L., Jr.,Phys. Rep. 410, 237 (2005).
[11] George E.P. and Hamada T., Phys. Letts. 67A, 369 (1978).
[12] Ordonez C.A. and Molina M.I., Phys. Rev. Lett. 72, 2407 (1994).