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Direct-drive DT implosions with Knudsen number variations

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Abstract. Direct-drive implosions of DT-filled plastic-shells have been conducted at the Omega laser facility, measuring nuclear yields while varying Knudsen numbers (i.e., the ratio of mean free path of fusing ions to the length of fuel region) by adjusting both shell thickness (e.g., 7.5, 15, 20, 30 μm) and fill pressure (e.g., 2, 5, 15 atm). The fusion reactivity reduction model showed a stronger effect on yield as the Knudsen number increases (or the shell thickness decreases). The Reduced-Ion-Kinetic (RIK) simulation which includes both fusion reactivity reduction and mix model was necessary to provide a better match between the observed neutron yields and those simulated.

1. Motivation

Recent work by Molvig *et al*. [1] examined how fusion reactivity may be reduced by the loss of fast ions to the imploding capsule-wall. Their theory of fusion reactivity reduction was formulated as a function of Knudsen number (i.e., the ratio of mean free path of ions to the length of fuel region) and implemented in a 1-D radiation-hydrodynamic code. In addition, their fusion reactivity reduction + mix model was benchmarked against existing direct-drive deuterium-tritium (DT) implosion data collected at the Omega laser facility between 2005 and 2011. Although Molvig *et al*. demonstrated that the fusion reactivity reduction + mix model provided a better match between the observed neutron yields and those simulated, the Omega experimental data had either large uncertainty in the initial target conditions (e.g., D/T mixing ratio and total DT gas pressure at shot time) or incomplete diagnostic information (e.g., no Knudsen number and shell area-density have been measured) to confirm that Knudsen effects are the cause of the discrepancies.

A platform for the study of Knudsen effects has been developed with the goal of measuring burn-averaged Knudsen numbers and yields as a function of the Knudsen number controlled via shell thickness and fill pressure variations.

2. Experimental setup

Nuclear and X-ray diagnostics were used to measure the performance of implosions and to infer the Knudsen number during implosions. The Knudsen number (N_K) in DT plasma is given by [1]

$$N_K = \frac{\lambda_i}{L} \approx 3.86 \times 10^{-2} \frac{1}{\ln \Lambda} \frac{T_i\,[keV]^2}{\rho L\,[mg/cm^2]},$$

where, λ_i is the mean free path of fusing ions, L is the system length (i.e., radius of fuel hot spot), and $\ln \Lambda = 3 + \ln\left(\frac{T_i\,[keV]^{\frac{3}{2}}}{\rho\,[g/cm^3]^{\frac{1}{2}}}\right)$ is the Coulomb logarithm [2]. In these expressions, T_i is the burn-averaged ion temperature in units of keV as measured by neutron time-of-flight (nTOF) diagnostics, and ρL is the fuel area-density in units of mg/cm^2 as measured by the knock-on deuteron spectrum from a charged particle spectrometer (CPS). Fuel density ρ is obtained by the measured ρL divided by the hot spot radius L captured using an X-ray framing camera.

Two different methods were used to vary the Knudsen number between shots. Since $N_K \sim T_i^2$, and T_i ~ implosion velocity ~ inverse of shell mass [3], we used four different thicknesses of plastic shells (7.5, 15, 20, 30 μm) at fixed inner diameter to vary the Knudsen number. The second way used to vary N_K was to have three different fill pressures (2, 5, 15 atm). Direct-drive implosions of these targets were conducted at OMEGA using 60 beams of frequency-tripled (351 nm) UV light in a 1.0 ns square pulse and a total energy of 27 kJ with smoothing by spectral dispersion and with SG4 pulse shape.

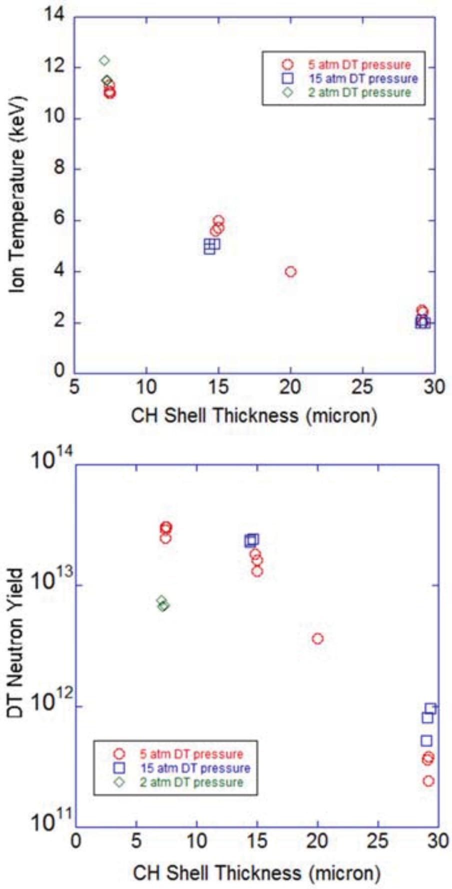

Figure 1: (a) Burn-averaged ion temperature and (b) DT neutron yields as a function of plastic shell thickness from 7.5 to 30 μm.

3. Experimental results

Time-integrated, burn-averaged ion temperature measurements using nTOF are shown in figure 1(a). As the wall thickness of plastic-shell increases from 7.5 to 30 μm, the burn-averaged ion temperature decreases significantly from ~ 12 to ~ 2 keV. There does not appear to be a strong temperature dependence with the DT fill pressure, although a slight decrease in ion temperature was observed going from 2 to 5 atm or from 5 to 15 atm, respectively. Figure 1(b) shows the DT neutron yield as a function of shell-thickness and DT fill pressure. Maximum neutron yield of (2-3)×10^{13} was achieved at 7.5 μm shell-thickness and 5 atm fill conditions. As the plastic-shell thickness increases from 7.5 to 30 μm, yield decreases nearly two order of magnitude. At 7.5 μm and 2 atm fill case, significant yield drop is observed compared to the 5 atm case. However, fill pressure variations at other shell thicknesses (e.g., 15 – 30 μm) do not affect yield as strongly.

Table I summarizes a subset of the data (i.e., 5 atm fill pressure and 7.5, 15, 20 μm thickness only) with shot number, capsule type, T_i, fuel ρL, hot spot radius, fuel mass density, $ln\Lambda$, N_K , fusion reactivity at $N_K = 0$ (i.e., $\langle\sigma v\rangle_0$), fusion reactivity at non-zero N_K (i.e., $\langle\sigma v\rangle_{N_K}$), and the resultant reduction factor for fusion reactivity expressed as $\langle\sigma v\rangle_{N_K}/\langle\sigma v\rangle_0$. No fuel ρL was recorded at 30 μm thickness capsule due to insufficient yield. As the shell thickness decreased from 20 to 7.5 μm, (1) the fuel ρL decreased from ~ 6 to ~ 2 mg/cm^2, (2) the hot spot radius increased from ~ 42 to ~ 60 μm, and (3) the Coulomb logarithm $ln\Lambda$ increased from ~ 5 to ~ 7. As a result, we achieved a minimum empirical Knudsen number N_K of ~ 0.025 at 20 μm shell thickness and a maximum N_K of ~ 0.36 at 7.5 μm shell thickness, which is nearly a factor of 14 variation in N_K in this data subset.

Table I: As-shot conditions for a subset of the data (i.e., 5 atm fill pressure and 7.5, 15, 20 μm thickness only) are shown with shot number, capsule type, $\boldsymbol{T_i}$, fuel $\boldsymbol{\rho L}$, hot spot radius, fuel density, $\boldsymbol{ln\Lambda}$, $\boldsymbol{N_K}$, fusion reactivity at $\boldsymbol{N_K = 0}$ **(i.e.,** $\boldsymbol{\langle\sigma v\rangle_0}$**)**, fusion reactivity at non-zero $\boldsymbol{N_K}$ **(i.e.,** $\boldsymbol{\langle\sigma v\rangle_{N_K}}$**)**, and resultant reduction factor for fusion reactivity expressed as $\boldsymbol{\langle\sigma v\rangle_{N_K}/\langle\sigma v\rangle_0}$

Shot#	DT(atm)CH[μm]OD[μm]	Ti (keV)	Fuel ρL (mg/cm^2)	Hot spot radius (μm)	Fuel mass density (g/cc)	$ln\Lambda$	N_K	$<\sigma v>_0$	$<\sigma v>_{NK}$	$<\sigma v>_{NK}$ / $<\sigma v>_0$
70858	DT(5.1)CH[20]883	4.0	4.9	42	1.17	5.0	0.025	6.00E-18	5.70E-18	0.95
70861	DT(5.4)CH[14.8]872	5.6	6.2	42	1.48	5.39	0.036	2.03E-17	1.90E-17	0.94
70860	DT(5.4)CH[15]868	5.7	5.3	42	1.26	5.49	0.043	2.15E-17	1.98E-17	0.92
70849	DT(5)CH[15.0]873	6.0	4.5	42	1.07	5.65	0.055	2.55E-17	2.28E-17	0.90
70882	DT(5)CH[7.5]865	11.0	2.5	60	0.42	7.03	0.266	1.44E-16	9.02E-17	0.63
70868	DT(5)CH[7.4]860	11.1	2.3	60	0.38	7.09	0.292	1.48E-16	8.85E-17	0.60
70862	DT(5.2)CH[7.4]866	11.3	2.0	60	0.33	7.19	0.343	1.54E-16	8.56E-17	0.56
70852	DT(5)CH[7.4]870	11.0	1.8	60	0.30	7.20	0.360	1.44E-16	7.70E-17	0.53

The $\langle\sigma v\rangle$ as a function of T_i and N_K provided by A. Simakov [4] are plotted in figure 2. The $\langle\sigma v\rangle$ increases as T_i increases and more interestingly, it decreases as N_K increases. The last three columns in Table I (i.e., $\langle\sigma v\rangle_0$, $\langle\sigma v\rangle_{N_K}$, $\langle\sigma v\rangle_{N_K}/\langle\sigma v\rangle_0$) were obtained from figure 2 using the measured T_i and N_K. The $\langle\sigma v\rangle_{N_K}/\langle\sigma v\rangle_0$ indicates how much the fusion reactivity decreases at given N_K condition and can be used to estimate the yield reduction. In this work, a nearly ~ 0.5 reduction factor was obtained at 7.5 μm shell thickness, whereas a 15-20 μm shell thickness provided only 0.90 – 0.95 reduction factor.

4. Discussion

1-D radiation-hydrodynamic simulations incorporated "reduced" (i.e., simplified or approximate) ion-kinetic (RIK) models [5] were performed to assess the relative importance of (1) mix and (2) fusion reactivity reduction. In this paper, the electron thermal flux limiter was equal to 0.06. To account for laser refraction past the capsule, the incident laser energy was reduced by a factor of 0.66. Two additional parameters affecting ion mass transport (f_{idiff} used in [5]) and ion thermal conduction (f_{icnd} used in [5]) are fixed to f_{idiff} = 1, f_{icnd} = 4, respectively. Turbulent mixing was accounted for using the buoyancy-drag model of Dimonte with a fixed drag coefficient of 2.5 and an adjustable initial scale length l [5]. An improved fusion-reactivity reduction model [4] was implemented in the simulation code, where the coefficient f_{KNU} can be varied.

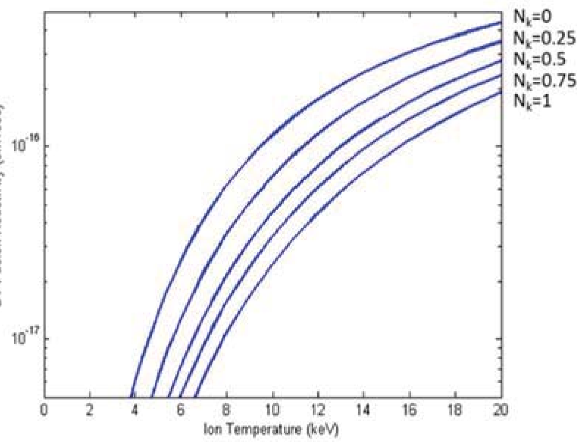

Figure 2: DT fusion reactivity as a function of ion temperature and Knudsen number [4]

In figure 3, DT neutron yields from 8 shots listed in Table I and additional 3 shots performed by 30 μm shell thickness and 5 atm fill pressure conditions are re-plotted as a function of T_i (red x mark). Three simulations were performed for each shot: first of which (the "nominal" simulation) did not invoke either the mix model (l = 0) nor fusion reactivity reduction (f_{KNU} = 0),

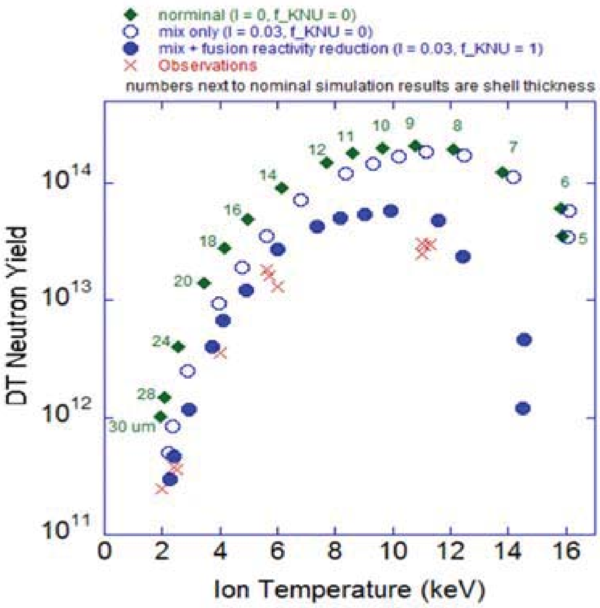

Figure 3: DT neutron yield as function of ion temperature for a norminal simulation (l = 0, f_{KNU} = 0), a mix only (l = 0.03, f_{KNU} = 0), a mix + fusion reactivity reduction (l = 0.03, f_{KNU} = 1), and experimental data

second of which (the mix only) invoked the mix model only (l = 0.03, f_{KNU} = 0), and third of which (mix + fusion reactivity reduction) invoked both (l = 0.03, f_{KNU} = 1). Turbulent mix shows a stronger effect on yield as shell thickness increases (or T_i and N_K decreases). However, the fusion reactivity reduction is more important than turbulent mix as T_i and N_K increases (or shell thickness decreases). However, the fusion reactivity reduction is more important than turbulent mix as T_i and N_K increases (or shell thickness decreases). For example, for an implosion with ~ 11 keV T_i, the observed yield over simulation (YOS) was ~ 0.19 by the nominal simulation, ~ 0.21 by the mix alone, and ~ 0.83 by the mix + fusion reactivity reduction. The Reduced-Ion-Kinetic (RIK) simulation which includes both fusion reactivity reduction and mix model was necessary to provide a better match between the observed neutron yields and those simulated.

5. Conclusion

Unlike the previous Omega DT experiments, empirical Knudsen number (N_K) was inferred by using nuclear diagnostics (i.e., nToF, CPS, X-ray framing camera). Systematic variation of N_K by a factor of 14 (0.025 - 0.36) was achieved by varying shell thickness (ion temperature) and fill pressure. As the N_K increases, the fusion reactivity reduction model was more important than turbulent mix to explain the discrepancies between simulated yield and measured yield. Turbulent mix showed a stronger effect on yield as shell thickness increases (or T_i and N_K decreases). The Reduced-Ion-Kinetic (RIK) simulation which includes both fusion reactivity reduction and mix model was necessary to provide a better match between the observed neutron yields and those simulated. Two future experiments may provide additional information to qualify fusion reactivity reduction [6]. First, a N_K higher than 0.36 may provide further qualification of the fusion reactivity reduction. Second, DT mixing ratio variation would separate fusion reactivity reduction physics and possible multi-species diffusion physics [7].

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