Neutron spectra and temperature diagnostics of imploded ICF plasma: models and 1D and 2D simulations

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1. Introduction

The spectrum of neutrons released by an inertially confined fusion (ICF) plasma provides valuable information on the emitting plasma [1]. This includes, but is not limited to, ion temperature and confinement parameter ρR. For instance, a neutron-averaged ion temperature is obtained from the width of unscattered portion of neutron spectra, $T \propto \Delta E_{\rm FWHM}$ [2]; see below. The confinement parameter of ignition-size targets is obtained from the down-scattered-ratio (DSR), i.e the ratio of the 14.1 MeV DT neutrons scattered in the 10–12 MeV range to the unscattered neutrons (neutrons in the 13–15 MeV range); approximately, $\rho R[\mathrm{g/cm^2}] = 21 DSR$.

General expressions for the production spectrum of neutrons (and fast charged particles) can be found in the literature [3, 4]. It is confirmed that energy distribution $f(E)$ of the neutrons emitted by a uniform source, at rest, with Maxwellian ion velocity distribution, is very well approximated by a Gaussian, $f(E) \propto \exp[-(E - <E>)^2/2\sigma^2]$, with average energy and rms deviation, respectively [2],

$$<E> = \frac{3}{2}T + \frac{m_{\rm o}}{m+m_{\rm o}}(Q + <K>); \qquad \sigma = \left(\frac{2m}{m+m_{\rm o}} T <E>\right)^{1/2},$$

where m and $m_{\rm o}$ are the masses of the neutron and of the other fusion product, respectively, Q is the reaction yield, $<K>$ the mean relative energy of the reacting nuclei, and T is the ion temperature in units of energy. (Slightly more accurate expressions, as well expressions for higher moments of the distribution can be found in [5]). In practice $\sigma \simeq [TQ(2mm_{\rm o}/(m+m_{\rm o})^2)]^{1/2}$, since typically both T and $<K>$ are much smaller than Q. The relations between FWHM of the energy distribution ($\Delta E_{\rm FWHM}$) and the reaction-weighted ion temperatures for DT and neutron branch of DD reactions follow immediately:

$$T_{\rm DT} = (\Delta E_{\rm FWHM}/176.8)^2; \qquad T_{\rm DDn} = (\Delta E_{\rm FWHM}/82.4)^2, \tag{1}$$

where both neutron energies and ion temperatures are measured in keV.

However, ICF imploded plasmas are space- and time-dependent, plasma motion effects can also be important (see the next section), and emitted neutrons can be scattered; see, e.g. Fig. 1, showing the spectrum emitted by a NIF-size ignited target. As a first step in the development of

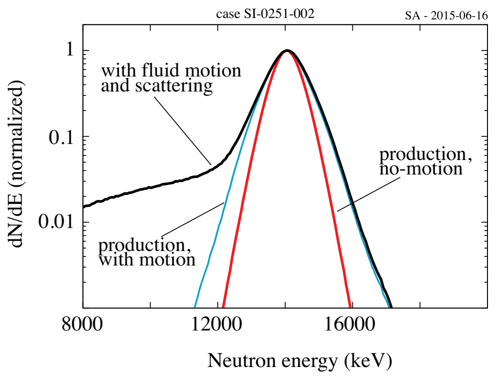

Figure 1: *DT neutron spectrum released by a reactor-size, shock-ignited target (see Sec. 3.3).*

a synthetic neutron diagnostics, we have included a neutron Monte Carlo package in the 2D ICF code DUED [6]. The source term accounts for both ion motion and bulk fluid motion. Scattering is also included, while, at the moment, secondary reactions and reactions by knocked-on nuclei are neglected.

2. Fluid motion effects

In most cases, scattering does not affect the width of the distribution, which provides information on ion temperature. Instead, fluid motion effects can be significant. Insight is provided by simple analysis, applying to both the angularly integrated spectrum from a point source in motion with velocity u, and to the spectrum released by a homogeneous and spherically symmetric plasma imploding/exploding with velocity u. We have tested that the production spectrum obtained from Eq. (35) of ref. [3] is accurately reproduced by the convolution of a Gaussian (with rms deviation σ) accounting for thermal motion only, and a distribution accounting for fluid motion only. The latter is a constant for energy in the interval $[E_0(1-w)^2]; E_0(1+w)^2])$ and is zero elsewhere, with $E_0 = (1/2)mv_0^2 = Qm_o/(m+m_o)$ the neutron energy in the fluid system, and $w = u/v_0$ and v_0 neutron velocity in the fluid system.

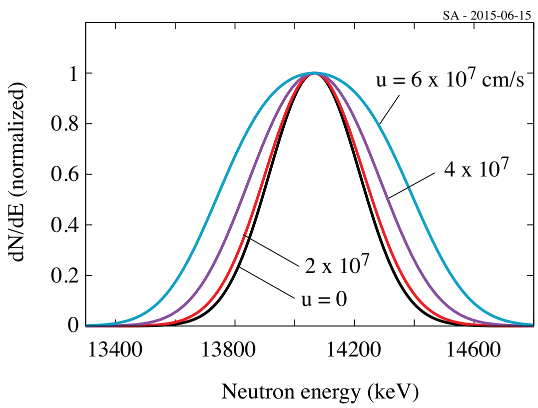

Figure 2: *DT neutron production spectrum, for a 4 keV plasma, and different values of the fluid velocity u.*

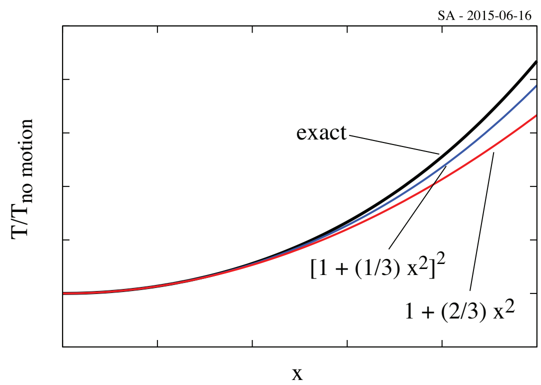

Figure 3: *Ratio* $T/T_{\text{no motion}}$ *vs the dimensionless parameter* $x = 2(u/v_0)(<E>/\sigma)$.

Distributions of DT neutrons from a 4 keV plasma are presented in Fig. 2 for different values of the fluid velocity u. In this case, motional effects become appreciable for velocities in excess of 2×10^7 cm/s. Simple analysis (based on power expansion of the convolution to third order in x; details will be given elsewhere) provides an approximate expression for the FWHM of the spectrum, as a function of T and the parameter $x = 2 <E> w/\sigma = 0.229(u_7/\sqrt{T})\sqrt{A_\text{n} + A_\text{o}}$, where u_7 is the fluid velocity in units of 10^7 cm/s, and A_n and A_o are the mass numbers of the reaction products. Using Eq. (1) to obtain a neutron-weighted ion temperature we can write

$$T \simeq T_\text{no motion}(1 + \frac{1}{3}x^2)^2 \simeq T_\text{no motion}(1 + \frac{2}{3}x^2). \quad (2)$$

Such expressions are a few per cent accurate for $x < 0.6$ (i. e. $u_7 < 1.2\sqrt{T}$, for DT), as can be seen from Fig. 3. Practical expressions for DT- and DD-weighted temperatures are, respectively $T_{DT} \simeq T_{DT\,\text{no motion}}(1 + 0.176u_7^2/T)$ and $T_{DD} \simeq T_{DD\text{no motion}}(1 + 0.14u_7^2/T)$. From these expressions one can expect significant fluid motion contribution to neutron-weighted temperatures in exploding pushers (where reactions occur when a strong shock hits the center) and in ignited targets (which explode with velocity well in excess of 10^8 cm/s), and only minor effects in conventional close-to-ignition targets (in which reactions occurs at implosion stagnation).

3. Coupled DUED hydrodynamics and neutron Monte Carlo simulations

We now discuss neutron spectra generated by DUED radiation hydrodynamics simulations with the Monte Carlo neutron package.

3.1 - High-density D^{3}He-filled exploding pusher implosions at OMEGA [7]. At low gas-fill density, 1D simulations largely overestimated both yields and temperatures, evidencing the role of kinetic effects [7]. At the highest densities (few mg/cm^3), fluid simulations were closer to experiments. Yields were overestimated by a factor 2–3, and temperatures were not far from the experimental values. In particular, experimental DD-weighted temperature were about 12 keV, while the temperature inferred from DUED-MC is about 10.3 keV; 8.8 keV when fluid motion effects are neglected. This is consistent with an average velocity of about 3.5×10^7 cm/s at the time of neutron emission.

3.2 -NIF-like, high-foot implosion implosions. We have performed 1D simulations of direct-drive targets with approximately same fuel mass (0.2 mg), implosion velocity (3.1×10^7 cm/s) and adiabat ($\alpha \simeq 2.5$) as the NIF high-foot experiments [8]. A typical spectrum is shown in Fig. 4. From such a spectrum we obtain $DSR = 0.045$ and DT weighted temperature $T_{DT} = 4$ keV (with a contribution smaller than 150 eV from fluid motion; the curves with motion included and neglected indeed nearly

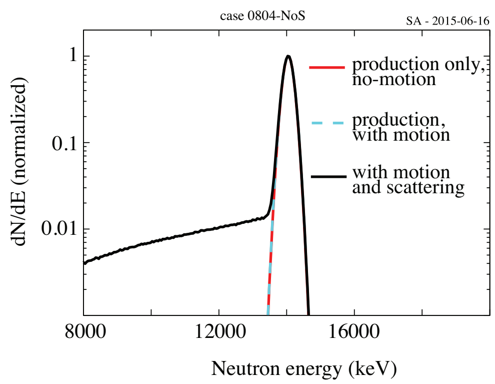

Figure 4: *Spectrum from a NIF-like high foot implosion.*

overlap in the figure). Such values, as well as other hot spot parameters are in reasonable agreement with experimental values. A significant discrepancy (also reported in Ref. [8]), instead concerns the difference $\Delta T = T_{DT} - T_{DD}$ of DT- and DDn-weighted temperatures. The simulations give $\Delta T = 200$-300 eV, only about one half of the experimental values. According to the results of Sec. 2, fluid motion (even turbulent motion) cannot account for such a larger ΔT difference. Such effects as fluid layering or species separation [9, 10, 11], not modelled by DUED, could instead contribute to increasing ΔT.

3.3 - High-gain shock-ignition targets. In particular, we refer to the *robust R* cases presented in Sec. 5 of Ref. [12]. Figure 1 shows the spectrum released by a target driven by an 830 kJ laser pulse, and achieving gain about 100 (85 MJ yield). In this case one notices the very large broadening due to fluid motion during thermonuclear burn (increasing the DT-weighted temperature from 25 keV to 45 keV). 2D simulations of targets failing to ignite due to excessive hot spot asymmetries (as the case shown in the lhs panels of Fig. 10 of Ref. [12]) show signficant effects of fluid motion, too, yielding $T_{DT} = 6.5$–7 keV and $T_{DT\,\mathrm{no\ motion}} \simeq 5$ keV. A possible explanation is that asymmetric implosions result in incomplete conversion of kinetic energy into internal energy.

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