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Kinetic studies of ICF implosions

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Abstract. Kinetic effects on inertial confinement fusion have been investigated. In particular, inter-ion-species diffusion and suprathermal ion distribution have been analyzed. The former drives separation of the fuel constituents in the hot reacting core and governs mix at the shell/fuel interface. The latter underlie measurements obtained with nuclear diagnostics, including the fusion yield and inferred ion burn temperatures. Basic mechanisms behind and practical consequences from these effects are discussed.

1. Introduction

In inertial confinement fusion (ICF) high temperature and density of the deuterium/tritium plasma are achieved through ablating the outer shell of the fuel capsule, which is then compressed by the rocket force. This process takes place over a short time scale, making large background gradients an inherent feature of ICF implosions. On the other hand, the major ICF modeling tool, rad-hydro codes, rely on the *single*-fluid framework. One should thus expect predictions of these codes to deviate from experimental observations with the plasma mean free path being comparable to the gradient length scale. Importance of the associated *kinetic effects* can be quantified with the Knudsen number $N_K = \lambda/L$, where λ and L are the characteristic mean free path and background scale, respectively.

Figure 1 shows N_K calculated by post-processing the temperature and density profiles from 1D HYDRA [1] simulations for two representative cases with L taken to be the hot-spot radius and λ the ion mean free path at the hot-spot center [2]. It can be observed that in the NIF case N_K does become of order unity during the course of implosion. Although it is predicted to drop down just before the burn, the initial conditions for this burn can thus be altered. Furthermore, in the thin shell Omega case N_K is predicted to be particularly large during the burn itself. Of course, one should not take these predictions at face value since the fluid simulations that give

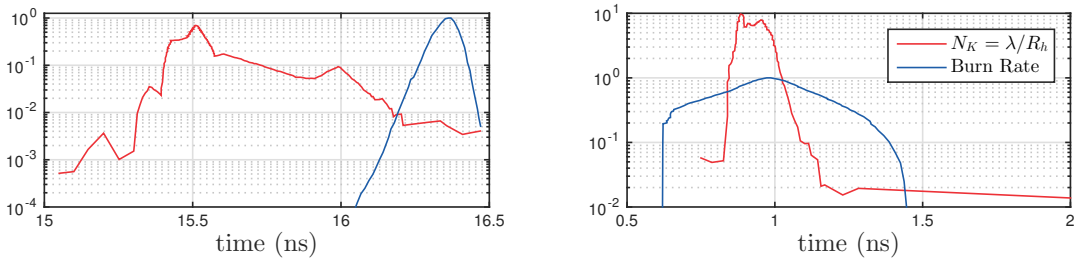

Figure 1. Knudsen number as a function of time, along with the burn rate normalized to its maximum value. Left: NIF high foot shot N130501, 1125 μm radius Si-doped CH capsule with 68.6 μm DT ice layer. Right: 865×7.4 μm CH capsule with 5 atm DT fill driven by a 27 kJ, 1 ns laser pulse.

them are no longer robust once N_K starts approaching even a fraction of unity. However, Fig. 1 does indicate that kinetic effects can play a role on ICF experiments.

In principle, such regimes can be investigated with fully kinetic simulations [3, 4, 5]. However, this path requires enormous computational resources that, in particular, makes it infeasible for modeling realistic 2D and 3D implosions. Neither is it applicable to dense plasmas with non-ideal equations of state and small Coulomb logarithms, as is the case at the fuel/shell interface. On the other hand, fully kinetic simulations can provide a benchmark for physics models, which can both deepen our understanding and allow describing practical implosions beyond the simplest 1D case.

A computationally inexpensive option is a mainline rad-hydro code with "kinetic patches" [6]. This framework involves free parameters, whose values are set through optimization process to fit experimental data, and so is somewhat phenomenological. In the present work we develop a first principles yet computationally efficient approach by noticing that a large class of kinetic effects can be encompassed through treating the thermal and suprathermal particles separately. For the former, the mean free path is smaller and distribution functions are often close to equilibrium, though the strong gradients can separate different ion species making the conventional *single*-fluid approach invalid. For the latter, the mean free path can be comparable to, or even larger than, L but these particles only constitute a small fraction by number and can be described by a reduced linear (as opposed to the full non-linear) kinetic equation. Sections to follow summarize our main theoretical results in these two research directions.

2. Inter-ion-species diffusion

The central hot plasma in a spherical implosion contains multiple ion species, which can include both low-Z and high-Z elements [7, 8, 9, 10, 11]. Their relative concentrations can evolve substantially over the course of implosion due to inter-ion-species diffusion [12, 13]. Observation of the resulting fuel stratification in experiments [14, 15, 16, 17] and fully kinetic simulations [3, 4] have recently been reported. The targets with high-Z dopants show particularly pronounced yield anomalies [8, 9, 18], suggesting that even stronger fuel stratification may take place. In addition, this is the same diffusion process that underlies the atomic mixing at the shell/fuel interface. This physics is not included in conventional rad-hydro codes, which therefore "force" the relative concentrations of the ion species to remain constant.

The concentration evolution of species α is governed by the so-called "diffusive flux" $\vec{i}_\alpha \equiv \rho_\alpha(\vec{u}_\alpha - \vec{u}_{\mathbf{c.m.}})$, where $\vec{u}_\alpha$ and $\vec{u}_{\mathbf{c.m.}}$ are fluid velocities of the species α and the overall plasma, respectively, and ρ_α is the mass density of species α. In the illustrative case of a plasma

with two ion species the diffusive flux of the lighter species takes the form

$$\vec{i}_l = -\vec{i}_h = -\rho D\Big(\nabla c + k_p \nabla \log p_i + \frac{e k_E}{T_i}\nabla\Phi + k_T^{(i)}\nabla \log T_i + k_T^{(e)}\nabla \log T_e\Big),$$

where $p_i = p_l + p_h$ is the total ion pressure, Φ is the electrostatic potential, T_i and T_e are the ion and electron temperature, respectively, and subscripts "l" and "h" denote the light and heavy ion species, respectively. To get an idea of how fast the concentration changes one needs to know the classical diffusion coefficient D and the so-called "diffusion ratios" k_p, k_E, $k_T^{(i)}$ and $k_T^{(e)}$.

We have first conducted first principles transport calculation to obtain these coefficients in the conventional, or *weakly coupled*, plasmas [19, 20]. Unlike the well-known case of neutral gas mixtures, thermo-diffusion ratios $k_T^{(i)}$, $k_T^{(e)}$ were found to be comparable to, or even much larger than, the baro-diffusion ratio k_p. Equally important, in low-Z/high-Z mixtures, $k_T^{(i)}$ and $k_T^{(e)}$ were found to attain large absolute values and slopes at small concentrations of the high-Z component [20]. Plasma thermo-diffusion may thus be potentially responsible for the anomalous yield reduction in doped capsule implosions [8, 9] in addition to the laser absorption effects considered earlier [18].

This calculation relied on the binary collision model that breaks down for dense *coupled* plasmas, in which particle correlations are significant. Such plasmas naturally occur during various stages of the implosion and, in particular, in the mixing layer between the shell and the fuel. To gain an insight into diffusion issues in this regime we have utilized the recently proposed effective potential theory, whose predictions for transport in dense plasmas proved in remarkable agreement with molecular dynamic (MD) simulations [21, 22]. Taking this idea further we have evaluated the full set of transport coefficients in multi-component plasmas. Most interestingly, thermo-diffusion was found to vanish in substantially coupled plasmas, making it somewhat similar to thermo-diffusion in neutral gas mixtures [23].

3. Suprathermal ions

In fully ionized plasmas, the particle mean free path scales with the square of this particle's energy. Suprathermal ions can therefore be far from Maxwellian even if their thermal counterparts are nearly equilibrated. It is these suprathermal, or *tail*, ions that fuse in subignited implosions. Their distribution is thus the key to proper interpretation of nuclear diagnostics employed at ICF experiments in general and to correct fusion yield prediction in particular.

The possibility of the reactivity reduction due to ion tail depletion was originally pointed out by Henderson and Petschek [24, 25]. More recently Molvig et al. reexamined the problem in connection to experiments at Omega laser facility and suggested a simple upper bound model for the reactivity reduction [26]. This work was followed by more accurate calculations by Albright et al. [27], Schmit et al. [28], Tang et al. [29], Davidovits and Fisch [30] and Cohen et al. [31]. All these studies considered the perfectly planar or spherical models and relied either on direct numerical solution [28, 29, 30, 31] or phenomenological assumptions that affect the structure of the kinetic equation, thereby introducing uncontrollable modifications to the reactivity [26, 27].

Hydro-instabilities that commonly exist at the shell/fuel interface suggest that the 1D results need to be revisited for realistic implosions. Indeed, we have found that the reactivity reduction can be substantially aggravated by these instabilities [32]. This analysis utilized the self-similarity feature of the suprathermal ion distribution, which has been verified in the 1D planar and spherical cases with the newly developed code solving the reduced kinetic equation. On the practical side this feature effectively gives that, as far as the reactivity is concerned, the suprathermal ions "feel" the distance to the hot-spot boundary only, thereby providing a computationally expedient yet reasonably accurate tool for evaluating the tail depletion effects.

Finally, we have demonstrated that the inferred ion burn temperature, as evaluated from the standard Brysk prescription [33], is lower than the actual one due to the same ion tail depletion effect. This mechanism has a stronger impact on the DD reaction than on DT, thereby making the apparent DD temperature lower than DT [32]. Such a trend is often observed at NIF [34] and explanations available to date include the bulk fluid motion [35, 36], neutron scattering and burn weighting due to reactivity dependence on temperature [34]. None of these mechanisms alone seems capable of giving the observed 25% difference between the DD and DT temperatures, so the newly predicted effect may contribute.

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