Experimental Validation of Low-*Z* Ion-Stopping Formalisms Around the Bragg Peak in High-Energy-Density Plasmas

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An understanding of the DT-α energy deposition and heating of a high-energy-density (HED) plasma is critical for determining the ignition threshold in hot-spot–ignition experiments. This requires a fundamental understanding of the DT-α stopping around the Bragg peak, where the ion velocity (v_i) is similar to the average velocity (v_{th}) of the thermal plasma electrons for a wide range of electron (T_e) and ion temperatures (T_i), and electron number densities (n_e). Ion stopping in HED plasmas has, therefore, been subject to extensive analytical and numerical studies for decades,[1–3] but a theoretical treatment of ion stopping especially around the Bragg peak remains a difficult problem. The consensus is that the ion stopping at $v_i \gg v_{th}$ is treated well by the Born approximation because the interaction between the fast ions and plasma electrons is small, resulting in small energy transfers compared to the kinetic energy of the ions. At $v_i < v_{th}$, the ion stopping is harder to characterize but generally described by collisional theories that treat two-body collisions and large-angle scattering between the ions and plasma electrons. At ion velocities near v_{th}, the Born approximation breaks down because scattering is no longer weak and collisional theories make it difficult to provide a complete, self-consistent picture of the ion stopping because of the dynamic dielectric response of the plasma electrons. Rigorous quantum mechanical treatments based on convergent kinetic theories[1] attempt to rectify these challenges by utilizing the strengths of the different approaches applied to the different regimes; however, it is not clear how best to combine them and quantify their errors. Precise measurements of the ion stopping around the Bragg peak are therefore essential to guide the theoretical efforts.

Although numerous efforts have been made to theoretically describe the behavior of ion stopping in HED plasmas, only a limited set of experimental data exists to test these theories. In addition, most of these experiments used only one particle with a distinct velocity in the high-velocity ion-stopping regime ($v_i > v_{th}$) and, therefore, did not simultaneously probe the detailed characteristics of the Bragg peak below and above v_{th}. To the best of our knowledge, only two experiments have attempted to simultaneously probe the low- and high-velocity side of the Bragg peak,[4,5] but the limitation of these experiments was that the HED plasma conditions could not be characterized to the level required for experimental validation of various ion-stopping formalisms. The work described here significantly advances previous efforts by providing the first accurate experimental validation of ion-stopping formalisms around the Bragg peak.

The experiments reported herein were carried out on OMEGA, where eight D^3He gas-filled, thin-glass capsules were symmetrically imploded with 60 laser beams, delivering up to 12.0 kJ to the capsule in a 1-ns square pulse. These capsules were also filled with a small amount of argon for a time- and space-resolved measurement of the electron-temperature and electron-number-density profiles.[6]

For accurate experimental validation of the ion stopping around the Bragg peak, the energy loss ($-\Delta E_i$) of DD tritons (DD-t), DD protons (DD-p), D^3He-α (D^3He-α), and D^3He protons (D^3He-p), while traversing the well-characterized HED-plasma conditions, were simultaneously measured. Examples of measured spectra of DD-t, DD-p, D^3He-α, and D^3He-p are shown in Fig. 1 for shot 75699. The vertical arrows in Fig. 1 indicate the median energy for each measured spectrum, and by contrasting these energies to the average-birth energies (vertical dashed lines), $-\Delta E_i$ was determined to an accuracy of ~10% and used to assess the ion stopping in the HED plasma. (See Ref. 7 for more details about these measurements.)

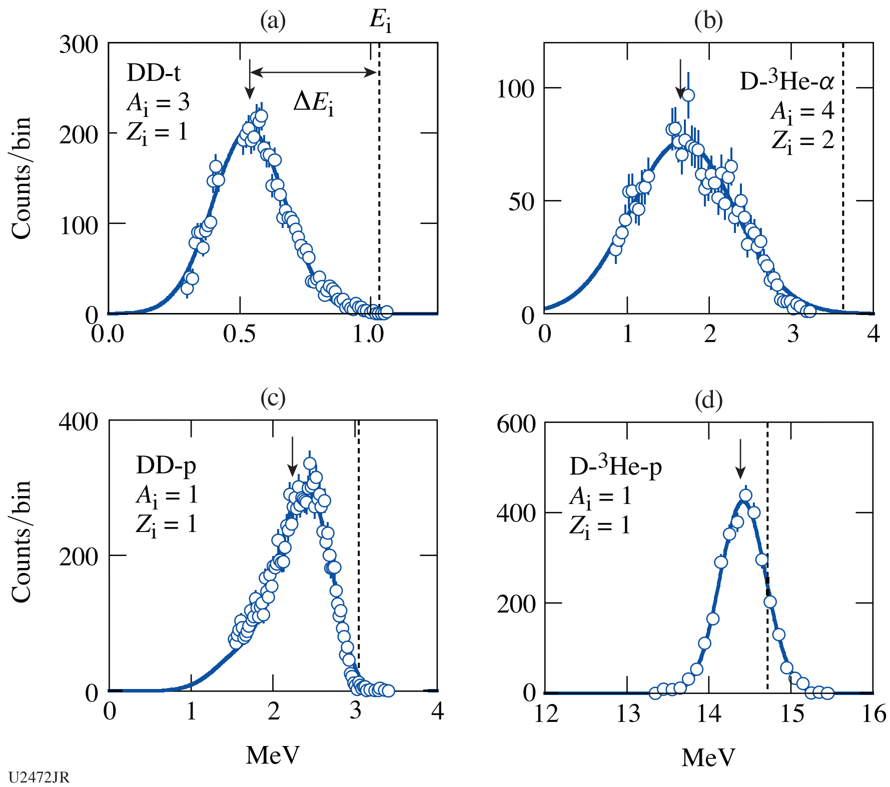

Figure 1
Measured spectra of DD-t, D^3He-α, DD-p, and D^3He-p for shot 75699. These fusion products are produced by the reactions: D + D ⟶ t (1.01 MeV) + p (3.02 MeV) and D + ^3He ⟶ ^4He (3.71 MeV) + p (14.63 MeV), where the energies in the parentheses are the fusion-product birth energies (at zero ion temperature).

To illustrate the measured energy loss of fusion products with different initial energy (E_i), charge (Z_i), and mass (A_i) passing through an HED plasma, the energy-loss data must be presented in the form of $-\Delta E_i/Z_i^2$ versus E_i/A_i. Figure 2 shows the $-\Delta E_i/Z_i^2$ versus E_i/A_i for shots conducted in this study. The solid curves in Fig. 2 were obtained by integrating the Brown–Preston–Singleton (BPS) plasma stopping-power function, describing only the ion–electron Coulomb interaction. Clearly, the data demonstrate that the BPS formalism is providing a good description of the ion stopping for these HED plasma conditions, except for the stopping of DD-t at $v_i \sim 0.3v_{th}$. At this velocity, the BPS formalism systematically underpredicts DD-t energy loss for all shots. This observation cannot be explained by the inclusion of ion–ion Coulomb scattering in the modeling because ion-stopping theories based on multi-ion component response predict that the contribution of the ion–ion Coulomb scattering to the total DD-t plasma-stopping power is ~10% at $v_i \sim 0.3v_{th}$. This points to the idea that the contribution from the ion–ion component to the total ion stopping at this velocity could, in fact, be larger than predicted by theories. This is certainly plausible since all theories ignore the ion–ion nuclear elastic scattering, which is more strongly weighted toward large-angle scattering than Coulomb scattering. To explain the data at $v_i \sim 0.3v_{th}$, the total ion stopping must be increased by ~20%, possibly a result of ion–ion nuclear elastic scattering. This postulation, if correct, would have an impact on our understanding of DT-α heating of the fuel ions in an ignition experiment.

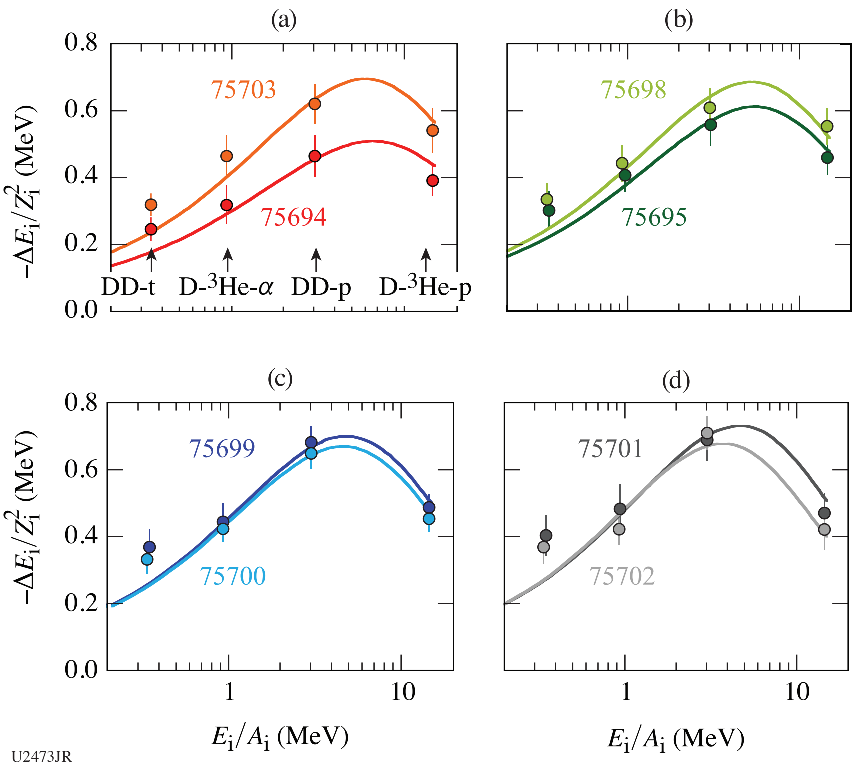

Figure 2
The measured and predicted ion stopping $\left(-\Delta E_i / Z_i^2\right)$ as a function of E_i / A_i for all shots. The data set is contrasted to BPS predictions (considering only ion–electron Coulomb interactions).

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