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Measurement of Charged-Particle Stopping in Warm Dense Plasma

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We measured the stopping of energetic protons in an isochorically heated solid-density Be plasma with an electron temperature of ~32 eV, corresponding to moderately coupled [(e2/a)/(kBTc + EF) ~ 0.3] and moderately degenerate [kBTc/EF ~ 2] “warm-dense matter” (WDM) conditions. We present the first high-accuracy measurements of charged-particle energy loss through dense plasma, which shows an increased loss relative to cold matter, consistent with a reduced mean ionization potential. The data agree with stopping models based on an ad hoc treatment of free and bound electrons, as well as the average-atom local-density approximation; this work is the first test of these theories in WDM plasma.

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Studying charged-particle stopping in dense plasmas is relevant to fundamental plasma physics and to the potential realization of laboratory-scale thermonuclear fusion. Dense plasmas in the warm-dense matter (WDM) regime, approximatively solid density and tens of eV temperature, are of great interest as a probe of stopping-power theories, with broader physics relevance to nonequilibrium statistical mechanics [1], dense plasma transport properties [2–4], and bound-free transitions in WDM plasmas [5]. Accurate theory for bound-free transitions is required to interpret data obtained with common laser-plasma diagnostics including Thomson scattering [6] and opacity-based areal density techniques [7].

In inertial confinement fusion (ICF), spherical implosion heats and compresses a small volume of fuel to, in principle, spark a runaway thermonuclear burn wave [8–10]. This burn wave propagates via fusion-produced energetic α particle self-heating. Understanding the transport of these α’s in plasmas at extreme conditions is required to accurately model ignition experiments at the National Ignition Facility (NIF) [11], where significant α self-heating has recently been achieved [12]. Charged-particle transport in and heating of dense plasmas is also highly relevant to alternative particle-beam-driven inertial fusion designs such as heavy-ion fusion [13] and proton fast ignition [14,15].

The stopping of energetic charged particles has been studied in cold (room-temperature) material for a century [16]; there, the energetic particle loses energy to bound electrons, for which theoretical models [17,18] are fit to a significant experimental database [19]. In a plasma, an energetic particle simultaneously interacts with a large number of particles via the Coulomb force, over a volume with dimensions given by the screening length (Debye-Hückel or Thomas-Fermi). Typically the stopping is treated as either a summation of two-body (binary) collisions [20–22], or a dielectric (density) response [22–25].

In this Letter, we report the first high-precision measurement of charged-particle energy loss in a dense moderately degenerate and moderately coupled plasma. The results are compared to theories in common use by simulation codes. For testing theory in this regime, these results are a significant improvement on previous experiments, which utilized simpler low-density non-degenerate plasmas [26–31] or had significantly less precision [32].

The OMEGA laser facility [33] was used to create a pulsed monoenergetic source of protons that probe a subject plasma isochorically heated to WDM conditions. Figure 1 shows the experimental configuration. A shock-driven “exploding pusher” implosion [34] filled with D3He fuel is used to produce the probing protons via the fusion reaction

$$D + ^3He \rightarrow ^4He + p(14.63 \text{ MeV}).$$

(1)

The implosion is driven by 20 of the OMEGA laser beams at 3ω (351 nm), delivering 10 kJ of energy in a 1 ns duration square pulse. These protons, produced over a ~100 ps burst, then traverse the x-ray isochorically heated subject plasma. The subject target consists of a plastic (CH) tube coated with 1–2 μm of Ag, with an inner diameter of
870 μm, a wall thickness of 24 μm, and 800 μm in length. A cylindrical Be plug is inserted into the tube, with total \( \rho L = 94.2 \pm 0.6 \, \text{mg/cm}^2 \), which serves as the subject material for the experiment [35]. Thirty of the OMEGA beams are incident upon the outer surface of the tube, arranged in three rings positioned along the axis of the cylinder. The lasers are defocused to create \( \sim 100 \, \text{μm} \) diameter illumination spots on the cylinder. The total drive energy on the subject target was 15 kJ, delivered in a 1 ns square pulse. The resulting intensity in each spot is \( \sim 10^{15} \, \text{W/cm}^2 \). This laser intensity generates Ag L-shell emission at 3–4 keV in the coronal surrounding the cylindrical target, which volumetrically heats the Be plug as the attenuation length in solid Be is negligible [38].

The implosion proton source was timed so that the proton probing occurs at 1.4 ns after the onset of the heating beams, at which time electrostatic charging [29,37] of the subject target is quiescent for comparable to the cylinder dimensions. The heating occurs over 1 ns, and the temperature is quiescent for another ns after the drive turns off [36]. This plasma can be understood by the dimensionless parameters for degeneracy (\( \theta \)) and coupling (\( \Gamma_e \)).

\[
\theta \equiv \frac{k_B T_e}{E_F}, \quad \Gamma_e \equiv \frac{e^2}{a(k_B T_e + E_F)},
\]

where \( \theta \) is the ratio of the thermal to Fermi energy (\( E_F \)), and \( \Gamma_e \) is the ratio of the electron interparticle Coulomb potential energy to average kinetic energy \( (k_B T_e + E_F) \), where \( a = [3/(4\pi n_e)]^{1/3} \) is the Wigner-Seitz radius. At these conditions, \( \theta \approx 2 \) and \( \Gamma_e \approx 0.3 \), indicating moderate degeneracy and coupling. The parameter space for the degeneracy and coupling versus electron density and temperature is shown in Fig. 2, with this work and prior experiments marked. We note that the Graziani et al. (Ref. [32]) experiments are close to this work in parameter space, but the uncertainty in their stopping-power data is significantly larger, and they were unable to differentiate any stopping models. In Ref. [32], the stopping-power uncertainty reported was \( \sim \)24%. In this work, the use of monoenergetic D\(^3\)He protons, wedge range filter (WRF) proton spectrometers [43,44] with intrinsic energy uncertainty \( \sim 40 \, \text{keV} \) [45], and a large subject plasma with \( \rho L \sim 100 \, \text{mg/cm}^2 \) enabled stopping-power measurements with precision of \( \sim 1.5\% \). On each shot, several WRFs were used: three WRFs measured the spectrum emitted from the source, while one measured the downshifted protons.
traversing the Be plasma. For the protons traversing the Be plasma, the small WRF solid angle corresponds to measuring protons traversing a ~400 μm diameter cross section in the center of the Be plasma.

Shots were taken with both undriven (i.e., cold) and heated (warm) Be targets. Data from each type of shot are shown in Fig. 3. Three WRFs measured the source spectrum; each is fit with a Gaussian to determine the mean energy. The weighted mean of the three measurements represents the initial proton energy, where the primary source of uncertainty is the WRF response and only relative (random or statistical) uncertainties are retained. Systematic calibration uncertainty is correlated between the WRFs since they are calibrated against the same proton source [46]. The D³He proton spectra are Doppler-broadened due to the plasma temperature and upshifted slightly from their birth energy [Eq. (1)] due to radial electric fields around the exploding-pusher implosion [29]. The initial ($E_i$) and final ($E_f$) proton energies are determined from a Gaussian fit; the downshift, or total energy loss, is $\Delta E = E_i - E_f$. The measured quantities for each shot are given in Table I. The data clearly show a larger $\Delta E$ in the plasma case than in the cold (undriven) case, which means that the stopping power increases in the WDM plasma.

For comparison, the energy loss can be obtained from theory by integrating the stopping power over the path-length traversed [47],

$$\Delta E = - \int_0^L \frac{dE}{dx} \, dx,$$

where $dE/dx$ depends on the particle energy and plasma conditions. A comparison of our data to several theories is shown in Fig. 4. The measurement uncertainty is due to the proton spectroscopy uncertainties. In the cold-matter theory calculations the primary uncertainty is the areal density uncertainty and initial energy variations, while the plasma theory uncertainties are dominated by the uncertainty in plasma conditions ($n_e$, $T_e$, and $Z$ where applicable).

First, we compare our cold data to the well-established SRIM [19] and ICRU [48] stopping powers, derived from fits to prior data, which show good agreement given our measurement uncertainty and an expected ~1% uncertainty in the SRIM/ICRU databases (not included in Fig. 4 error bars).

The warm data (shots 72018 and 72024) show a clear enhancement in stopping power (downshift) relative to the cold material. $dE/dx$ is enhanced by the long-range nature of stopping on the plasma (free) electrons relative to the atomic (bound) electrons. There are three common theoretical techniques for treating the partially ionized material in the warm subject plasma: either an ad hoc combination of independent bound- and free-electron components [49,50], or using an inhomogeneous WDM theory such as the average-atom local-density approximation (AA-LDA) model [51,52], or with a Bethe-style effective ionization potential.

In the first case, the partially ionized plasma is approximated by treating free and bound electrons entirely separately; we use Zimmerman’s model [50] for the bound

TABLE I. Data summary: initial ($E_i$) and final ($E_f$) energies, and downshift ($\Delta E$) for each shot.

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<thead>
<tr>
<th>Shot</th>
<th>$E_i$ (MeV)</th>
<th>$E_f$ (MeV)</th>
<th>$\Delta E$ (MeV)</th>
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<tr>
<td>72018 (Warm)</td>
<td>15.019 ± 0.020</td>
<td>12.167 ± 0.039</td>
<td>2.851 ± 0.044</td>
</tr>
<tr>
<td>72024 (Warm)</td>
<td>15.025 ± 0.029</td>
<td>12.043 ± 0.037</td>
<td>2.981 ± 0.047</td>
</tr>
<tr>
<td>72025 (Cold)</td>
<td>15.075 ± 0.018</td>
<td>12.355 ± 0.036</td>
<td>2.720 ± 0.040</td>
</tr>
<tr>
<td>72026 (Cold)</td>
<td>15.004 ± 0.017</td>
<td>12.296 ± 0.040</td>
<td>2.708 ± 0.044</td>
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transferred to a plasma electron during a collision. This can be modeled using a Bethe-style stopping-power equation,

\[ \frac{dE}{dx} = -\frac{4\pi Z^2 e^4}{m_e v_f^2} n_e \ln \left( \frac{2m_e v_f^2}{\bar{I}} \right), \]

(4)

where physically, in the Coulomb logarithm, \(2m_e v_f^2\) represents the maximum energy transfer to an electron (a head-on collision), and \(\bar{I}\) is the “mean ionization potential” representing the minimum energy transfer, which is sensitive to the electron configuration (bound vs free). This is a simple form of the Coulomb logarithm, neglecting quantum diffraction, dynamical screening, and strong collisions [55, 56], but this form can be used to further understand the experimental data. We fit the downshift data using the known target areal density and Eq. (4) to infer \(\bar{I}\). The best-fit values are shown in Fig. 5. The data clearly show a higher \(\bar{I}\) in the cold case than in the warm, which corresponds to the observed increase in stopping power (Fig. 4). The inferred values of \(\bar{I}\) show good agreement with the Andersen-Ziegler value [57] in the cold-matter stopping case. The ideal high-energy-projectile plasma limit, \(\bar{I} = h\omega_{pe}\), represents a lower bound on \(\bar{I}\), shown by the shaded region in Fig. 5. As expected, the WDM case falls between the cold-matter and ideal-plasma limits.

These measurements of the mean ionization potential in a WDM plasma are a strong constraint on modeling of atomic physics and transport phenomena [58], as \(\bar{I}\) can be straightforwardly calculated from any electronic structure model. Theoretical values of \(\bar{I}\) are calculated in the cold (\(\bar{I} = 54.7\) eV) and WDM (\(\bar{I} = 45.7^{+3.1}_{-6.8}\) eV) cases using a Kohn-Sham density-functional theory and shown in Fig. 5. While this theory slightly underpredicts the data and Andersen-Ziegler values in the cold-matter case, it is in good agreement with the data in the WDM case. Additional tests of such electronic structure models or density functional theory predictions [59] are valuable as these models are applicable to a wide range of transport properties in...
dense plasmas, for example, the phenomena of ionization potential depression [60,61], which is the subject of intensive recent study [62,63], is connected to the mean ionization potential as studied in this work. Other WDM collisional transport rates, such as resistivity and thermal conductivity, cannot be directly tested using this technique, but can be separately calculated using models like the AA-LDA in this work.

In conclusion, we report the first high-precision energy-loss measurements for energetic D³He protons traversing an isochorically heated WDM Be plasma, which show an enhanced stopping power relative to cold matter. By using high-energy protons, the measurement is insensitive to temperature and degeneracy effects, and we thus probe the relative importance of the inhomogeneous electron distribution (bound states) on the stopping power. The partially-ionized material may be treated by an ad hoc combination of independent bound and free components, using the AA-LDA model, or by using a Bethe-style mean ionization potential depression [60,61], which is the subject of recent study [62,63], is connected to the mean ionization potential [64].

Accurate theory of charged-particle stopping in dense, degenerate, strongly-coupled and/or partially-ionized plasmas is a fundamental challenge. We anticipate that this technique will be a robust platform for further stopping-power studies, such as probing at various electron degeneracies, plasma couplings, degrees of ionization, and with other materials to further constrain modeling of WDM plasma physics and stopping in partially ionized material. Finally, lower-energy particles such as DD-p, DD-T, and D³He-α will be used to increase the experimental sensitivity to temperature and degeneracy effects.

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[35] The Be used was of 99.8% atomic purity, purchased from Goodfellow, with measured mass density $1.77\pm 0.01$ g/cm$^3$. Each target plug was laser-machined from a single sheet with average thickness 532.1 µm and 1σ variation of 1.2 µm, so that each target had the same total $\rho L$ to within 0.2%.
[38] The absence of electrical charging of the target, or electromagnetic deflections of protons was verified with proton radiography.
[42] X-ray Thomson scattering to diagnose the Be-plasma conditions simultaneously with the stopping-power measurement was unsuccessful, so we use results previously reported for the determination of $T_e$ and $n_e$.
[45] The spectrometers employ a single-particle-counting technique using CR-39, with resulting signal-to-noise ratio $\sim 100$. The $\sim 40$ keV energy uncertainty is dominated by the CR-39 proton response (see Ref. [44]).
[47] For these conditions the path- and linear-distance energy losses are equivalent to better than 0.1%, since large-angle Coulomb scattering is negligible.