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Brief Reports

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Effect of target thickness on the He$^+$ stopping power

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It is shown that the time delay in reaching charge equilibrium introduces a deviation in the linear dependence of the energy loss on the target thickness. An analytical expression is given for the thickness-dependent stopping power of He$^+$ ions passing through solid foils.

Preequilibrium effects in the stopping power of He projectiles traversing thin carbon films is a controversial matter. In a ΔE-vs-Δx plot, positive[1] or negative[2,3] ΔE intercepts have been found. Since, obviously, ΔE must go to zero with Δx, a nonzero intercept reflects a variable stopping-power value through the foil. This enhanced ($\Delta E_0 > 0$) or depressed ($\Delta E_0 < 0$) electronic stopping power at the entrance surface is currently attributed to some preequilibrium effects before the conventional (bulk) stopping value has been reached. Here ΔE_0 is the intercept on the ΔE axis of a linear best fit of experimentally obtained ΔE values versus the foil thickness. The slope of the straight line is the equilibrium (bulk) stopping value. The reported results were obtained in situations where the dwell time of the projectile through the carbon foils was typically much larger than 1 fs. The dwell time τ is defined as the ratio of the foil thickness (Δx) by the projectile velocity (v).

Nonequilibrium effects for projectiles containing one or more electrons (H^0, He$^+$, H$_2{}^+$, H$_3{}^+$, HHe$^+$) traversing very thin solid foils have been reported.[4] They are clearly observed as the different charge states of the emergent beam are selected and their relative populations are measured. When the outgoing charge state is chosen to be the same as the ingoing one, an exponential decrease of the population is observed for very short dwell times. For He$^+$ incident and emergent beams passing through amorphous carbon foils the situation is very well studied and nonequilibrium and equilibrium charge fractions are well determined.[5] The interpretation of these observations is that the emergent beam is a superposition of a transmitted (original) beam that decays exponentially keeping its own electron and a reconstituted beam that traverses the foil in an equilibrated charge state and picks up an electron at the back surface. The slope of the exponentially decaying component is related to the electron-loss cross section (σ_l) and since this slope is the same for all incident energies in the range 600 keV–2.4 MeV it must be concluded that σ_l is inversely proportional to v. For He$^+$ this slope was found[5] to be $\tau_0 = 0.26 \pm 0.02$ fs. For larger values of the dwell time the single exponential decay curve gradually levels off to constant values (B) corresponding to the energy-dependent equlibrium charge fractions. Since at these energies the emergent neutral fraction is negligible, the He$^+$ (F_1) and the He^{2+} (F_2) fractions are, respectively,

$$F_1 = e^{-t} + B(1-e^{-t}) \ , \tag{1a}$$

$$F_2 = 1 - F_1 \ , \tag{1b}$$

where $t = \tau/\tau_0$ is the reduced dwell time.

Recently[6] it was shown that when He$^+$ incident and emergent beams are selected, "anomalous" energy losses in extremely thin carbon foils are observed. The interpretation of the results seems quite natural. The original component of the emerging He$^+$ beam traversing the foil with its original electron is seen by the solid as an alpha particle partially shielded by one electron; in fact, the determined effective charge was $Z_{\text{eff}} = 1.1 \pm 0.3$. On the other hand, the reconstituted component presents the normal effective charge 2ξ, where

$$\xi = [1-\exp(-\alpha v/v_0)]/[1-\exp(-v/v_0)] \ ,$$

with $\alpha = 2^{-2/3}$ and v_0 being the Bohr velocity. Then[6]

$$\Delta E(\text{He}^+) = \left[\frac{(Z_{\text{eff}}/2\xi)^2 + B(e^t - 1)}{1 + B(e^t - 1)} \right] S_\alpha \Delta x \ , \tag{2}$$

where S_α is the value of the stopping power obtained in the equilibrium situation (bulk value).

When the final charge state is not selected it is necessary to average over the F_1 and F_2 fractions. In the considered range of energies the F_2 fraction is by far the most important and the deviations from the "normal" stopping power are strongly attenuated.

For an incident He$^+$ beam and considering all charge states in the emergent beam, $\Delta E = S_\alpha(t)\Delta x$, where the thickness-dependent stopping power will be given by

$$S_\alpha(t) = S_\alpha[1 - \beta\exp(-\Delta x/v\tau_0)] \ , \tag{3}$$

with $\beta = 1 - (Z_{\text{eff}}/2\xi)^2$.

Of course, nonequilibrium effects disappear as $\Delta x \gg v\tau_0$

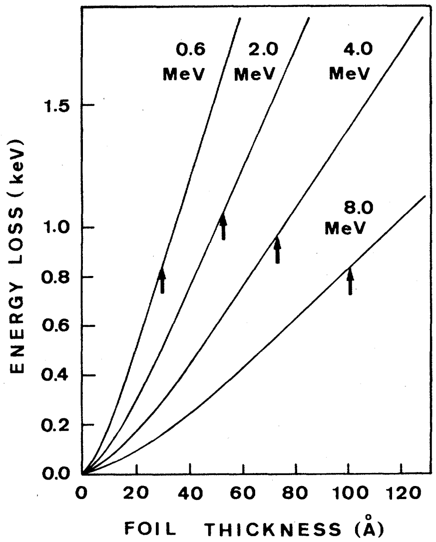

FIG. 1. The nonlinear aspect of the ΔE vs Δx curve due to preequilibrium effects. The projectile is He^+ and the target is amorphous carbon foil. All emergent charge states were considered. The arrows indicate the position of the inflection points.

or, conversely, preequilibrium effects cannot be observed unless the thickness of the target is of the order of or less than $v\tau_0$. This quantity can be defined as an "effective energy-dependent surface thickness." In this framework the preequilibrium stopping effect is attributed to the time delay in reaching charge equilibrium. Other surface effects can be important, such as the surface-plasmon losses that are responsible for an enhanced stopping near the surface.[7] Multiple scattering can also introduce a dependence of dE/dx on foil thickness but this is of no interest here.

In Fig. 1, ΔE vs Δx curves including preequilibrium effects are presented for different values of the projectile energy. They were obtained from Eq. (3) with $\tau_0 = 0.26$ fs. For the sake of simplicity Z_{eff} was taken equal to 1 and S_α is from Ref. 8. The carbon density has been taken to be 1.65 g/cm^3.

The behavior of these curves deserves some comments. Their asymptotes are straight lines with slope $S_\alpha(v)$ and passing through the origin; it is not surprising that no conclusive effects are observed when relatively thick targets are employed. As $\Delta x \rightarrow 0$ the tangents to the curves are $\beta(v)S_\alpha(v)$. Then the value of $(\Delta E)_0$ depends on the range of thickness which was chosen to measure the ΔE intercept. The t dependence of this intercept is given by $-S_\alpha \tau_0 v \beta t^2 \exp(-t)$. The maximum absolute value of ΔE_0 is then $(4/e^2)S_\alpha \tau_0 v \beta$, a value which is approximately stationary around 2 MeV and equal to ~ 200 eV. This occurs at the inflection point $t = 2$. At this point the energy loss differs by about 10% from that calculated with the asymptotic value of S_α. The difference between the asymptotic and the exact values of the energy loss reaches its maximum at $t = 1$ and is given by $S_\alpha \tau_0 v \beta / e$ which amounts to ~ 150 eV in the energy range considered. Then the problem is quite difficult from the experimental point of view, chiefly if a selection of the emergent ions which have not changed charge is not made. If the incident energy is below 1–2 MeV, extremely thin carbon foils must be used and foil-thickness calibration is a very hard task. For higher energies, 6 or 8 MeV, for example, foils with 1 or 2 μg/cm^2 are adequate but the relative energy losses $\Delta E/E$ are too small to be accurately measured.

The value of $\Delta x \sim 9$ Å found by Lennard *et al.*[3] for the preequilibrium region of stopping near the surface of carbon targets, for 620-keV He ions, is in fair agreement with these predictions. The generalization of these results to other incident ions depends on the knowledge of the characteristic electron loss and capture cross sections inside the solid target.

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