Progress in Understanding Low-Velocity Electronic Stopping

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At the latest HRDP workshop in Uppsala we reported that extraction of electronic stopping cross sections from transmission experiments in the velocity range below the Bragg peak requires knowledge of impact-parameter dependent energy loss [1]. Distinct differences were pointed out [2], in particular for heavy ions in gas targets, between reported stopping cross sections and revised values based on impact-parameter-dependent energy losses extracted from the PASS stopping code [3–5].

Since then we turned our efforts toward stopping of protons, stimulated by a wellknown discrepancy between experimental data found in reflection and transmission experiments, as exemplified for protons in silver in refs. [6] and [7], respectively.

As a first step we carried out Monte Carlo simulations of reflected-ion spectra [8], following the procedure applied in studies like ref. [6]. Reflected-ion spectra found from characterizing slowing-down by PASS stopping cross sections reproduced results found in previous simulations [6], whereas significant differences were found when impact-parameter-dependent energy losses were applied.

As a next step we explored the significance of coupling between nuclear and electronic processes. Standard textbook knowledge treats electronic and nuclear stopping as mutually independent. While this is well established at moderate and high beam energies, problems occur in the velocity range below the Bragg peak, which become serious in the energy range below 10 keV/u.

While there must be coupling terms of higher order between electronic and nuclear *stopping* [9], a more serious effect is the influence of *nuclear scattering* on *electronic stopping*.

In standard theory, the elementary excitation event is described as the interaction of an ion in uniform motion passing a nucleus at rest, while all dynamics affect the electrons of the target and/or projectile. Deviations from this picture become exceedingly important with decreasing beam energy, where the change in relative velocity during the interaction cannot be neglected. A simple estimate of this effect can be obtained by replacing the impact parameter by the distance of closest approach. We denote the resulting change in predicted stopping cross section as the RM correction.

Although this simple model is inherent in the Firsov energy loss formula [10], it has consistently been ignored in numerous applications of Firsov's formula in stopping theory. We emphasize that this correction is important in theoretical predictions of both transmission and reflection measurements, and it is missing in most current descriptions of electronic stopping.

We have explored the RM correction applying the PASS code. Here follows a list of results:

- RM-corrected PASS stopping cross sections agree well with data reported from reflection measurements for protons in several materials such as Ni, Cu, Ag, Au [11].
- Monte Carlo simulations including the RM correction lead to good agreement with measured reflection spectra [11].
- RM-corrected stopping cross sections show a conductor-insulator difference, since electronic energy loss in a free electron gas is not coupled directly to an impact parameter [11].
- The RM correction suggests the existence of an isotope effect in electronic stopping at low velocity [11]. Positive experimental evidence has been found [12], but a systematic search would be desirable.
- For transmission experiments, the reduction of the extracted stopping cross section due to the finite width of the detected beam [1] competes with the RM correction. The relative significance of the two corrections is found to depend on the projectile as well as the target.
- Ion-target reciprocity [13] cannot be expected to remain valid in the presence of a sizable RM correction because of different symmetry properties of electronic stopping and nuclear scattering.

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