On the phase effect in electronic stopping

P Bauer†, F Kastner†, A Arnaud†, S Salin‡, V H Ponce† and P M Echenique‡
† Institut für Experimentalphysik, Johannes-Kepler-Universität Linz, A-4040 Linz, Austria
‡ Departamento de Física de Materiales, Universidad del País Vasco, Apartado 1072, San Sebastián, Spain
§ Laboratoire des Collisions Atomiques, Université de Bordeaux I, 351 Cours de la Libération, 33405 Talence Cédex, France
‖ Centro Atómico Bariloche and Instituto Balseiro, 8400 Bariloche, Argentina

Abstract. We discuss the physical mechanisms contributing to the phase effect in electronic stopping.

The phase effect in electronic stopping of ions is the influence of the state of aggregation of the target on the stopping cross section (SCS), $\epsilon$, (Thwaites (1992) and references therein). The aim of this contribution is to summarize the processes relevant for its understanding. We discuss three different regimes, depending on projectile velocity, $v$, and its atomic number, $Z_1$: fast ($v \gg v_0 = c/137$) heavy ($Z_1 \geq 18$) ions, fast light ($Z_1 \leq 2$) ions and slow ($v \approx v_0$) light ions. The general expression for $\epsilon$ is (Allison et al 1962):

$$\epsilon = \sum_i \phi_i \epsilon_i + \sum_{i,j,\alpha,\beta} \phi_i \sigma_{ij}(\alpha, \beta) W_{ij}(\alpha, \beta).$$

(1)

The first sum describes the target inelastic processes (excitation and ionization), and the second one describes projectile inelastic processes (capture by $H^+$ and excitation and ionization of $H^0$). $\phi_i$ is the probability to find a projectile in charge state $i$, $\epsilon_i$ the SCS for fixed $i$, and $\sigma_{ij}(\alpha, \beta)$ and $W_{ij}(\alpha, \beta)$ the cross section and the corresponding energy loss when the projectile goes from charge fraction $i$ to $j$, while the electrons of both projectile and target evolve from state $\alpha$ to $\beta$.

Geissel et al (1982) studied the energy loss of fast heavy ions in metals and noble gases and found $\epsilon_{\text{gas}} < \epsilon_{\text{solid}}$ even in cases where for the mean ionization potentials $I_{\text{gas}} < I_{\text{solid}}$ holds (corresponding to $\epsilon_{\text{gas}} > \epsilon_{\text{solid}}$ for bare ions). They interpreted their results in terms of a higher charge state of the ions in the solid (Bohr and Lindhard 1954), neglecting the contribution of charge changing collisions to $\epsilon$. Evidently, for fast heavy ions it is the projectile state effect which dominates.

The physical processes become simpler if fast light ions are considered as projectiles, being point charges whose interaction with target electrons is well described by Bethe theory plus correction terms (Andersen 1985). For $v \gg v_0$, a number of subshells will contribute to the stopping process. Therefore the phase effect will be small and entirely due to changes in the target valence states.

At low velocities, even for light projectiles the relevant processes become more complex, but now the interaction is weak enough to permit a perturbation treatment (Bauer et al 1992). For metals, a large effect has been expected (Oddershede and Sabin 1984, Sabin and Oddershede 1989): the interaction of a proton with an electron gas is much less effective than that with an atom (see figure 1(a)), due to the dynamic screening by the electron
gas (Echenique et al. 1986, 1990). Except for the measurements of the effective charge by Meckbach and Allison (1963), there were no phase effect measurements in a metal until recently (Bauer et al. 1992) where proton stopping in gaseous and metallic zinc in the range 20–700 keV u−1 was studied: a phase effect was found which increases with decreasing energy (see figure 1(a)), up to εgas/εsolid ≈ 1.6, well below the prediction. This may be explained as follows: below 100 keV u−1, the neutralization of the protons in the gas phase becomes important, and for H0 the long range interaction is reduced due to screening: at 50 keV u−1, for the 4s2 electrons in the Zn gas, ε+/ε0 ≈ 6 holds (Arnau et al. 1992). Furthermore, at this velocity, the contribution of the projectile inelastic processes is large. In figure 1(b), we compare the measured phase effect of hydrogen projectiles in zinc to perturbation calculations of target and projectile inelastic contributions (see equation (1)). Detailed calculations will be presented elsewhere (Arnau et al. 1992). Evidently, for dressed projectiles the target inelastic processes contributing to the phase effect are drastically reduced as compared to bare ions, but the projectile inelastic processes contribute considerably to the gas–solid difference in electronic stopping.

![Figure 1](image)

**Figure 1.** (a) ε+ and ε0 due to 4s2 contribution in gas and solid targets. (b) Relative phase effect δε = (εgas−εsolid)/εsolid, showing the partial contributions of target inelastic processes (projectile elastic), and projectile inelastic (i.e. projectile excitation, capture and loss, together with target elastic or inelastic transitions).

From the theoretical point of view, a simple system with a minimum of processes involved and a large phase effect would be alkali targets interacting with slow antiprotons.

**References**


