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Velocity dependence of heavy-ion stopping below the maximum

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ABSTRACT

In the slowing-down of heavy ions in materials, the standard description by Lindhard and Scharff assumes the electronic stopping cross section to be proportional to the projectile speed v up to close to a stopping maximum, which is related to the Thomas–Fermi speed v_{TF}. It is well known that strict proportionality with v is rarely observed, but little is known about the systematics of observed deviations. In this study we try to identify factors that determine positive or negative curvature of stopping cross sections on the basis of experimental data and of binary stopping theory. We estimate the influence of shell structure of the target and of the equilibrium charge of the ion and comment the role of dynamic screening.

1. Introduction

In the characterization of the slowing down of ions in matter it is customary to talk about the velocity-proportional regime, when the projectile speed v lies well below the Thomas–Fermi speed $v_{TF} = Z_1^{2/3} v_0$, where Z_1 is the atomic number of the projectile and v_0 the Bohr speed [1]. This classification, proposed by Lindhard and Scharff [2], is one of the corner stones in the theory of ion implantation [3] and ion-beam-induced radiation effects [4].

The assertion of approximately velocity-proportional *electronic stopping* is supported by evidence from range measurements, although deviations from strict proportionality are well known: Fastrup et al. [5] parameterized measured electronic stopping cross sections in the velocity regime around v_0 by a power law, $S \propto E^p$, where E is the ion energy and p a coefficient dependent on the ion-target combination that may differ noticeably from 0.5. Moak and Brown [6,7] found stopping cross sections for heavy ions linear in v at velocities well above v_0, but when extrapolated to lower speeds, those straight lines pointed at an apparent nonvanishing threshold velocity. Empirical tabulations of stopping cross sections [8,9] show significant deviations from velocity-proportional stopping.

The assumption of velocity-proportional electronic stopping draws support from numerous theoretical studies initiated by Fermi and Teller [10], Lindhard [11,12] and Firsov [13,14]. Strictly speaking, these theoretical schemes imply ion speeds significantly below the lowest electron speed in the target material or, roughly spoken, $v \ll v_0$. General theoretical arguments suggesting to extend this regime up to near the Thomas–Fermi speed have not been proposed to our knowledge. This is remarkable in view of the fact that the ratio v_{TF}/v_0 can be as high as ~ 20 for heavy ions.

Recently, Lifschitz and Arista [15] asserted the observation of an apparent velocity threshold to be a consequence of dynamical screening and increasing equilibrium charge. In an attempt to theoretically reproduce experimental results by Brown and Moak [7], an apparent threshold was indeed found when stopping cross sections calculated for higher energies were extrapolated to lower energies. Calculations were performed for Br, I and U ions in C. While this work is interesting, it raises several questions:

- Is the behavior observed by Brown and Moak typical for heavy-ion stopping?
- Why do the calculations by Lifschitz and Arista overestimate measured stopping cross sections, even though not all contributions to stopping are taken into account in the calculations?
- What is the role of the target shells?

The matter is important in our opinion both from a practical and a fundamental point of view. Measured stopping cross sections in the low-energy range are only available for a small fraction of all ion-target combinations (Z_1, Z_2), and the scatter between different data sets is significant and occasionally dramatic. Tabulations are based on interpolation [8,9], for which the use of guiding principles such as reciprocity [16,17] is desirable.

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In the present work we first try to extract general features from available experimental data. Instead of discussing apparent thresholds – which, to our knowledge, never have been asserted to represent real thresholds – we shall talk about deviations from velocity-proportional stopping in terms of positive or negative curvature. Lifschitz and Arista found that in a linear–linear plot versus speed, stopping cross sections follow an S-shaped curve starting with a linear portion at the low-v end, followed up by an interval with positive curvature, a quasilinear regime and, finally, a bend-over to negative curvature towards the stopping peak.

Following up on this we perform calculations with our PASS code that implements binary stopping theory [18] to study primarily the effects of target shells and ion charge on the curvature of the stopping cross section.

2. Experimental findings

Fig. 1 shows experimental data by Brown and Moak [7] – which formed the basis for the analysis by Lifschitz and Arista [15] – plotted together with other data for Br, I and U ions penetrating through C. The case of Br (upper graph) shows a rather consistent behavior of four data sets. The low-energy data by Hvelplund [19] are consistent with velocity proportionality, the bend-over toward a higher slope is covered by Zhang et al. [20]. Those data agree with Brown and Moak in the overlap regime. The latter data bend over toward negative curvature, where they are consistent with Anthony [21].

For iodine ions the scatter between data sets is larger than in Br–C at all energies. Nevertheless, despite the absence of low-v data it is clear that a behavior similar to Br–C must be expected. Uranium ions show a similar behavior, although the change in slope at $v/v_{TF} \simeq 0.2$ appears more abrupt than what has been found in the two former cases.

Fig. 2 shows two combinations with Al as a target. For I–Al (upper graph) different conclusions can be drawn, dependent on which data are trusted: The data of Zhang et al. [20] together with those of Anthony and Lanford [21] resemble the Br–C case in Fig. 1. Conversely, the data of Bridwell et al. [22] indicate a linear velocity dependence up to the turn-over to negative curvature. For Au–Al (lower graph), existing data seem too scarce to allow conclusions without reference to theory or scaling relations.

Fig. 3 shows ion-target combinations where no evidence is seen for a positive curvature. For H–C, actually a negative curvature is observed. For Cl–C and Ar–C a straight-line dependence is found up to $v/v_{TF} \simeq 0.6$, although there is considerable scatter in the case of Ar–C. This upper limit fits into the trend seen in Fig. 1. For Kr–C, a linear dependence can be extracted up to $v/v_{TF} \sim 0.4$, although data are missing in the interval between $v/v_{TF} \simeq 0.1$ and 0.3.

As a result of this preliminary survey we may conclude that there are significant deviations from the behavior of the data by Brown and Moak, both in competing data on the same ion-target combinations and on other ion-target combinations. In view of incomplete coverage with data, theory is needed to arrive at more definitive conclusions.

3. Nuclear stopping

It appears essential at this point to discuss the role of nuclear stopping. Fig. 4 shows nuclear and electronic stopping cross sections for I–Al according to Refs. [3,8]. It is seen that the contribution of nuclear stopping to the total stopping force is almost negligible in the quasi-linear velocity range above $v/v_{TF} \sim 0.15$, whereas this contribution is dominating below $v/v_{TF} < 0.05$.

In a previous study [44] it was pointed out that corrections for nuclear stopping were performed in different ways by different authors and, with very few exceptions, insufficiently documented. There are at least two major uncertainties:

- Nuclear energy loss is accompanied by angular deflection. For a narrow detection angle the effective nuclear stopping cross section will, therefore, be smaller than the full nuclear stopping cross section [5].
- Interatomic potentials and, hence, nuclear stopping cross sections involving very heavy ions, are poorly known.

For heavy ions, when the ion mass exceeds the target mass, angular deflection is a weak effect, so that the correction for nuclear stopping will come close to the full nuclear stopping cross section. As far as the contributions in Figs. 1–3 are concerned, corrections for nuclear stopping have been applied by the authors

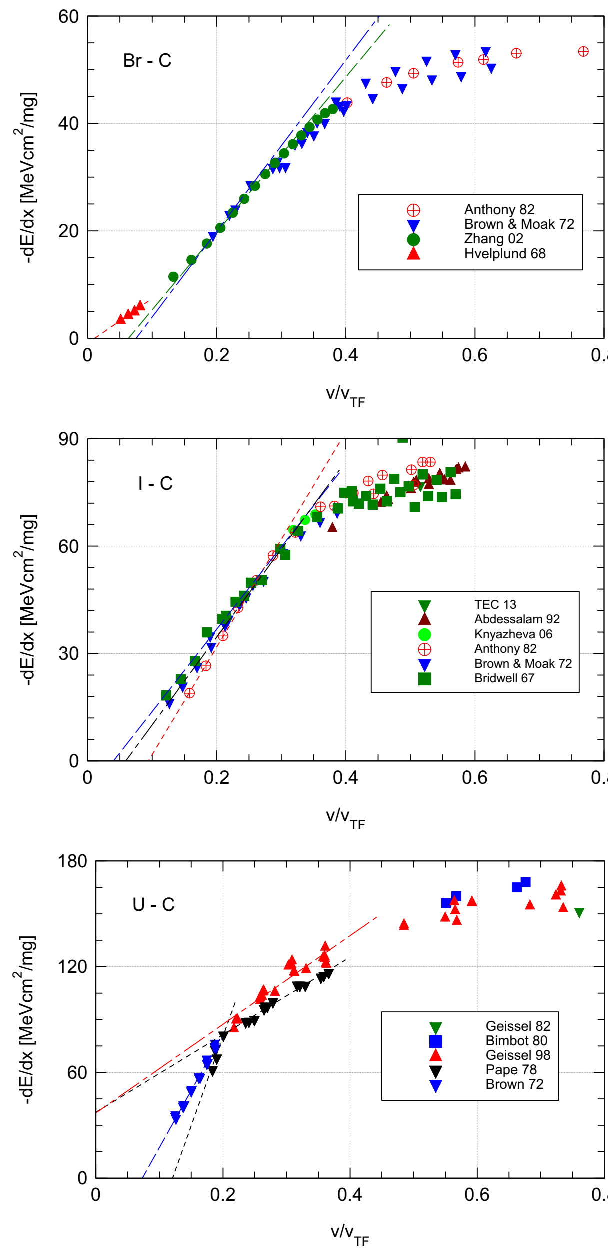

Fig. 1. Measured stopping forces of C on Br, I and U ions, compiled by Paul [9]. Original data from Refs. [7,19–29]. Dotted and stippled straight lines represent extrapolations from experimental data. Abscissa variable is the Thomas–Fermi speed $v_{TF} = Z_1^{2/3} v_0$.