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Stopping of high-Z ions at intermediate velocities

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Abstract

The stopping of heavy ions at intermediate velocities is influenced by projectile screening, shell corrections, Barkas–Andersen effect and charge exchange. These effects are accounted for in the binary theory of stopping and implemented in the PASS code. Previous applications of this scheme have focused on ions up to argon. The present work is a first attempt to apply the PASS code to very heavy projectiles. It is known that as the ion/target atomic-number ratio increases, the stopping force becomes increasingly sensitive to the ionic charge state. Therefore, care has been taken to incorporate realistic mean charges based on experimental data. Calculated stopping cross sections are found to agree well with experiment at energies above ~2 MeV/u, while a systematic overestimate of up to 20% is found at lower projectile speeds. Possible causes are studied. Charge-state averaging is shown to have a significant effect at low speed.

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1. Introduction

Considerable progress has been made over the past decade in the theoretical understanding and quantitative prediction of the stopping of heavy ions [1,2]. Several schemes are available to estimate stopping forces over a very wide range of beam velocities [3–6] based on a variety of physical models for electronic excitation.

Extensive comparisons between experimental data, empirical tabulations and theoretical calculations have been performed recently [7] which led to the conclusion that the agreement with experiment of calculations on the basis of the binary theory of stopping [3,8] was comparable with that of existing empirical tabulations. This statement, however, was limited to ions with atomic numbers $Z_1 \leqslant 18$. Comparisons for heavier ions have been performed for some theoretical schemes, in particular by Lifschitz and Arista [9] for a limited set of experimental data.

The present study represents a comparison of predictions of binary stopping theory with experimental data for ions in the high-Z_1 regime of the periodic table and in the critical energy regime around the stopping maximum. Theoretical considerations [10] indicate increased sensitivity with increasing Z_1 of the stopping force to the ionic charge state of the projectile. Therefore, ion–target combinations have been chosen for the present comparison where data are available covering both stopping forces and equilibrium charge states. At the same time, the simple Thomas–Fermi *ansatz* for the mean equilibrium charge state applied in [3,7,8],

$$q_{\mathrm{mean}} = Z_1\left(1 - \mathrm{e}^{-v/Z_1^{2/3} v_0}\right), \quad \text{Thomas–Fermi} \qquad (1)$$

has been replaced by the expression [3]

$$q_{\mathrm{mean}} = Z_1\left(1 - \mathrm{e}^{-Av/Z_1^{0.45} v_0}\right)^C, \quad \text{modified Thomas–Fermi} \qquad (2)$$

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which allows for dimensionless constants A and C that can be adapted to the measured equilibrium charge state for each individual system.

In terms of equilibrium charge fractions P_J, the mean projectile charge q_{mean} can be written as

$$q_{\mathrm{mean}} = \sum_J P_J q_J. \tag{3}$$

If $S(q_J)$ is the stopping cross section at charge state q_J, we have in general

$$S_{\mathrm{mean}} = \sum_J P_J S(q_J) \neq S(q_{\mathrm{mean}}) \tag{4}$$

apart from a contribution from charge-changing collisions. The standard output of the PASS code is $S(q_{\mathrm{mean}})$ plus, optionally, a contribution from charge exchange. In contrast to Grande and Schiwietz [5] who found a significant difference between S_{mean} and $S(q_{\mathrm{mean}})$, this difference was found insignificant in the binary theory for the cases studied [3]. In the present case of very heavy ions, however, it appears appropriate to look into this aspect again.

2. Xe, Au and Pb ions in carbon

For the purpose in mind we have tried to find ion–target combinations covered reasonably well with experimental stopping data in the critical region around the maximum and, at the same time, experimental data ensuring a reliable estimate of the mean charge state. The latter requirement narrowed in the choice of available target materials to carbon. Coverage with stopping data appeared best for Xe, Au, Pb and U ions amongst the heaviest ions. Leaving out intermediate atomic numbers $19 < Z_1 < 53$ for later study we focused on the four systems Xe–C, Au–C, Pb–C and U–C.

Fig. 1 shows charge states and stopping forces for Xe–C. There is good agreement between measured charge states and the interpolation formula of [11] as well as Eq. (2), whereas Eq. (1) predicts significantly lower values. It is well-known that material and density dependence of the equilibrium charge state get more pronounced for heavier ions [7].

Good agreement is found between measured and calculated stopping forces for the modified Thomas–Fermi charge state above 2 MeV. This includes the stopping maximum where the difference between the charge states (1) and (2) is significant. At lower velocities, experimental data seem to fall midways in between the calculations for the two charge states. The upper graph indicates that this discrepancy (10–20%) is unlikely to be caused by an error in the underlying charge state. On the other hand, there is some uncertainty about experimental stopping forces around 2 MeV. The apparent step-like dependence on ion energy is hardly real.

Figs. 2 and 3 show similar results for Au–C and Pb–C. The coverage with experimental stopping data is less comprehensive here, especially for gold ions. For Pb ions, similar conclusions emerge as for Xe. Note the rather implausible interpolation of the SRIM tabulation.

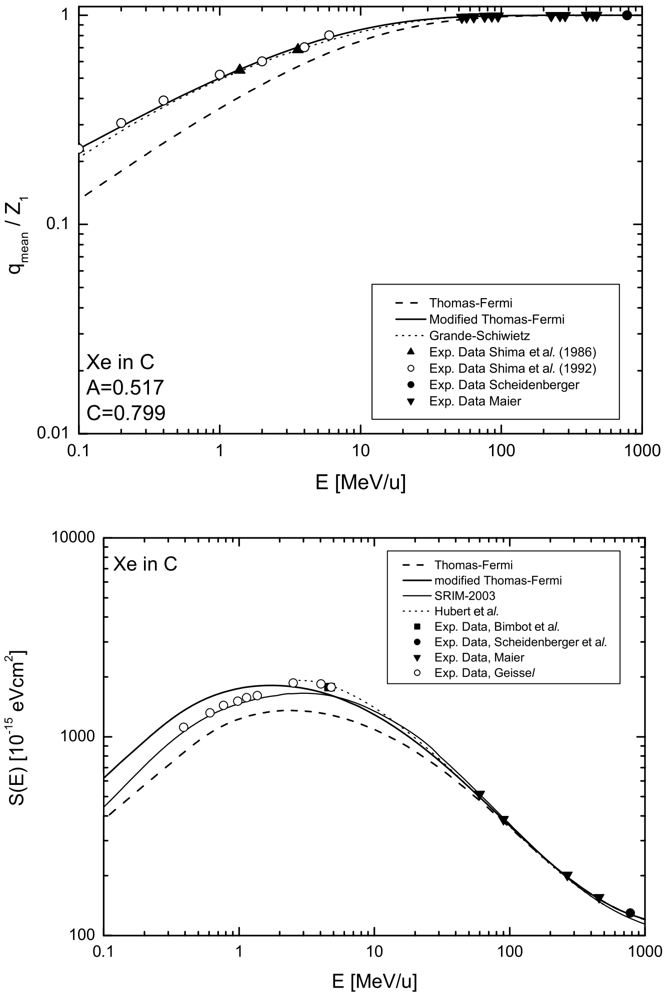

Fig. 1. Mean equilibrium charge (top) and stopping force (bottom) for xenon in carbon. Thomas–Fermi: mean charge state (1). Modified Thomas–Fermi: mean charge state (2). Schiwietz–Grande: mean charge state according to [11]. Measured charge states from [12–14]. Data labelled 'Scheidenberger' are previously unpublished [19]. Tabulated stopping forces from [15,16]. Experimental stopping data from the compilation [17] as well as [14]. Data labelled 'Geissel' are re-evaluated from previous experiments [18]. The difference to previously published data is $\lesssim 5\%$.

3. U ions in carbon

Fig. 4 shows results for uranium in carbon very similar to those for xenon ions. However, the apparent step between stopping data below and above 2 MeV/u has almost disappeared. Very good agreement with calculations is found above 2 MeV/u, while below 2 MeV/u, the theoretical estimate lies ~20% above experiment.

We note that a difference of the same sign and similar magnitude was found for 1 MeV/u Au and Pb ions in C by Lifschitz and Arista [9] who did not include uranium ions in their comparison.