First-step benchmark of collision cross-sections for heavy ions using charge-state evolutions after target penetration

Alex M Imai* [1], **Viatcheslav P Shevelko**†

* Department of Nuclear Engineering, Kyoto University, Nishikyo, Kyoto 615-8540, Japan,
† P.N. Lebedev Physical Institute, 53 Leninskiy Prospekt, Moscow, Russia.

Synopsis A new method for assessment and evaluation of sets of calculated collision cross-sections using very accurate experimental data for charge-state evolutions after target penetration is presented with some examples.

Both accuracy and completeness are strongly required when applying atomic collision data to the related fields like astrophysics, plasma physics, and so on. Although the number of studies devoted to collision cross-section measurements has been notably decreased recently, immense improvements in computer power have brought new developments in theoretical procedures, which have synergistically realized calculations for more complicated collision systems in more details, and a number of calculated collision cross-sections have become available. As for the accuracy of these theoretical cross-sections, there still is no established technique to evaluate those diverse cross-sections other than comparing them with measured cross-sections for limited collision systems, in spite of continuous attempts to such uncertainty assessments [1]. It is also true that available measured cross-sections include not-a-small error especially for gas-target collisions.

We propose to make use of measured charge-state evolutions after foil penetration, which has very high accuracy of 0.3%, as a first order benchmark of the validity of a set of theoretical cross-sections. In penetrating through targets, ions change their charge-states until they establish the equilibrium charge-state distribution, in which increases and decreases in population of each charge-state balance each other and the population seems to remain unchanged. Before establishing the charge equilibrium, fractions for each *nl*-substate in all possible charge-states dynamically evolve according to a set of rate-equations

$$\frac{dF_i(x)}{dx} = \sum_j F_j(x)\sigma_{ji} - \sum_j F_i(x)\sigma_{ij}, \quad \sum_i F_i(x) = 1,$$

where $F_i(x)$ denotes the fraction of specific *i*-substate at the penetration depth x, and σ_{ij} denotes collision cross-sections or transition rates from substate *i* to *j*, i.e., those for excitation, collisional and radiative de-excitations, ionization, and partial charge transfer processes.

As an example, four sets of calculated cross-sections for 2.0 MeV/u C^{q+} (q = 2−6) and S^{q+} (q = 6−16) ions through C-foil targets were used to derive the charge-state evolutions and the reproducibility of the measured evolutions [2] were checked for non-equilibrium evolutions and for equilibrium charge-state distributions by keeping scores. The ETACHA code [3] solves these *nl*-substate oriented rate equations, through calculating the set of collision cross-sections inside the code, which were rather satisfactory. Better reproducibility was achieved for a set of calculated cross-sections which was obtained by taking the density effect into account but only *n*-state oriented transfers were accounted for.

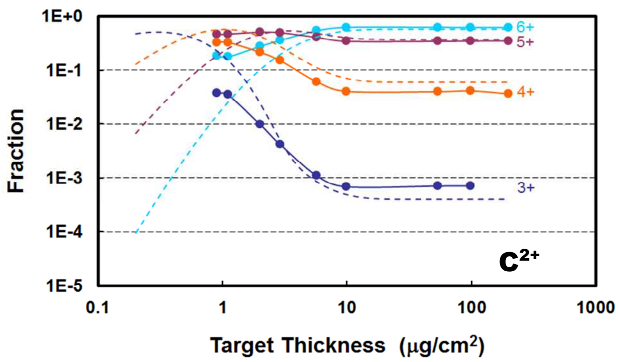

Figure 1. Full curves: Charge-state evolution for 2.0 MeV/u C^{2+} projectile ions through C-foil targets. Dashed curves: Calculated evolutions that best reproduced the measured evolutions.

References

[1] H.-K. Chung *et al.* 2016 *J. Phys.D* **49** 363002
[2] M. Imai *et al.* 2015 *Nucl. Instr. Methods B* **354** 172, *ibid.* **267** 2675, *ibid.* **256** 11, *ibid.* **230** 63
[3] E. Lamour *et al.* 2015 *Phys. Rev. A* **92** 042703

[1] E-mail: imai@nucleng.kyoto-u.ac.jp