Projectile Ionization in Collisions of U^{28+} with Gases

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The n-CTMC method has been used to calculate the stripping cross sections for collisions of U^{28+} with several gases. The method numerically solves the classical Hamiltonian for an n-body collision [1]. The initial electronic state of the projectile ion and target atom are based on the experimental binding energies of the electrons and their radial expectation values. Both the electron-electron and electron-nucleus interactions are included between centers.

In these calculations 36 electrons were used in the description of the U^{28+} ion which consisted of the $4s^24p^64d^{10}4f^{14}5s^25p^2$ outer shell electrons. On the nitrogen target all 7 electrons were included, while for Ar we found only the L- and M-shells were active for a total of 16 electrons. Thus, at the maximum, 54 bodies were carried in the n-CTMC calculations, resulting in the solution of the time evolution of 324 first order differential equations for each trajectory.

As a benchmark, a comparison between calculated and experimental electron loss cross sections [1] for $Xe^{18+} + N_2$ collisions are displayed in Fig. 1. There is reasonable agreement in magnitude and energy dependence with the largest discrepancy being approximately 25% at the lowest energy of 2 MeV/u. Both experiment and theory show an overall energy dependence of approximately $E^{-0.5}$ with the slope increasing slightly above 10 MeV/u in the calculated values.

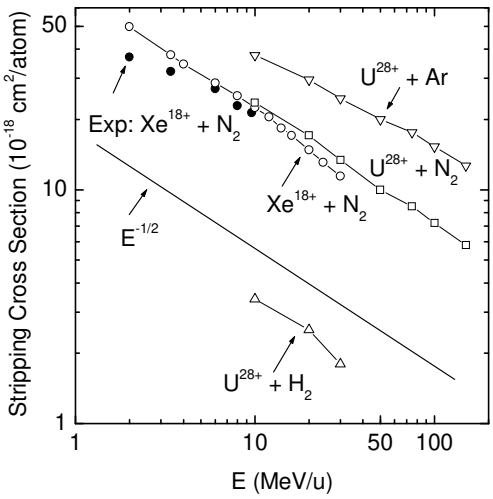

Fig. 1: Total cross sections for electron removal from the projectile by various gases: solid circles are experimental data [1] for $Xe^{18+} + N_2$, the n-CTMC calculations are given by open symbols with circles – $Xe^{18+} + N_2$, triangles – $U^{28+} + H_2$, squares – $U^{28+} + N_2$, and inverted triangles – U^{28+} + Ar.

Presented on the same graph are the calculated stripping cross sections for U^{28+} on H_2, N_2, and Ar. The $U^{28+} + N_2$ cross sections are almost identical to those for $Xe^{18+} + N_2$. Note that the U^{28+} cross sections have an energy dependence of approximately $E^{-0.5}$. This becomes important in the prediction of ion beam lifetimes in an accelerator structure.

The calculated U^{28+} cross sections were used to predict ion loss due to charge changing in the GSI-Darmstadt SIS beam line. Very recently, measurements were made of the ion beam lifetime in the present SIS ring for energies from 10 to 150 MeV/u [2]. The composition and the concentration of residual gas in the ring was determined at a background pressure of $7.7x10^{-11}$ mbar. The results deviated significantly from lifetimes deduced from stripping cross sections determined by one-electron Born calculations [3,4]. At the highest energies, the difference was on the order of a factor of three, Fig. 2.

The n-CTMC cross sections given in Fig. 1 were used to estimate the U^{28+} beam lifetime for the parameters given in the SIS measurements. The results are in reasonable accord with the data in both shape and magnitude, Fig. 2. The $E^{-0.5}$ dependence on the stripping cross sections of Fig. 1 yield an almost constant lifetime for all energies. The error bars on the calculations reflect the uncertainty in the H_2 target calculations whose contribution to the lifetime is calculated to be approximately 30% at the energies where the H_2 cross sections could be made. There is a slight increase in the calculated lifetime at the highest energy due to the relativistic correction to the collision velocity.

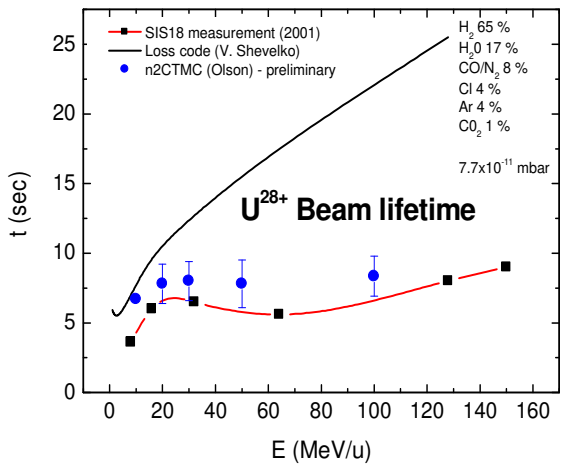

Fig. 2: U^{28+} beam lifetime as a function of energy at $7.7x10^{-11}$ mbar. The solid line is from the work of Shevelko et al [3,4], the solid circles are from the cross sections of Fig. 1 that were calculated by the n-CTMC method, and the solid squares are the measurements from GSI-Darmstadt [2].

[1] Olson, R. E., et al., *J. Phys B.* **35**, 1893 (2002).
[2] Krämer A., et al., *Proc. of EPAC2002*, Paris (2002).