CHARGE-STATE DEPENDENCE OF ENERGY LOSS IN RANDOM SOLIDS

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It has previously been shown that under the conditions of ion channeling, where ion charges (q) are maintained ("frozen") throughout their passage, the energy loss for bare ions is strictly proportional to q^2. [3,4] For channeled ions bearing one or two electrons at ~2 MeV/u, the effective charge for energy loss, q_{eff}, is reduced by about 0.9 units per electron (imperfect screening).[3] A number of studies on the effect of charge state on stopping power and effective screening by bound electrons in random solids have been carried out. These have been limited to systems in which only a few charge-changing collisions occur[5] and to cases where only two charge states are involved.[6] In these cases, the data may be adequately treated on the basis of a two-state model. Recently, Sigmund has developed expressions for the mean energy loss penetrating solids specified into entrance and exit charge states.[7] A program now exists called SRIM[8] which includes the TRIM and STOP codes. This is a useful code using principally fittings, but there is no full *ab-initio* theory used.[9] In this work, the pertinant atomic parameters have been linked directly to experimental data. A more complex system has been chosen and energy loss has been measured as a function of charge state and impact energy at a target thickness which gives very close to charge-state equilibrium. These measurements were performed at the ORNL EN Tandem accelerator, employing the Elbek magnetic spectrograph. An array of computed atomic collision cross sections (i.e., for excitation, ionization, and charge transfer) and charge-state - dependent stopping powers were then taken and, using a classical transport simulation, integrated energy losses as a function of input charge state were derived and the equilibrium charge distributions were calculated.

By simulating collisions of ions with foils, we can test and extend our understanding of the processes leading to the observed experimental results. For example, such quantities as ion charge state and stopping power as a function of foil thickness can be examined. Such simulations also represent a significant challenge in that a wide range of atomic collision cross sections must be computed in order to treat the most important reactions which impinging ions suffer in their passage through the foil. These reactions determine the time-dependent charge state of the ion, and therefore its accumulated energy loss.

In particular, the collision of an ion with a solid can be simulated by utilizing a classical transport approach. First, we have calculated the reaction cross sections, using the classical trajectory Monte Carlo (CTMC) method[10] as applied to binary ion-atomic collisions. The choice of this method is motivated by the fact that a wide range of reactions must be treated (i.e., state-selective charge transfer from both target K and L shells, and state-selective projectile stripping for 10-, 16-, and 25-MeV O^{4-8+} + C collisions). Therefore, the theoretical method must be applicable to treating this many systems and channels quickly and reliably. The validity of the CTMC method is well established for this range of energies and collision partners; specifically, collisions involving principally one-electron processes such that q/v ~ 1, v being the collision velocity.

The energy loss as a function of ionic charge state for various oxygen ions impinging on the thin carbon foil for three incident energies was measured. The

departure from a constant value of the stopping power reflects the fact that the foil thickness is comparable to the equilibration distances. Our calculations show that equilibration is reached after a few mg/cm^2 and therefore the rise for high charge states is due to differences in energy loss accumulated over the path length prior to equilibration. These results can be contrasted to previous experiments at lower energies which have shown that charge-state equilibration may be reached within one or very few atomic layers.[11] The satisfactory agreement between the simulation and experiment indicates that the large quantity of atomic collision cross sections and the basic assumptions of scaled proton – carbon stopping powers are reasonable models for this case.

The agreement between theory and experiment for O^{5+} relies on the enhancement of the stopping power due to incomplete screening by bound electrons. We have also performed measurements for impinging 30-MeV Cl ions, and our calculations indicate that the incomplete atomic screening effect accounts for the significant enhancement of Cl ions over O ions of equal ionic charge. Due to the large number of electrons in Cl, we find that, for example, the experimental energy loss of Cl^{8+} is a factor of two larger than that for O^{8+}.

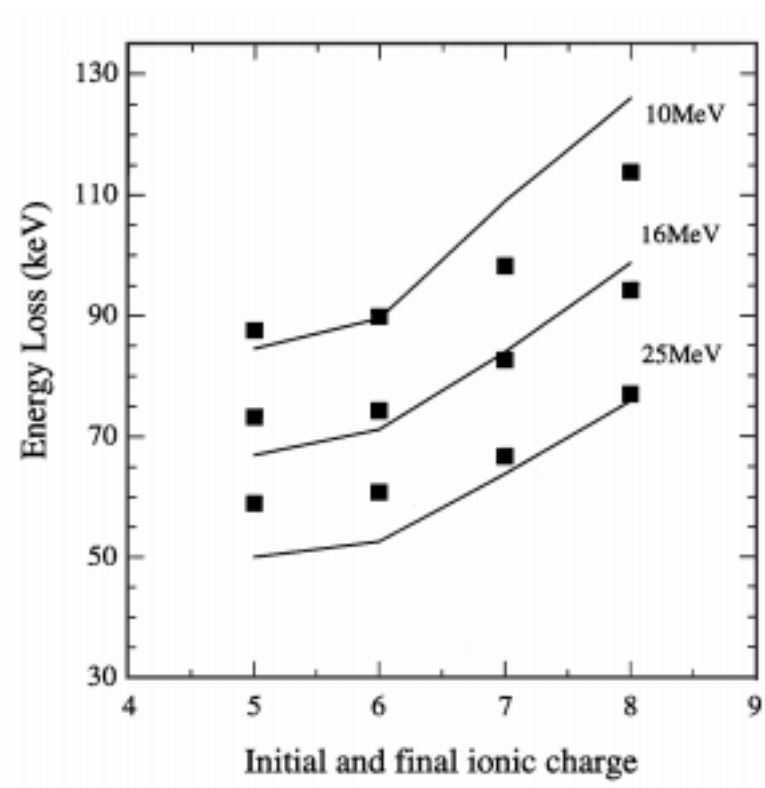

Fig. 1. Energy loss of 10, 16, and 25 MeV $O^{5\text{-}8+}$ ions passing through a 7.5 mg/cm^2 carbon foil. Solid symbols indicate the present experimental results and the curves give the result of the present simulation. Note that the experiment and simulation results are determined for ions which have the same exit charge as they possessed when incident on the foil.

Table 1. Energy loss of O^{+q} ions in a 7.5 mg/cm^2 carbon foil as a function of their energy and entering (q_i) and exit (q_0) charge states. The quoted errors in DE are based on a 1-mm position resolution. They are probably much smaller.

Energy q_i, q_0	D*E*(keV) 10 MeV	16 MeV	25 MeV
4^+	87.6 ± 1.0	72.2 ± 1.6	
5^+	87.5 ± 1.0		58.9 ± 2.5
6^+	89.8 ± 1.0	74.2 ± 1.6	60.8 ± 2.5
7^+	98.2 ± 1.0	82.6 ± 1.6	66.7 ± 2.5
8^+	113.8 ± 1.0	94.2 ± 1.6	76.9 ± 2.5

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3. S. Datz et al., *Phys. Rev. Lett*. **38**, 1145 (1977).

4. J. A. Golovchenko et al., *Phys. Rev. B* **23**, 957 (1981).

5. See e.g., L. B. Bridwell et al., *Nucl. Instrum. Meth.* **13**, 123 (1986).

6. See e.g., H. Ogawa et al. and M. Tosaki, *Nucl. Instrum. Meth. Phys. Res.* **115**, 66 (1996).

7. P. Sigmund, *Phys. Rev. A* **50**, 3197 (1994).

8. J. F. Ziegler, J. P. Biersack, and U. Littmark, *The Stopping and Range of Ions in Solids* (Pergamon Press, New York, 1985), updated in SRIM Version 96.xx.

9. G. Schiwietz, private communication.

10. R. Abrines and I. C. Percival, *Proc. Phys. Soc.* **88**, 861 (1966); R. E. Olson and A. Salop, *Phys. Rev. A* **16**, 531 (1977).

11. R. Herrmann et al., *Phys. Rev. A* **50**, 1435 (1994).