K-shell Ionization by Secondary Electrons

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In typical collisions between a stationary target and heavy ion projectiles, multiple inner-shell vacancies are created both in the projectile and in the target atoms. These vacancies are subsequently filled with electrons, which results in the emission of x rays or Auger electrons. Fast electrons can also be produced in two additional processes. One of them involves the capture of target electrons into the continuum states of the projectiles (electron capture to continuum, ECC) and the excitation of electrons originally bound to the projectiles to their own continuum (electron loss to continuum, ELC). The other mechanism is the so-called binary encounter mechanism and it includes the Coulomb scattering of target electrons from the projectile nuclei and Coulomb scattering of projectile electrons from the target nuclei. ECC and ELC produce electrons with velocities equal to the velocity of the projectiles, while the binary encounter mechanism produces electrons having a broader range of velocities, with a distribution peaking approximately at four times the projectile velocity.

X rays and electrons produced in ion-atom collisions can induce secondary ionization of target atoms. The contribution from this secondary ionization has to be taken into account in the experimental determination of cross sections for inner shell ionization by heavy ions, so that the results can be directly compared with the applicable theories.

Our calculations apply to K-shell ionization of Cu target atoms by secondary radiation produced in collisions with 10 MeV/u heavy ion projectiles. The results describing ionization by secondary x rays are presented in the preceding report, so that in this report the focus is on ionization by secondary electrons.

Since the energy of electrons produced by the ECC and ELC mechanisms (5.49 keV) is below the threshold energy E_0 for K-shell ionization of copper (8.98 keV), and the contribution from the Auger electrons in the collision systems studied turned out to be negligible, only the binary encounter secondary electron production mechanism needs to be considered here. The doubly differential cross section for this process in the center-of-mass frame is given by the product of the Rutherford scattering cross section and the distribution of the electron momenta (the Compton profile) in the initial state. It has to be transformed into the laboratory frame, multiplied by the number of projectiles, target atom density, and target thickness, and then integrated over solid angle to get the number of binary encounter electrons per electron energy interval. This needs to be further multiplied by the number of secondary Cu K x rays produced per electron from the given energy interval (dN_x/dN_e) and integrated over electron energy to get the total number of Cu K x rays produced. To get the number of detected Cu Kα x rays, this number has to be multiplied by the appropriate fluorescence yield and corrected for detector efficiency and x-ray absorption.

dN_x/dN_e is a product of the effective cross section for Cu K-shell ionization by electron impact (σ^e_{eff}), target atom density, and effective target thickness (d_{eff}) for electrons. It is the determination of these two "effective" quantities that makes these calculations difficult. The difficulty arises from the fact that the velocity of electrons changes drastically in magnitude and direction as the electrons undergo collisions inside the target. The effective target thickness is then equal to the effective range of electrons having a given initial energy before their energy drops below the threshold energy E_o for Cu K-shell ionization. The effective cross section is the average value of the cross section for Cu K-shell ionization by electron impact and includes contributions (with the appropriate statistical weights) from electrons having energies at the time of impact between their initial energy and zero.

According to Lencinas *et al.* [1], the range $R(E_e)$ of electrons having initial energy E_e is given by the formula

$$R(E_e) = A\ [E(\text{keV})]^n ,$$

where $A = 5.76\ \mu\text{g/cm}^2$ and $n = 1.69$. This formula was derived from measurements involving electrons with energies E_e between 1646 eV and 7000 eV. By assuming that its validity extends beyond the specified energy interval, the effective target thickness can be approximated with

$$d_{eff} = A\ \{[E_e(\text{keV})]^n - [E_o(\text{keV})]^n\} .$$

The cross section σ^e for Cu K-shell ionization by impact of electrons having energy E_e has been parametrized by Green and Cosslet [2] as

$$\sigma^e(\text{b}) = 2.297\ 10^6\ [E_o(\text{keV})]^{-2} \ln(u) / u,$$

where $u = E_e / E_o$. For $u \leq 1$, $\sigma^e(\text{b}) = 0$.

The proper way to calculate the effective cross section is to average it over the *time* the electron spends in each energy interval, so that

$$\sigma^e_{eff} = \int \sigma^e\, dt / \int dt ,$$

where $dt = (2\, m_e\, E_e)^{1/2}\, dE_e / S$, m_e is the mass of the electron, and S is its energy loss. From the formula of Lencinas *et al.*, if can be deduced that S is proportional to E_e^{-n+1}, so that the effective cross section is given by the formula

$$\sigma^e_{eff}(\text{b}) = 2.297\ 10^6\ f(u) / [E_o(\text{keV})]^2 ,$$

in which $f(u)$ can be expressed analytically in closed form.

The formulas above were used to calculate the contribution from binary encounter electrons to the Kα diagram line peaks in the Cu x-ray spectra for four different thick targets as a function of the projectile atomic number. The results are shown in Figure 1. Apparently, the calculations yield the correct dependence on target thickness and projectile atomic number, and they are of the right order of magnitude. However, a scale factor of 7 (regardless of the projectile atomic number) is needed to reproduce the experimental data. To improve the accuracy of the results, a more accurate description of electron transport is required. Additional complications arise in the calculations involving thin targets, especially those evaporated on a backing, due to the increased importance of finite target thickness effects.

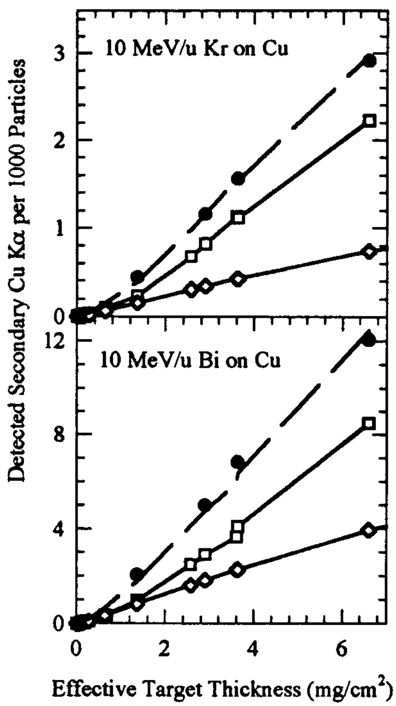

Figure 1. The number of detected secondary Cu Kα x rays as a function of target thickness in collisions with 10 MeV/u Kr and Bi projectiles. The experimental data are represented by filled circles, while squares connected by a solid line show the calculated contribution from fluorescence by secondary x rays. The calculated contribution from secondary binary encounter electrons has been multiplied by a factor of 7 and represented by diamonds connected by a solid line. The sum of the x-ray fluorescence and binary encounter electron contributions is shown by dashed lines.

References

[1] S. Lencinas *et al.* , Phys. Rev. A **41,** 1435 (1990).

[2] M. Green and V. E. Cosslet, Proc. Phys. Soc. London **78**, 1206 (1961).