[Journal of the Arkansas Academy of Science](http://scholarworks.uark.edu/jaas)

Volume 45 Article 19

1991

K-Shell Ionization Measurements for Light Incident Icons

Rahul Mehta
University of Central Arkansas

George Bissinger
East Carolina University

K-SHELL IONIZATION MEASUREMENTS FOR LIGHT INCIDENT IONS

RAHUL MEHTA
Department of Physics
University of Central Arkansas
Conway, AR 72032

GEORGE BISSINGER
Department of Physics
East Carolina University
Greenville, NC 27858

ABSTRACT

The ionization of the K-shell in targets of copper, silver, dysprosium and gold was investigated with incident ion beams of proton and helium ions in the range 0.5 MeV/u to 3 MeV/u. The x-rays were detected by a HpGe detector. K-shell x-ray production cross section were determined by normalization of the x-ray yield to the incident beam flux, the Rutherford-scattered ions and the nuclear-Coulomb excited gamma ray yield. The multiple normalization procedures minimize the errors in these cross section measurements. The data are compared with the predictions of the ECPSSR theory for K-shell ionization. The atomic number dependence of these K-shell cross section is discussed.

INTRODUCTION

In the interaction of energetic ions with atoms, the inner shell electrons can be excited to higher shells or captured to the bound or continuum states of the projectile. The probability for ionization depends on the atomic numbers of the ion and the target and the energy of the incident ion-beam (Lapicki, 1989). The ionization cross section for a particular shell can be determined from measured yields for the radiative decay mode like the x-ray emission. Knowing the fluorescent yield (Bambynek *et al.*, 1972) for the shell one can convert the x-ray production cross sections into ionization cross sections.

The dominant modes of vacancy production in an ion-atom collision are the direct ionization of the shell (DI) and the electron capture (EC) process. In addition, excitation of the nucleus can lead to ionization of the atom in nuclear decay via e.g. internal conversion processes and other mechanisms. For the K-shell, DI of a target electron to the continuum has been shown to be a principle mode of interaction for $Z_1 << Z_2$ and $v_1 >> v_{2K}$ where Z_1 & Z_2 refer to the projectile ion and the target atomic numbers while v_1 & v_{2K} refer to the incident ion and target K-shell electron velocities, respectively (Merzbacher and Lewis, 1958; Khandelwal *et al.*, 1969; Rice *et al.*, 1977). For $Z_1 \leq Z_2$ and $v_1 \leq v_{2K}$, K-shell electron capture (EC) to bound states of the incident ion is important. The ECPSSR theory (Brandt and Lapicki, 1981) for DI and (Lapicki and McDaniel, 1980) for EC accounts for the energy loss (E) and Coulomb deflection (C) of the incident ion as well as for the Perturbed Stationary States (PSS) and the Relativistic nature (R) of the inner shell electrons. The ranges of Z_1/Z_2 and v_1/v_{2K} parameters investigated were $0.012 < Z_1/Z_2 < 0.069$ and $0.05 < v_1/v_{2K} < 0.24$, respectively.

The measurement of ionization by measuring the x-rays involves normalizing the x-ray yields to simultaneously measured other quantities that pertain to the same ion-atom interaction. These variable quantities have error involved in their measurements. A variety of normalization variables allow one to determine and report the x-ray production cross sections with greater precision. The experimentally measured cross sections can be compared with the prediction of the existing theories (Lapicki, 1989) and conclusions can be drawn regarding the validity of the theories and the accuracy of the measurements.

In the present experiment the beam of protons or helium ions were produced by the East Carolina University 2MV Tandem Van de Graaff accelerator. Thin targets of copper, silver, dysprosium (natural and enriched) and gold were produced by vacuum evaporation of the elements on thin carbon substrates. The K-shell x-rays and other photons produced in the ion-atom collision were detected and measured with a HpGe detector that had a resolution of 195 eV at 5.9 keV and 488 eV at 122 keV. The K-shell x-ray energies ranged from 8.0 keV for copper K_α to about 68 keV for K_α for gold targets. Rutherford scattered ions were measured with a silicon surface barrier detector. More details of the experimental procedure, the scattering chamber setup and analysis of the data are given elsewhere (Bissinger *et al.*, 1989; Mehta *et al.*, 1991).

The 43.8 keV gamma ray excited in the dysprosium targets (due to the presence of the ^{161}Dy isotope) was measured together with the K-shell x-rays of dysprosium and was later used to normalize the K-shell x-ray production cross section (Celler *et al.*, 1979) through the accurately known cross section for gamma ray production (Brown *et al.*, 1978). In addition the relative detector efficiency was also established through these gamma ray measurements. The K-shell x-ray production cross sections, σ_{KX}, were obtained using the following equations:

$$\sigma_{KX} = [\, Y_X / \varepsilon\, n_0 n_1 \,] \quad (1)$$
$$\sigma_{KX} = [\, Y_X/ \varepsilon \,]\,[\, \sigma_R\ \Omega / Y_R \,] \quad (2)$$
$$\sigma_{KX} = [\, Y_X / \varepsilon \,]\,[\, \sigma_\gamma \varepsilon_\gamma / Y\gamma \,] \quad (3)$$

where Y_X is the K x-ray yield, ε and ε_γ are the efficiency of the HpGe detector at the K x-ray energy and the 43.8 keV gamma rays, respectively, n_0 is the target thickness in atoms/cm^2, n_1 is the beam flux (determined from Q, the charge collected in the Faraday cup), σ_R and σ_γ are the cross section for Rutherford scattering and 43.8 keV gamma ray emission, respectively, Ω is the solid angle subtended by the silicon surface barrier particle detector, Y_R and Y_γ are the Rutherford scattered particle yield and the 43.8 keV gamma ray yield, respectively. Equation (3) was used only for the dysprosium targets and the percentage of ^{161}Dy in the target was employed in these computations.

RESULTS AND DISCUSSION

In Figure 1, the K-shell x-ray production cross section, σ_{KX}, in barns

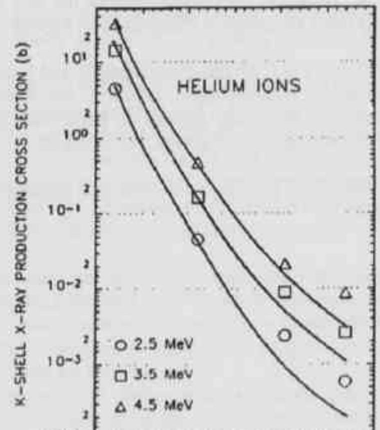

Figure 1. K-shell x-ray production cross section in barns, σ_{KX}, versus the target atomic number Z_2 for incident helium ions at 2.5 (circle), 3.5 (square) and 4.5 (triangle) MeV. The cross section scale is in powers of ten. The three solid curves represent the prediction of the ECPSSR theory in order of increasing energy e.g. the lowest solid curve is for 2.5 MeV helium ions.

is plotted versus the target atomic number Z_2 for incident ^4He ions at energies of 2.5, 3.5 and 4.5 MeV. The cross sections decrease with increasing atomic number of the target. Going from copper to gold targets, at identical beam energy this decrease is dramatically large (by a factor of ~2000 or more). Also this decrease is greater for higher energy helium ion beam. In other words the cross section for incident helium ion beam in the energy range shown here are greatest for the lowest atomic number target (Z_2=29) at the highest beam energy (4.5 MeV).

In Figure 2, the K-shell x-ray production cross section, σ_{KX}, in barns are plotted versus the target atomic number for proton and helium ion beam, both at identical energy per unit mass of 1.0 MeV/u representing identical velocity ions. Again for each ion beam a dramatic decrease in cross section is seen with increasing Z_2. The stronger nature of the decrease in the cross sections for the helium ions over those for the protons is evident in the larger slope among the open squares. The larger cross section for the helium ion over those for the proton beam for a particular target is because of the larger atomic number of the helium ion over that of a proton.

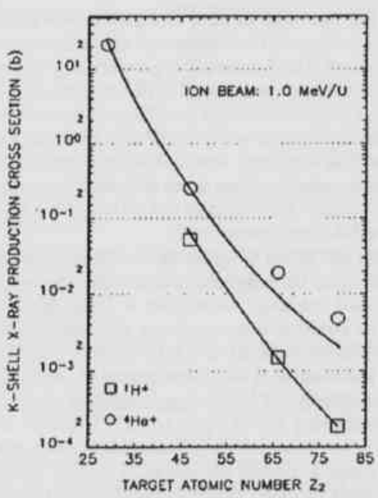

Figure 2. K-shell x-ray production cross section in barns, σ_{KX}, versus the target atomic number Z_2 for identical velocity proton and helium ions. The symbols circle and square represent the helium and the hydrogen ion data, respectively. The solid curve portrays the predictions of the ECPSSR theory. The upper curve is for helium and lower for proton beam.

In Figures 1 and 2, the solid curves representing the prediction of the ECPSSR theory (Lapicki, 1989) shows good agreement with the measured cross sections. The theory accurately predicts the trend in these cross sections as discussed in previous paragraphs. The agreement ranges from excellent for proton data for all the elements and silver in the helium data studied here and fair to poor for helium data for dysprosium and gold. As discussed (Bissinger *et al.*, 1989) for the dysprosium targets a complex correction needs to be made to account for the internal conversion contributions to the inner-shell vacancy production.

The largest error in these measurements comes from the error in the determination of the efficiency of the detector (Mehta *et al.*, 1991). The multiple normalization techniques using equations (1)-(3) reduce the error in these cross sections (Bevington, 1969) and provides a cross check for the consistency among these normalization procedures.

LITERATURE CITED

BAMBYNEK, W., B. CRASEMAN, R.W. FINK, H.-U. FREUND, H. MARK, C.D. SWIFT, R.E. PRICE, and P. VENUGOPALA RAO. 1972. X-ray fluorescent yield, Auger, & Coster-Kronig transition probabilities. Rev. Mod. Phys. 44:716-813.

BEVINGTON, P.R. 1969. Data reduction and error analysis for the physical sciences. McGraw-Hill Book Co. New York. 336 pp.

BISSINGER, G., R. MEHTA, and J.M. JOYCE. 1989. Nuclear-Coulomb-Excitation-Normalized K X-Rays Yields for α_K=0 Targets. Nucl. Inst. & Meth. in Phys. Res. B40/41:459-461.

BRANDT W. and G. LAPICKI. 1981. Energy-loss effect in inner-shell Coulomb ionization by heavy charged particles. Phys. Rev. A23:1717-1729.

BROWN, P.F., C. BAKTASH, J. O'BRIEN, and J.X. SALADIN. 1978. B(E2) values in ^{155}Gd, ^{161}Dy, ^{163}Dy, ^{167}Er, and ^{175}Lu. Phys. Rev. C18:666-670.

CELLER, A., J. KANTELE, M. LUONTAMA, and J. ZYLICZ. 1979. Determination of Ion-induced K-shell Ionization cross sections by comparison with Nuclear Coulomb Excitation. Nucl. Inst. & Meth. 163:221-225.

KHANDELWAL, G.S., B.H. CHOI, and E. MERZBACHER. 1969. Tables for Born approximation calculations of K- and L- shell ionization by protons and other charged particles. Atomic Data 1:103-120.

LAPICKI, G. and F.D. McDANIEL. 1980. Electron capture from K shells by fully stripped ions. Phys. Rev. A22:1896-1905. (Eratum A23:975).

LAPICKI, G. 1989. Cross sections for K-shell x-ray production by Hydrogen and Helium Ions in elements from Beryllium to Uranium. J. Phys. Chem. Ref. Data 18:111-218.

MEHTA, R., G. BISSINGER, and J.M. JOYCE. 1991. Reduced Error in σ_{KX} via nuclear-coulomb excited absolute detector efficiency normalization for targets with Z = 29-79. Nucl. Inst. & Meth. in Phys. Res. B56/57:30-32.

MERZBACHER, E. and H.W. LEWIS. 1958. X-ray production by heavy charged particles. Handbuch der Physik. 34:166-192.

RICE, R., GEORGE BASBAS, and F.D. McDANIEL. 1977. Extended tables for plane-wave Born-approximation calculations of direct Coulomb ionization of the K-shell by charged particles. At. Data & Nucl. Data Tables. 20:503-511.