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K-SHELL X-RAY PRODUCTION CROSS SECTIONS OF SELECTED ELEMENTS Sc TO Ni FOR 4.0 TO 38.0 MeV ^{10}B IONS*

G. Monigold, F. D. McDaniel, J. L. Duggan, R. Mehta, and R. Rice
North Texas State University†
Denton, Texas 76203

and

P. D. Miller
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Abstract

K-Shell x-ray production cross sections for the target elements Sc, Ti, V, Mn, Fe, Co, and Ni have been measured for incident ^{10}B ions over the energy range 4.0 to 38.0 MeV. The cross section data were compared to the theoretical predictions of the Binary Encounter Approximation (BEA); the Plane Wave Born Approximation (PWBA); and the PWBA modified to include corrections for increased binding energy (B), Coulomb deflection of the incident ion (C), orbital perturbation due to polarization (P), and relativistic effects (R). In addition, fluorescence yield variations (W_K) and contributions to the cross sections from electron capture (EC) have been included. It was found that the predictions of the fully modified PWBA with contributions from electron capture and fluorescence yield variations included provided the best fit to the experimental data over the entire energy range for each target element. The Kβ/Kα x-ray intensity ratios were compared to theoretical values that assume single hole ionization, and the x-ray energy shifts presented as a function of the energy of the incident ion. These two measurements provided confirmation of the occurrence of multiple ionization for ^{10}B bombardment of target elements in the range $21 \leq Z_2 \leq 28$.

Introduction

Recent progress in the investigation of inner shell ionization processes has been made by a number of research groups. Summaries of previous light ion results are given by Garcia, Fortner, and Kavanagh[1] and Rutledge and Watson.[2] Others have extended the work to include heavier projectiles.[3-6] Review papers by Saris[7] and Richard[8] summarize experimental and theoretical results for the heavier ion-atom interactions. All these studies were concerned with inner-shell vacancies being filled through the emission of either characteristic x-rays or Auger electrons and it was concluded that the inner shell excitation mechanisms for heavy ion-atom interactions may be different from that for lighter ions. For the heavier ion bombardment, multiple ionization of the target atom[8], target thickness effects,[9] and electron promotion processes[10] add considerably to the complexities of data analysis and theoretical interpretation.

Earlier experimental findings have been compared to several theoretical predictions of Coulomb ionization of inner-shell electrons. The quantum mechanical plane wave Born approximation (PWBA) and the classical binary encounter approximation (BEA) have generally been found to be in better agreement with the experimental data.

The PWBA[11] K-shell ionization has been modified by Basbas, Brandt, and Laubert to include effects for increased target electron binding energy due to penetration of the K-shell by the incident ion and also for the deflection of the incident ion from a straight line trajectory due to the Coulomb interaction.[12,13] This modified PWBA has been found to give reasonably good predictions of the K-shell ionization cross section for light ions (Z≤4) over a fairly wide energy range.[12,14] However, difficulties in fitting experimental data have arisen at higher incident ion energies using the PWBA modified for increased binding energy and Coulomb deflection effects. At these higher energies, the experimental results have been underpredicted by as much as 100% in some cases.[3] Further modification of the PWBA has included corrections arising from polarization of the target atom electron wave function by higher energy incident ions.[13,15-17] This additional modification has been shown to give reasonably good predictions of experimentally measured K-shell x-ray production cross sections for ^{16}O ions.[5] Also, it has been reported that the use of a relativistic atomic electron wave function can be another important modification to the PWBA prediction for low incident ion energies on high Z targets.[3,18-20]

For heavier incident ions, electron capture from the K-shell of the target to the K'-shell of the projectile has been shown to be important to target ionization.[21] Multiple ionization of the target atom by these heavy ions also produces changes in the fluorescence yield which relate x-ray production to vacancy production.

The purpose of this study was to experimentally determine the K-shell x-ray production cross section for a series of target elements in the range $21 \leq Z_2 \leq 28$ when bombarded by ^{10}B ions over the energy range 4.0 MeV to 38.0 MeV. The range of target elements was chosen in order to investigate the inherent requirement of the theories that the ratio of the projectile charge (Z_1) and the target atomic number (Z_2) have the property that $Z_1/Z_2 \ll 1$. The ^{10}B projectile was chosen as earlier experimental investigations have shown that multiple ionization effects are seen for ^{14}N ions[6] but not for ^{7}Li ions[3] on targets in the approximate same range of Z_2. Consequently, in addition to determining K-shell x-ray cross sections, the Kβ/Kα x-ray intensity ratios and shifts in the Kα and Kβ x-ray energies were measured as a function of incident ion energy. The latter two effects have been established as indicators of the occurrence of multiple ionization.[8,22-25]

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Experimental Procedure

The ^{10}B ion beam was collimated by two Ta apertures located ~61 cm in front of the scattering chamber and by a 3.175 mm diameter C aperture at the chamber entrance. The experimental procedure has been presented in detail earlier and will only be briefly discussed here.[3,6,26] The scattering chamber accommodates 24 targets which are placed at 45 deg. to the incident beam direction when rotated into the beam line. The targets used in this experiment ranged in thickness from 17 to 85 $\mu g/cm^2$. Carbon backings 10-50 $\mu g/cm^2$ in thickness were used for target support. An Ortec Si(Li) detector with a full width at half maximum (FWHM) resolution of 179 eV at 5.9 KeV was positioned inside the target chamber approximately 5 cm from the target and at 90 deg. to the incident beam direction. Si surface barrier detectors were mounted in the scattering chamber at 30- and 45-deg. to the incident beam direction to detect the ^{10}B ions elastically scattered from the target elements. The absolute magnitude of the experimental cross sections were calculated by normalizing the x-ray yield to the Rutherford differential cross section of the scattered ^{10}B ions as described elsewhere.[3,26] In anticipation of non-Rutherford contributions to the elastic scattering process from the target elements at the higher incident ion energies, a 100 $\mu g/cm^2$ self-supporting Au foil was installed 20 cm behind the scattering chamber at an angle of 45 deg. to the incident beam direction. A surface barrier detector was mounted at 90 deg. to the incident beam direction with a 4.76 mm diameter aperture approximately 10 cm from the Au target. It was expected that the ^{10}B ions elastically scattered from the Au foil would be purely Rutherford over the entire energy range.[27,28] This measurement allowed the determination of the constant ratio of the Rutherford yield from the Au to the Rutherford yield from the target material at the lower incident ion energies. As a result, absolute normalization to the Rutherford differential cross section was used over the entire energy range.

The absolute efficiency of the Si(Li) detector was measured using standard calibrated radioactive sources of ^{54}Mn, ^{57}Co, and ^{241}Am. The procedures for measuring the efficiencies are outlined elsewhere.[29-31] At x-ray energies below 3.3 KeV, the steepness of the measured efficiency curve yielded uncertainties in the range 35% - 50%. To increase the confidence in the efficiency at the lower energies, the efficiency was calculated using the method described by Gallagher and Cipolla.[32]

The x-ray and charged particle spectra were both input to 1024 channels of a Tennecompt Pace System analog to digital converter (ADC) which was interfaced with a PDP 11/45 computer. The computer had light pen spectra reduction capabilities. The counting rates were low enough that the detector dead time remained essentially zero so the dead time of the ADC was used to determine the dead time correction to the measured yields. The dead time of the ADC was generally less than 10%.

Data Analysis

The simultaneous collection of the x-ray yield and the Rutherford scattering yield during ion bombardment of a given target element eliminates the need of normalization to target thickness and incident ion flux in determining the x-ray production cross section. The K-shell x-ray production cross section for a particular energy ion beam is calculated by the expression

$$\sigma_{kx} = \left(\frac{Y_{K\alpha}}{\epsilon_{K\alpha}} + \frac{Y_{K\beta}}{\epsilon_{K\beta}}\right) \frac{\Omega_R(\theta)}{Y_R(\theta)} \frac{d\sigma}{d\Omega_R} \cdot T , \qquad (1)$$

where $\Omega_R(\theta)$ is the solid angle subtended by the charged particle detector at the laboratory angle θ, $Y_R(\theta)$ is the total yield of Rutherford scattered ions at the angle θ corrected for dead time and background subtraction, $d\sigma/d\Omega_R$ is the theoretical differential Rutherford scattering cross section for the incident ion of energy E through the angle θ. $Y_{K\alpha,\beta}$ are the α,β x-ray yields corrected for dead time and background subtraction. $\epsilon_{K\alpha,\beta}$ are the Si(Li) detector efficiencies. The correction for target thickness, T, is described by Laubert et al.[33] It includes approximate corrections for the energy loss of the incident ions passing through targets of finite thickness in both x-ray and scattered ion yields.

Results and Conclusions

$K\beta/K\alpha$ x-ray intensity ratios and their absolute uncertainties are shown in Fig. 1 for representive elements. The primary contributions to the uncertainties were from counting statistics and the x-ray detection efficiencies. A definite deviation was

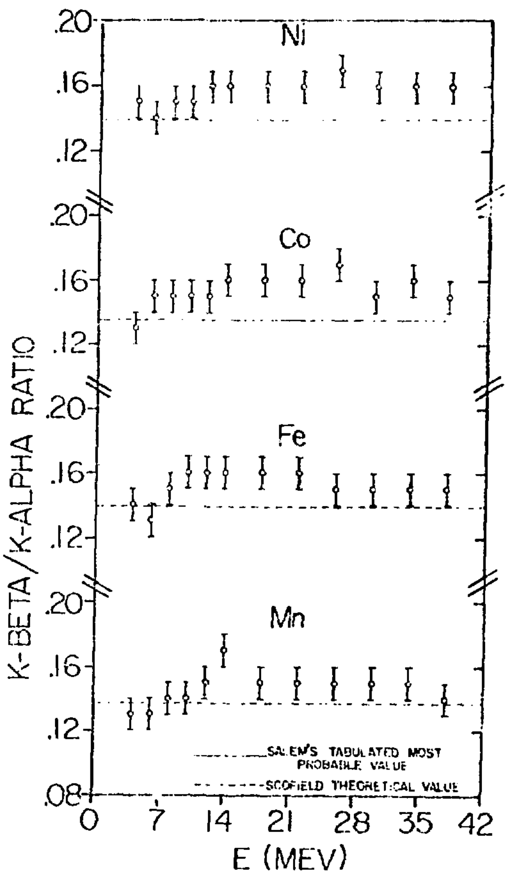

Figure 1. $K\beta/K\alpha$ x-ray intensity ratios.

[illegible] revealed by comparison of the experimental ratios with the calculated values of Scofield[35] or the [illegible] values of Salem et al.[36] in which it was assumed that no multiple ionization existed at the time of the K vacancy decay. The experimental values showed increases above the single hole values by as much as 30%. This deviation correlated exactly with the Kα and Kβ energy shifts shown in Fig. 2 for representive elements and confirmed the occurrence of multiple ionization. Maximum shifts of approximately 100 eV were detected in each element for Kβ and approximately 50 eV for Kα. The energies at

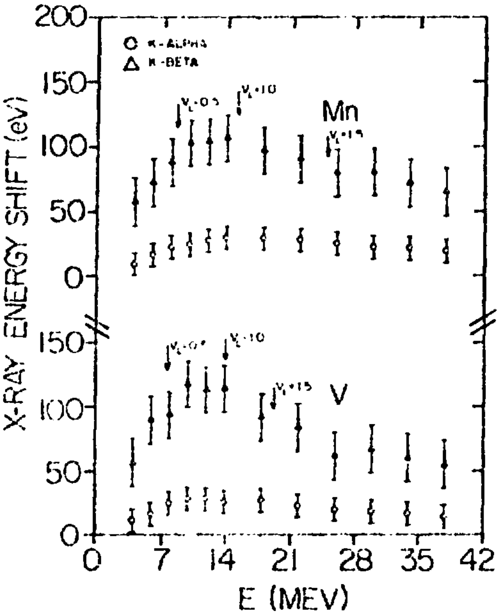

Figure 2. Kα and Kβ x-ray energy shifts. V_L is the ratio of incident ion velocity to the average velocity of the target L-shell electrons.

which the maximum x-ray energy shifts occurred were given by the equation $V_L = (E_B/\lambda U_L)^{1/2}$ where V_L is the ratio of the incident ion velocity to the average velocity of the target atom L-shell electrons, E_B is the ^{10}B ion energy, λ is the ratio of the ^{10}B mass to the electron mass, and $\bar{U}_L$ is the weighted average L-shell binding energy for the target atom. It was found that the x-ray energy shift maxima occurred when the velocity of the incident ion was most nearly matched to the velocity of the L-shell electrons in the target atom. This implied that additional vacancies in the L-shell were the primary contribution to the fluorescence yield changes. The single-hole fluorescence yields were corrected using the procedure of Larkins.[36]

The experimental x-ray production cross sections and the theoretical predictions to which the data were compared were calculated using the computer code KIDDLE. The fluorescence yield values of Bambynek et al.[37] as calculated by McGuire[38] were used in KIDDLE for determining the theoretical predictions. Comparisons of the experimental K-shell x-ray production cross sections for ^{10}B bombardment to the predictions of the BEA, PWBA, PWBABC, PWBABPCR, and PWBABPCR (ECW_K) are shown for representative elements of Ti and Fe in Figs. 3 and 4. The PWBABPCR is the prediction of the PWBA modified to include increased binding energy (B), Coulomb deflection (C), polarization (P), and relativistic effects (R). The PWBABPCR(ECW') includes the effects of K-shell fluorescence yield variations due to multiple ionization (W'), after the procedure of Larkins[36] and the contribution to the x-ray cross section from electron capture by the projectile (EC).[39]

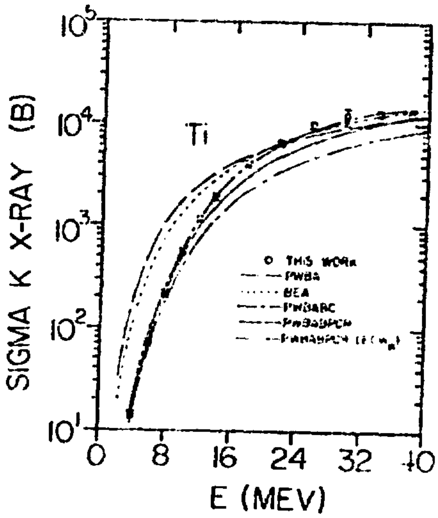

Figure 3. Ti K-shell x-ray production cross sections for incident ^{10}B ions.

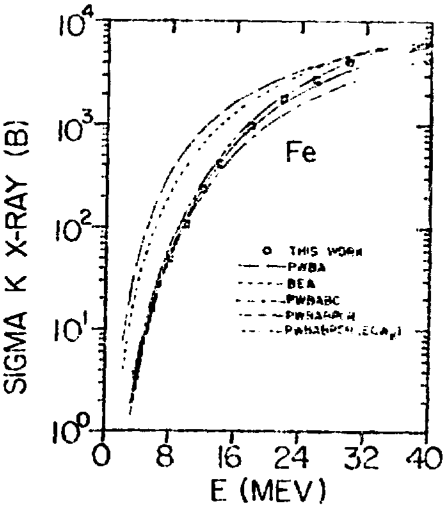

Figure 4. Fe K-shell x-ray production cross sections for incident ^{10}B ions.

The error bars in each figure represent the absolute uncertainty in the data. The sources and ranges of [illegible] uncertainties have been discussed in earlier publications.[4] It was found that for the target elements and projectile involved in this study, the contributions from the Coulomb deflection and relativistic modifications to the PWBA were negligible.

The effect of the electron capture contribution [illegible] more important at the higher projectile energies [illegible] the equilibrium charge state distribution of the ion beam contains larger amounts of 4+ and 5+ charge states. As the atomic number of the target material increases, the probability of electron capture by the projectile decreases which in turn diminishes the importance of this modification. The inclusion of the contributions of electron capture and changes in the fluorescence yields due to multiple ionization provides excellent agreement with the experimental values over the entire energy range of this study.

Summary

The x-ray production cross sections for ^{10}B ions incident on selected targets of Sc to Ni were measured over an energy range from 4.0 to 38.0 MeV. The experimental values of the cross sections were obtained by normalizing the x-ray yields to the Rutherford differential cross section of the ^{10}B ions. The theoretical prediction of the PWBA modified to include the effects of increased binding energy, Coulomb deflection of the incident ion, polarization of the target atom electronic orbitals at high projectile energies, relativistic considerations, and contributions from electron capture by the projectile and K-shell fluorescence yield variations provided excellent estimates of the experimental data over the entire energy range.

The comparison of the experimentally measured [illegible] ratios to values of Scofield[19] or Salem et al.[20] which assume single hole vacancies indicated a definite occurrence of multiple ionization. This was confirmed by the measured values of the [illegible] x-ray energy shifts.

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