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Cu K x-ray production as a function of projectile atomic number, energy, and incident charge state

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Cu K x-ray production cross sections for 1.7-MeV/amu C, N, O, and F ions were determined in the limit of vanishingly thin solid Cu targets. These data were used in a systematic study of the Z_1 dependence of Cu K x-ray production for projectiles from H to Cl at 1.7 MeV/amu. Studies of the energy dependence of Cu K x-ray production for F ions at 1.7, 2.0, 2.2, and 2.5 MeV/amu were also made for incident projectiles with 0, 1, and 2 initial K-shell vacancies. These data require the inclusion of electron transfer from the target K shell to the projectile in addition to direct ionization of the target in order to explain the charge-state and Z_1 dependences of the x-ray-production cross sections.

I. INTRODUCTION

In a previous paper[1] we reported measurements of the target-thickness dependence of Cu K x-ray production for 1.7-MeV/amu F, Al, Si, and S ions incident upon thin solid Cu foils. We introduced the three-component model for target x-ray production, which included effects on the measured target K x-ray yields associated with ions moving in the target with 0, 1, or 2 K-shell vacancies. Target-thickness dependences in measured target K x-ray yields are related to electron transfer from the target K shell to the projectile K shell. Measurements of the target K x-ray yield as a function of target thickness may be extrapolated to zero target thickness to obtain the single-collision cross section. This extrapolation is used to determine target K x-ray cross sections for incident projectiles with 0, 1, or 2 K-shell vacancies. We have extended the measurements of the target-thickness dependence of Cu K x-ray production to incident C, N, and O ions at 1.7 MeV/amu and to incident F ions at energies of 2.0, 2.2, and 2.5 MeV/amu. These results are combined with those from the published literature for a systematic study of σ_{K0}, σ_{K2}, and σ_{sat} for a range of ions ($Z_1 = 1-17$) incident upon Cu at 1.7 MeV/amu. The quantities σ_{K0} and σ_{K2} are the target K x-ray-production cross sections determined for vanishingly thin targets for projectiles with no initial K-shell vacancy and with two initial K-shell vacancies, respectively. The quantity σ_{sat} is the target K x-ray yield per incident ion in units of cross section determined for targets having a thickness sufficient to give saturation in the target K x-ray yield. The data are compared to the sum of the calculated target x-ray-production cross sections for direct Coulomb ionization plus electron transfer from the target K shell to the projectile.

II. EXPERIMENTAL RESULTS AND ANALYSIS

The target x-ray yields per incident ion were measured for incident F^{q+} ions with $q = 9$ and 8 and $q \leq Z_1 - 2$ as a function of the target thickness using techniques described previously.[1] The target-thickness dependences for incident F^{8+} and F^{9+} ions follow the trends reported previously.[1] The target x-ray-production cross sections were determined by extrapolating the measured target-thickness dependences of the target K x-ray yield per incident ion to zero target thickness. By this method the target cross sections σ_{K0}, σ_{K1}, and σ_{K2} for incident F ions with 0, 1, and 2 initial K-shell vacancies, respectively, were determined at incident energies of 1.7, 2.0, 2.2, and 2.5 MeV/amu.

The target x-ray production cross sections σ_{K0}, σ_{K1}, and σ_{K2} are shown in Fig. 1 as a function of projectile energy. The calculated K x-ray-production cross sections in Fig. 1 are based upon direct Coulomb-ionization (CI) and electron-transfer calculations (ET). The comparisons are made using the relations

$$\sigma_{K0}(\text{expt}) = \sigma^{\text{th}}(\text{CI}, q = Z_1) + \sigma^{\text{th}}(\text{ET}, K \to L, M, N, \ldots)\,, \tag{1}$$

$$\sigma_{K1}(\text{expt}) = \sigma^{\text{th}}(\text{CI}, q = Z_1) + \sigma^{\text{th}}(\text{ET}, K \to L, M, N, \ldots) + \tfrac{1}{2}\sigma^{\text{th}}(\text{ET}, K \to K)\,, \tag{2}$$

$$\sigma_{K2}(\text{expt}) = \sigma^{\text{th}}(\text{CI}, q = Z_1) + \sigma^{\text{th}}(\text{ET}, K \to K, L, M, \ldots)\,, \tag{3}$$

where σ^{th} is the theoretical x-ray-production cross section for the indicated process. In Eqs. (1) and (2) we do not consider the effects of screening of the projectile nucleus by its atomic electrons. In previous work[2] we have shown that agreement between calculations and data for σ_{K0}

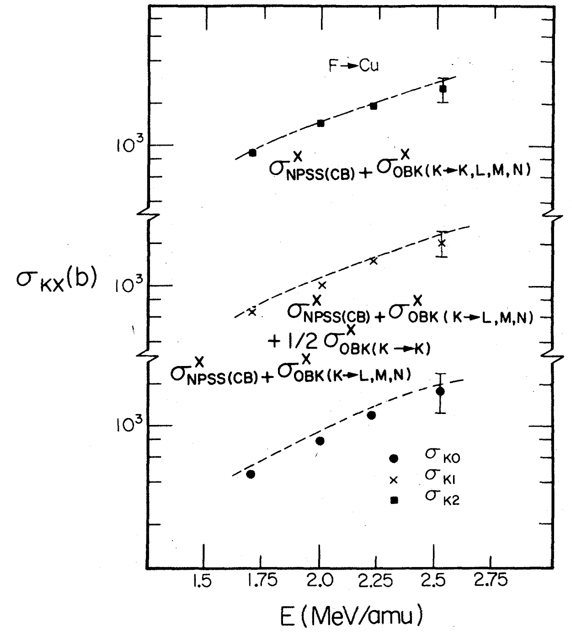

FIG. 1. Target K x-ray-production cross sections for F^{q+} ($q+=9$, 8, $\lesssim 6$) projectiles on solid Cu targets as functions of incident energy determined in the limit of vanishing target thickness. The calculated cross sections use the relations defined by Eqs. (1)–(3).

is obtained for perturbed stationary-state calculations[3] (PSS). There are several different PSS calculations which will give comparable agreement with measured target K x-ray-production cross sections for incident heavy ions. Specifically, PSS calculations which include the effects of Coulomb deflection (C), target binding-energy modification (B), and target polarization (P), thus giving PSS(CBP) calculations[3] (which *do not* include the cutoff approximation reported by Basbas *et al.* for the binding-energy effect), are in best agreement with *properly* measured target K x-ray-production cross sections, i.e., σ_{K0}. In addition PSS calculations[3] which include *only* the binding-energy and Coulomb-deflection effects together with cutoff radii in the calculation of the binding-energy effect [NPSS(CB)] are in agreement with data for σ_{K0}. We have chosen to compare the present results to the NPSS(CB) calculations with the realization that the question of the appropriateness of these calculations is unresolved. The small contribution due to target K shell to projectile L- , M- , ... shell electron transfer is included in the calculation given in Fig. 1. The electron-transfer calculations are discussed below. Neutral atomic-fluorescence yields,[4] ω_K were used in these calculations. The effects of multiple ionization on ω_K are estimated[5] to be $\lesssim 15\%$ and hence are comparable to the experimental errors. The calculated cross sections agree with the data for σ_{K0} as a function of energy for F ions incident upon Cu.

The cross sections σ_{K1} and σ_{K2} were calculated by adding contributions of electron transfer from the target K shell to projectile K shell (K to K) to the NPSS(CB) calculations. The K to K electron-

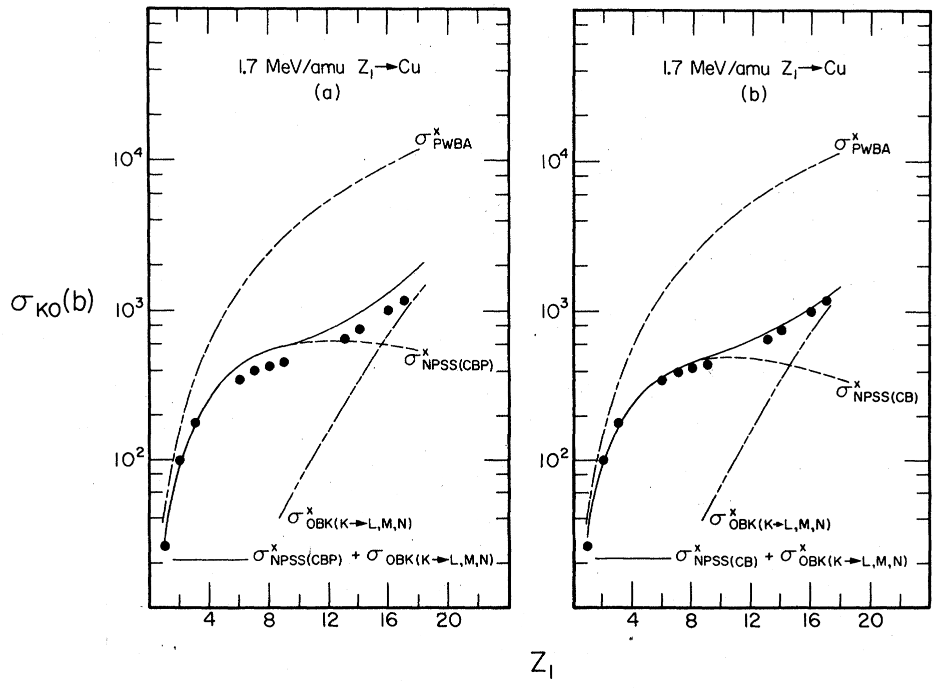

FIG. 2. (a) Target K x-ray-production cross sections for ions (H to Cl) incident upon thin solid Cu targets as a function of the projectile atomic number, Z_1. The Cu K x-ray-production cross sections for $Z_1 \geq 6$ were determined in the limit of vanishing target thickness for incident ions with 0 initial K-shell vacancies. The NPSS(CBP) calculations are from Ref. 3. The electron-transfer calculations ($K \to L$, M, N, ...) are from Ref. 6 with scaling factors as described in the text. (b) The same as (a) with NPSS(CB) calculations for direct ionization of the Cu K shell taken from Ref. 3.

transfer cross sections were calculated from scaled Oppenheimer-Brinkman-Kramer (OBK) calculations using the results of Nikolaev.[6] The electron-transfer calculations for F on Cu were scaled by a multiplicative factor of 0.1. Calculations of K to K processes using the results of Lapicki and Losonsky[7] give contributions which are smaller than the scaled OBK calculations. We shall return to this point in the discussion of the Z_1 dependence of the Cu K x-ray-production cross section. The calculated target K x-ray-production cross sections for σ_{K1} and σ_{K2} are in good agreement with the measurements for F ions incident upon Cu targets.

In order to test the appropriateness of the direct Coulomb-ionization calculations for σ_{K0} in the MeV/amu energy range, we have taken published cross sections for Cu K x-ray production together with additional measurements from the present work as a function of Z_1 at an incident energy at 1.7 MeV/amu. Data for ^{1}H ions are from Lear and Gray,[8] ^{4}He are from Carlton *et al.*,[9] ^{7}Li are from McDaniel *et al.*,[10] ^{19}F, ^{27}Al, ^{28}Si, and ^{32}S are from Gardner *et al.*,[1] and ^{35}Cl are from Gray *et al.*[11] The present results for ^{12}C, ^{14}N, and ^{16}O ions incident upon Cu at energies of 1.7 MeV/amu are used. The systematic variation of the experimental Cu K x-ray-production cross section σ_{K0} is shown in Fig. 2 as a function of Z_1 for ions ranging from ^{1}H to ^{35}Cl. Shown in Fig. 2(a) is a comparison of these data to the "universal ionization cross section" calculations NPSS(CBP) (multiplied by ω_K), shown as a dashed curve, recently published by Basbas *et al.*[3] The NPSS(CBP) calculations agree with the data for ^{1}H, ^{4}He, and ^{7}Li ions. However, the NPSS(CBP) calculations overestimate the measured cross sections for ^{12}C, ^{14}N, ^{16}O, and ^{19}F ions on Cu. It is noted that Basbas *et al.*[3] compare NPSS(CBP) calculations to data for Ni K x-ray-production cross sections. However, their data *did not* take into account the effects of the finite target thickness (180 μg/cm^2) on their measured target K x-ray yields. For the heavier ions ^{27}Al, ^{28}Si, ^{32}S, and ^{35}Cl, the NPSS(CBP) calculations do not give the correct Z dependence. The agreement between the data and calculations for ^{27}Al ions on Cu is fortuitous. The calculation including target K shell to projectile L- , M- , ... shell electron transfer given by the solid line in Fig. 2(a) gives the correct Z_1 dependence but is larger in magnitude than the experimental σ_{K0} cross sections. Thus the present results disagree with the earlier conclusion of McDaniel *et al.*[12] which suggests that the target K ionization cross section σ_{K0} is properly described solely by the NPSS(CBP) cross section for $0.44 \leq Z_1/Z_2 \lesssim 0.67$.

We show in Fig. 2(b) that the target K x-ray-production cross section σ_{K0} can be represented by the NPSS(CB) plus $\sigma^x_{\mathrm{OBK}}(K \rightarrow L, M, \ldots)$ cross sections. Shown in Fig. 2(b) by a dashed line is the NPSS(CB) cross section. For ions up to F, the agreement between data and conclusions is excellent, whereas for the heavier ion species the NPSS(CB) calculations begin to decrease in magnitude because of the dominance of the binding-energy correction. When we add to the direct ionization the contributions to target K ionization, represented by the solid line in Fig. 2(b), associated with the transfer of a target K electron into the $L, M, N, \ldots$ shells of the projectile using a scaled OBK calculation, both the Z_1 dependence and the magnitude are in agreement with the data. The scaling factors used in these calculations were 0.1 at F and 0.06 at Cl. The scaling factors were determined at points intermediate between F and Cl by linear interpolation and are in agreement with earlier results by Guffey.[13] These calculations show that for $Z_2 = 29$ and $Z_1/Z_2 < 0.3$ direct ionization dominates target K-shell ionization. For $Z_2 = 29$ and $Z_1/Z_2 > 0.3$ additional contributions

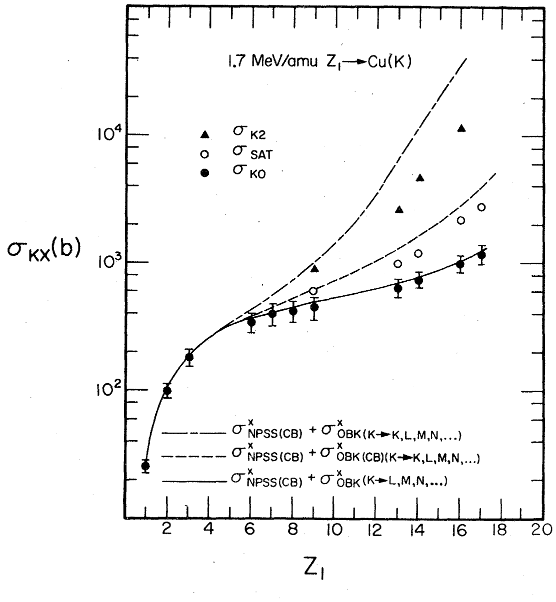

FIG. 3. Z_1 dependence of the Cu K x-ray-production cross sections for incident ions (H to Cl). The target cross sections σ_{K0} ($Z_1 \geq 6$) are for incident ions with 0 initial K-shell vacancies, while σ_{K2} are the target x-ray-production cross sections for bare incident projectiles. The electron-transfer cross sections $\sigma^x_{\mathrm{OBK}}(K \rightarrow K, \ldots)$ and $\sigma^x_{\mathrm{OBK}}(K \rightarrow L, M, N_{(\mathrm{CB})}, \ldots)$ are scaled calculations from Ref. 6, while $\sigma^x_{\mathrm{OBK(CB)}}(K \rightarrow L, M, N, \ldots)$ are taken from Ref. 7. The quantity σ_{sat} is the measured target K x-ray yield per incident ion in units of cross section for targets of thickness sufficient to give saturation in the target-thickness dependence of the K x-ray yield.

from electron-transfer processes involving the target K shell and projectile outer shells begin to be important. As the symmetric-collision case is approached, the electron-transfer processes become the dominant mode of interaction in the few MeV/amu energy regime.

Target K x-ray-production cross-section data for bare ions of F, Al, Si, and S are shown in Fig. 3 (denoted as σ_{K2}). These data are compared to calculations which include direct ionization with electron transfer to the $K, L, M, N, \ldots$ shells of the projectile (σ_{K0}^x). The calculations of the electron-transfer contributions are based upon scaled OBK calculations and OBK calculations by Lapicki and Losonsky.[7] The scaled OBK calculations overpredict the observed cross sections with the disagreement increasing for larger Z_1. The Lapicki and Losonsky calculations fall below the data by factors of $\lesssim 3$.

In Fig. 3 we also show the measured target K x-ray yields per incident particle in units of cross section (σ_{sat}) for targets of sufficient thickness to give saturation in the target-thickness dependence of the averaged target K x-ray yield. These data illustrate the need to properly account for target-thickness effects encountered for heavy ions on thin solid targets for $Z_1/Z_2 \gtrsim 0.3$. The interpretation of data for σ_{K0} and σ_{K0} in terms of single-collision concepts does not suffer from the complications resident in measurements of σ_{sat}.

III. CONCLUSIONS

The present work agrees with the results of McDaniel *et al.*[12] in that the target K x-ray-production cross sections for bare and hydrogenlike F ions can be calculated through the use of target to projectile electron transfer and direct-ionization contributions to the target K-ionization process. However, the universality of the NPSS(CBP) calculations in describing target K-shell ionization for $0.4 \leq Z_1/Z_2 \leq 0.67$ is not supported by the present work for $Z_2 = 29$. It is found, however, that the NPSS(CB) calculations for direct ionization, plus contributions from electron transfer from the target to the projectile shells other than the K shell, reproduce the observed Z_1 dependence of the target K x-ray-production cross section for 1.7-MeV/amu ions ranging from ^{1}H to ^{35}Cl on thin Cu targets. It is once again pointed out that only those measurements of target x-ray production made in the limit of vanishingly thin solid targets are appropriate for comparisons to calculations of K-shell ionization, particularly for $Z_1/Z_2 \gtrsim 0.3$.

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[1] R. K. Gardner, Tom J. Gray, Patrick Richard, Carl Schmiedekamp, K. A. Jamison, and J. M. Hall, Phys. Rev. A 15, 2202 (1977).

[2] Tom J. Gray, Patrick Richard, Glenn Gealy, and Joal Newcomb, Phys. Rev. A (to be published).

[3] George Basbas, Werner Brandt, and Roman Laubert, Phys. Rev. A 17, 1655 (1978).

[4] W. Bambynek, B. Crasemann, R. W. Fink, H. U. Freund, H. Mark, C. D. Swift, R. E. Price, and P. Venugopala Rao, Rev. Mod. Phys. 44, 716 (1972).

[5] Tom J. Gray, Patrick Richard, Robert L. Kauffman, T. C. Holloway, R. K. Gardner, G. M. Light, and J. Guertin, Phys. Rev. A 13, 1344 (1976).

[6] V. S. Nikolaev, Zh. Eksp. Teor. Fiz. 51, 1203 (1966) [Sov. Phys. JETP 24, 847 (1967)].

[7] G. Lapicki and W. Losonsky, Phys. Rev. A 15, 896 (1977).

[8] R. Lear and Tom J. Gray, Phys. Rev. A 8, 2469 (1973).

[9] R. F. Carlton, R. P. Chaturvedi, C. C. Sachtleben, J. Lin, and J. L. Duggan, Bull. Am. Phys. Soc. 18, 257 (1973).

[10] F. D. McDaniel, Tom J. Gray, R. K. Gardner, G. M. Light, J. L. Duggan, H. A. Van Rinsvelt, R. D. Lear, G. H. Pepper, J. William Nelson, and Arlen R. Zander, Phys. Rev. A 12, 1271 (1975).

[11] Tom J. Gray, Patrick Richard, K. A. Jamison, J. M. Hall, and R. K. Gardner, Phys. Rev. A 14, 1333 (1976).

[12] F. D. McDaniel, J. L. Duggan, George Basbas, P. D. Miller, and Grzegorz Lapicki, Phys. Rev. A 16, 1375 (1977).

[13] J. A. Guffey, Master's thesis (Kansas State University, Manhattan, Kan. 1974) (unpublished). In this work by Guffey, comparisons are made between the OBK calculations of Ref. 6 and the experimental total electron-capture cross sections for bare incident projectiles on thin gas targets as functions of incident projectile energy. The scaling procedures used in the present work are taken from the results of this systematic comparison of theory and experiment for electron capture.