[16] S. J. Czyzak, T. K. Krueger, H. E. Saraph, and J. Shemming, Proc. Phys. Soc. (London) 92, 1146 (1967).

[17] R. J. W. Henry, Planetary Space Sci. 16, (1968).

PHYSICAL REVIEW VOLUME 178, NUMBER 1 5 FEBRUARY 1969

Ionization of the Aluminum *K* Shell by Low-Energy Hydrogen and Helium Ions*

Werner Brandt and Roman Laubert
Department of Physics, New York University, New York, New York 10003

(Received 10 October 1968)

The yields for characteristic *K*-shell x rays in aluminum are measured as produced by H^1, He^3, and He^4 ions in the energy range 25–200 keV. The ionization cross sections deduced from these data are in detailed agreement with the theory, if the Coulomb deflection of the incoming particle by the target nucleus and the binding of the *K*-shell electrons to the incoming particle are included in the Born approximation.

INTRODUCTION

Until very recently, measurements of ionization cross sections of inner atomic shells by heavy charged particles were essentially limited to protons.[1] In a previous paper,[2] data on *K*-shell ionization cross sections of Mg, Al, and Cu were reported for low-energy hydrogen and helium atoms. It was shown that the large discrepancies between theory and experiment found earlier for protons[3] can be removed if, in addition to the effect of the Coulomb deflection of the incoming particle by the target nucleus, one incorporates the binding of the target electrons to the moving particle. The present paper reports new experimental data to test in detail on aluminum this expanded theory.

EXPERIMENTAL

The apparatus is similar to that described earlier.[2] An ion beam, after characterization by particle energy and mass, impinges on a thick target of high-purity aluminum. The target is inclined by 45° with respect to the ion beam axis and to the line of sight of a proportional counter. The target is heated to 150°C to suppress carbon deposition and insulated from the ground to measure the incident particle current accurately. The x rays emitted from the target are viewed by a flow-mode proportional counter whose output is connected to a multichannel analyzer. The total x ray yield is obtained from an appropriate integration over the spectrum as recorded for preset values of the integrated beam current.

RESULTS AND DISCUSSION

From the measurements of the Al (*K*) x ray yield Y, one extracts the x-ray production cross section $\sigma_x(E_1)$ in a standard manner by the formula[1]

$$\sigma_x(E_1)=\frac{1}{N_2}\left[\left(\frac{dY(E)}{dE}\right)_{E_1}S_2(E_1)+\mu_2 Y(E_1)\right], \quad (1)$$

and calculates the *K*-shell ionization cross section σ_K according to

$$\sigma_K(E_1)=\sigma_x(E_1)/\gamma_K. \quad (2)$$

E_1 is the energy of the incoming particles, N_2 the density of target atoms, $S_2(E_1)$ the stopping power of the target for particles of energy E_1, μ_2 the absorption coefficient of the target for its own characteristic x rays, and γ_K the *K*-shell fluoresence yield. The differentiation of the experimental yield curves with respect to energy introduces an uncertainty of ~15%, which is comparable with the uncertainty introduced by the stopping power. We used recent stopping-power data[4–6] and data obtained in this laboratory.[7] The ionization cross sections in absolute units are calculated by normalizing our data to the ionization cross section $\sigma_K = 53$ b reported by Khan *et al.*[3] for protons at 100 keV. This cross section is obtained by assuming that $\gamma_K = 0.03$, independent of the atomic number and the energy of the incoming particle. The uncertainty of this value is ±30%.[8]

The resulting *K*-shell ionization cross sections for H^1, He^3, and He^4 on aluminum are shown in Figs. 1–3, respectively. The large error bars represent the uncertainty in the absolute cross sections, the small error bars indicate the uncertainty of the points relative to each other. The data for protons on aluminum (cf. Fig. 1) agree with the results of Khan *et al.*[3] at all energies.

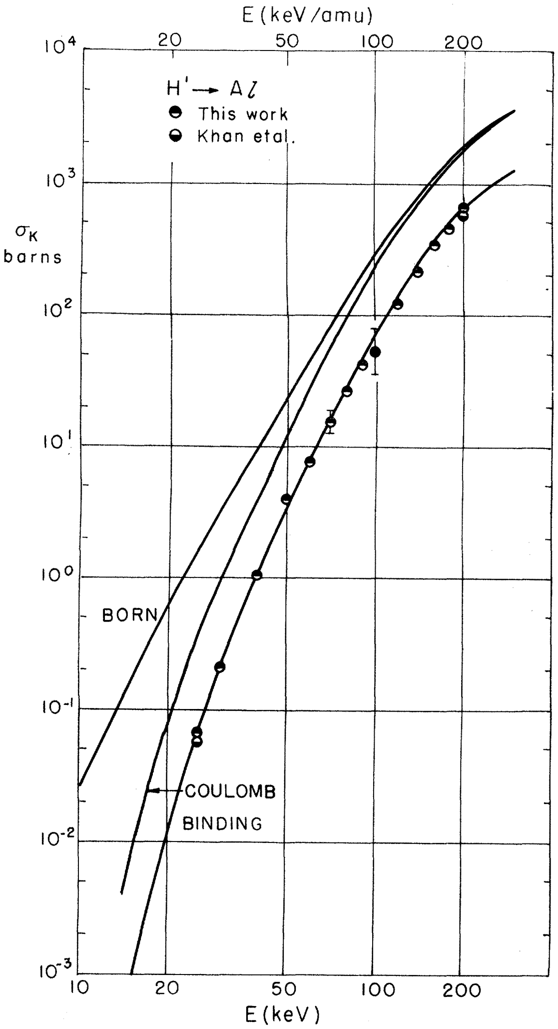

FIG. 1. Aluminum K-shell ionization cross section for protons

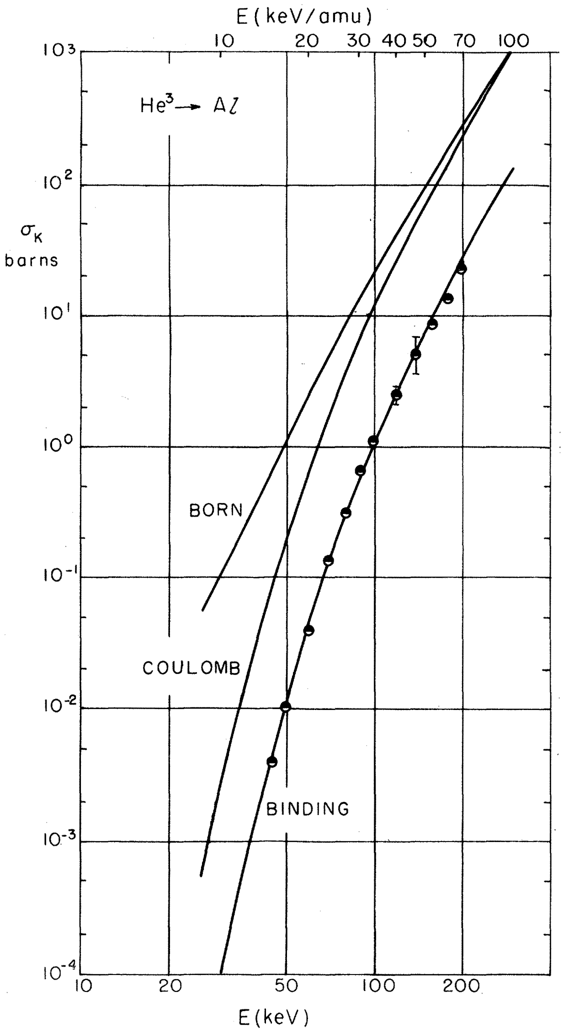

FIG. 2. Aluminum K-shell ionization cross section for He^3.

The curves marked "Born" represent the theoretical K-shell ionization cross sections $\sigma_K{}^0$ for slow heavy particles as calculated by Merzbacher and Lewis.[1] In these calculations the Coulomb interaction between the particles and the target nuclei is neglected. At low energies the asymptotic form of the cross sections is[9]

$$\sigma_K{}^0 \simeq C_{2K}(Z_1{}^2 Z_2{}^2/v_1)q_0{}^{-9}, \tag{3}$$

where Z_1 is the atomic number of the incident particle of velocity v_1 and energy E_1, Z_2 is the atomic number of the target atoms, C_{2K} is a target constant, and $q_0 \equiv \omega_{2K}/v_1$, where ω_{2K} is the binding energy of the electrons to be ejected.

Bang and Hansteen[10] calculated in a semiclassical approximation the effect of the Coulomb deflection of the incoming particle by the target nucleus on the differential cross section. Incorporating their results to leading terms, one obtains[2]

$$\sigma_K = 9E_{10}(\pi d q_0)\sigma_K{}^0, \tag{4}$$

where $2d = Z_1 Z_2/E_1$ is the distance of closest approach; $E_{10}(x)$ is an exponential integral which is tabulated.[11] The curves marked "Coulomb" are calculated from Eq. (4). Clearly the Coulomb deflection accounts only for part of the discrepancy between theory and experiment.

Brandt *et al.*[2] showed that in slow collisions the interaction between the K electrons of the target and the incoming particle can have a marked effect on the ionization cross section. If this interaction is incorporated as a perturbation on ω_{2K} one finds to leading terms

$$\sigma_K = 9\epsilon^{-9}E_{10}(\pi d q_0 \epsilon)\sigma_K{}^0, \tag{5}$$

where $\epsilon = \epsilon(Z_1, Z_2, v_1)$ is given in Ref. 2. The curves in Figs. 1–3 marked "Binding" represent Eq. (5). Within experimental accuracy, the data

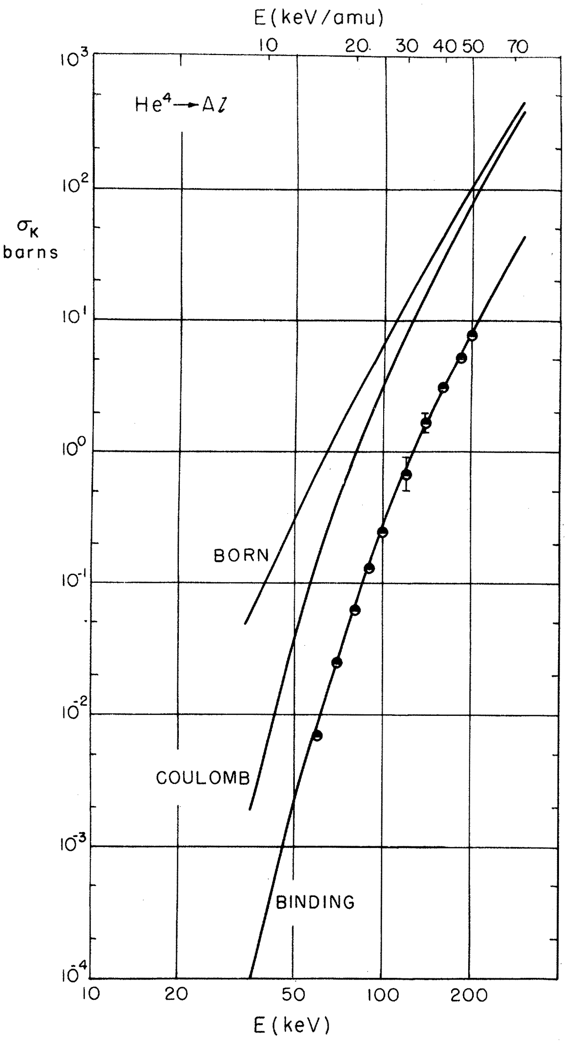

FIG. 3. Aluminum *K*-shell ionization cross section for He^4.

agree with the theory in this form.

A sensitive test of the theory can be made by analyzing at equal velocities the ratio of the cross sections for H and He as a function of particle velocity. The uncertainties in the absolute magnitude of the cross sections cancel. The results are shown in Figs. 4 and 5. Figure 4 plots the velocity dependence of the ratio $\sigma_K(\mathrm{He}^4)/\sigma_K(\mathrm{He}^3)$. It tests the Coulomb correction in Eq. (4), because the difference in the binding correction contained in Eq. (5) is less than 5% for these two isotopes, i.e., less than the uncertainty of the data. In this sense, Fig. 4 gives direct experimental evidence of the effect of the Coulomb deflection of the incoming particle by the target nucleus on the *K*-shell cross sections for ionization by slow charged particles. The ratio $\sigma_K(\mathrm{He}^4)/4\sigma_K(\mathrm{H}^1)$ shown in Fig. 5 varies over a factor of 2 in our energy range and exhibits clearly the effect of the binding of the *K* electrons to the incoming particle. In fact Fig. 5, in conjunction with the conclusion drawn from Fig. 4, is direct experimental confirmation of the effects of Coulomb deflection and of binding on the cross sections as predicted by Eq. (5).

In conclusion we find for protons and helium ions on aluminum that the experimental ionization cross sections agree with the theory as given by Brandt *et al.*[2]

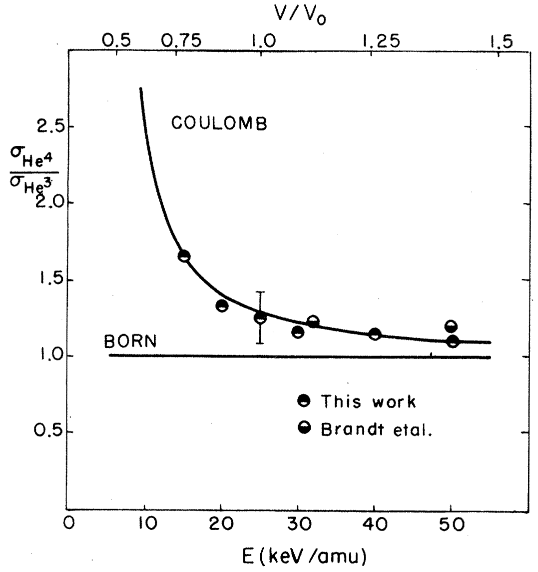

FIG. 4. The cross section ratio $\sigma_{\mathrm{He}^4}/\sigma_{\mathrm{He}^3}$ for aluminum as a function of incident ion energy per amu.

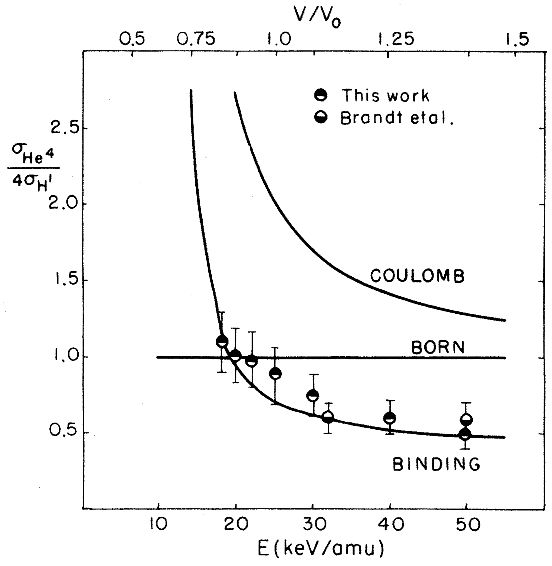

FIG. 5. The cross section ratio $\sigma_{\mathrm{He}^4}/4\sigma_{\mathrm{H}^1}$ for aluminum as a function of incident ion energy per amu. The two values of σ_{H^1} below 22 keV/amu are extrapolations (cf. Fig. 1).

ACKNOWLEDGMENT

We thank Mr. R. Robinson for his help in the accelerator operation and his assistance in performing the experiments.

---

*Work supported by the U. S. Atomic Energy Commission.

[1] For a general review, cf. E. Merzbacher and H. W. Lewis, Encyclopedia of Physics, edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. 34, p. 166.

[2] W. Brandt, R. Laubert, and I. Sellin, Phys. Rev. 151, 56 (1966).

[3] J. M. Khan, D. L. Potter, and R. D. Worely, Phys. Rev. 139, A1735 (1965).

[4] J. H. Ormrod, J. R. MacDonald, and H. E. Duckworth, Can. J. Phys. 43, 280 (1965).

[5] R. D. Moorhead, J. Appl. Phys. 36, 394 (1965).

[6] W. White and R. M. Mueller, J. Appl. Phys. 38, 3660 (1967).

[7] R. Laubert and W. Brandt, Bull. Am. Phys. Soc. 12, 1074 (1967).

[8] R. W. Fink, R. C. Jopson, Hans Mark, and C. D. Swift, Rev. Mod. Phys. 38, 513 (1966).

[9] T. Huus, J. Bjerregaard, and B. Elbek, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 30, No. 17 (1956).

[10] J. Bang and J. M. Hansteen, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 31, No. 13 (1959).

[11] Handbook of Mathematical Functions, edited by M. Abramowitz and I. A. Stegun, National Bureau of Standards (U. S. Government Printing Office, Washington, D. C. 1964), Appl. Math. Ser. 55, Chap. 5, p. 245 *ff*.

PHYSICAL REVIEW VOLUME 178, NUMBER 1 5 FEBRUARY 1969

Charge-Transfer Cross Sections for Negative Ions on Atomic and Molecular Targets*†

W. R. Snow,[†] R. D. Rundel,[§] and R. Geballe

Department of Physics, University of Washington, Seattle, Washington 98105

(Received 23 September 1968)

Charge-transfer cross sections for H^- on O, O_2, and NO_2; O^- on H, O, H_2, O_2, and NO_2; and C^- on H and O have been measured over an energy range of 0.5 to 4 keV using a modulated crossed-beam apparatus. The experimental cross sections are compared with theories of resonant and nonresonant charge transfer based on a two-state approximation. For the reactions $H^- + O \rightleftarrows O^- + H$, the cross sections are found to be consistent with detailed balancing. The effect of electron detachment on charge-transfer cross sections is discussed.

INTRODUCTION

Charge-transfer collision phenomena involving negative ions have not generally been investigated as extensively as those involving positive ions. Measurements of charge-transfer cross sections for atmospheric negative ions have been made in the range of a few electron volts to a few hundred electron volts by Bailey,[1] Rutherford and Turner,[2] and Paulson.[3] In the energy range of a few hundred to a few thousand electron volts, which is covered by the present work, Hummer,[4] *et al.*, have made an absolute measurement of the $H^- + H$ resonant charge-transfer cross section, and Bydin[5] has measured charge-transfer cross sections for negative ions of some of the alkali metals.

This paper contributes experimental data which, it is hoped, will further the understanding of negative ions in general and the charge-transfer process in particular, and discusses these data in terms of current theoretical approaches to charge transfer for both negative and positive ions.[6–11]

Measurements have been made over an energy range of 0.5 to 4 keV, for the following reactions:

$$O^- + O_2 \rightarrow O + O_2^- , \tag{A}$$

$$H^- + O_2 \rightarrow H + O_2^- , \tag{B}$$

$$O^- + H_2 \rightarrow O + H + H^- , \tag{C}$$

$$O^- + NO_2 \rightarrow O + NO_2^- , \tag{D}$$

$$H^- + NO_2 \rightarrow H + NO_2^- , \tag{E}$$