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Role of K-shell vacancies in determining charge-state fractions for heavy ions emerging from solids*

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The development of projectile K vacancies in heavy ions passing through solids has recently been studied using both target and projectile x-ray yields. The analysis of these results implies that the post-foil charge-state fractions will exhibit a target thickness dependence which is related to the vacancy production and quenching processes for the K shell of the projectile as it moves in the solid. We report experimental results for the charge-state fractions of 54-MeV S ions on thin foils of C, Al, Ti, and Ni. We propose a model which accounts for both the target thickness and the target-atomic-number dependences of the individual charge-state fractions.

I. INTRODUCTION

The description of nondeviable components observed in the study of canal rays was formulated by Wien[1] in 1908. His interpretation of the experimental observations assigned the origin of these components to ions which have undergone neutralizing collisions with the surrounding atomic systems. The system was analyzed using differential equations which described the ion-atom interactions in terms of the mean free path per electron for charge-changing collisions. In the following years a large number of results by many workers ensued. In 1958, Allison[2] summarized the state of knowledge for H and He charge-changing collisions in gases and solids. Allison presents a system of rate equations appropriate to the description of two- and three-component systems. These equations form the basis upon which such simple systems have been studied and analyzed.

With the availability of higher-energy particle accelerators and heavier ions, a natural extension of the studies of charge-changing collisions to more complex systems has evolved. In 1972, Betz[3] summarized the state of such studies for heavy ions moving in target media ranging from dilute gases to solids. In the case of dilute gases he set forth a system of rate equations which are an extension of the description previously given by Allison.[2] Specifically, the differential equation describing the rate of change in the charge fraction Y_q with respect to the the target thickness X, measured in appropriate units, is

$$\frac{dY_q}{dX}=\sum_{q\neq q'}[\sigma(q,q')Y_{q'}-\sigma(q',q)Y_q], \tag{1}$$

where $\sigma(q,q')$ and $\sigma(q',q)$ are the cross sections associated with charge-changing collisions in which q' goes to q and q goes to q', respectively. In practice there have been three basic restrictions on the use of Eq. (1): (i) The cross sections describe charge-changing collisions only, and hence elastic scattering collisions and collisions in which excitations occur are excluded; (ii) the target system is dilute enough so that the collision frequency can be neglected, i.e., all ions are assumed to be in their ground states at the time of a charge-changing collision; and (iii) the influence of cascade transitions leading to rearrangement of the charge-state fractions are not included. These three restrictions are intimately related and are a result of the exclusion of excitations for the ion species Y_q. Indeed, a large collection of data for charge-changing collisions studied under single-collision conditions has resulted (see Ref. 3).

In his review article, Betz also addresses the question of ions undergoing changes in charge state while penetrating solid targets. The three restrictions listed above are violated for ions moving in solids. Previous descriptions for the charge states of ions moving in solids at high velocities have been presented by Bohr and Lindhard[4] (BL) and Betz and Grodzins[5] (BG). Their two models attemp to resolve the differences observed in charge-state fractions for ions moving in dilute gases and in solids. The basis for both models is the incorporation of a high degree of excitation in the ion as it moves through the solid. In the BL model it is assumed that the excitations result in the loss of loosely bound electrons, thus causing a shift in the average charge state to a larger value than is found for charge-changing collisions in dilute gases. The BG model assumes that the interactions in the solid lead to a charge fraction system which exists in a state of high excitation, and hence cascading processes outside the solid lead to the higher observed average charge states. The basic question raised by these two points of view is found in whether the outer electrons are still loosely bound to the ion when it exits the foil or have they been lost in the continuum while inside the solid. These two models have been the subject of study and controversy. There has been to date a lack of definitive evidence upon which a delineation between the two models can be based. It is worthwhile to note that both the BL and BG models are based upon excitation of the ionic system as it progresses through the solid. However, the explicit dependence of the individual charge-state fractions on the fundamental ion-atom interactions is not developed in either model.

There have been two basic types of experimental results reported recently which establish the importance of inner-shell excitations in the ion as it traverses a solid target:

(a) Betz *et al.*[6] employed a two-component model to describe the development of a K vacancy in an ion moving through a solid in order to develop a method of determining the lifetimes of excited states associated with the filling of that vacancy. In this model, the K-vacancy-bearing fraction of the beam, $Y_1(X)$, is given by

$$Y_1(X) = (\sigma_V/\sigma)(1 - e^{-\sigma X}) , \tag{2}$$

where σ_V is the vacancy production cross section for the K shell of the projectile, σ is the total cross section for the K shell of the projectile, i.e., $\sigma = \sigma_V + \sigma_Q$ where σ_Q represents the interactions leading to the filling of the K vacancy, and X is the target thickness in appropriate units. Cocke *et al.*[7] have used this result to describe metastable K-vacancy-bearing fractions in beams of Si, S, and Cl emerging from thin solid targets of C, Al, Ti, and Ni. Bell *et al.*[8] have also used this approach to describe the equilibrium populations of multiplet states for S ions passing through thin solids.

(b) The two-component model has also been used in the analysis of target K-shell x-ray production for heavy ions incident on solids. Hopkins[9] studied the changes of K-shell vacancy populations for Cl ions moving in C. He used a thin layer of Cu on the C foils to detect the changes in K-vacancy populations taking place in the C foils. Groeneveld *et al.*[10] and Feldman *et al.*[11] have reported results for heavy ions incident on solid Al targets. Gray *et al.*[12] extended these types of measurements for Cl on solid Cu targets of varying thickness by studying the behavior of the target x-ray production cross sections for incident ions with and without K-shell vacancies. Gardner *et al.*[13] extended these results to include the development of a three-component model in which ions with 0, 1, and 2 K-shell vacancies are treated. Schiebel *et al.*[14] have applied the results of Ref. 12 to target x-ray production for the L shell in the case of F ions incident upon solid Ag targets.

Both techniques rest upon the same basis. The measurements of target x-ray production for heavy ions has provided further evidence that the consideration of excitations in the projectile system are very important. The creation and annihilation of K-shell vacancies in the projectile and the coupling of those vacancies to the target shell of interest through the electron-transfer channel rests on the basic assumptions inherent in the description of the projectile inner-shell vacancy populations. In the case of studies of projectile x rays, the K vacancies are observed through the radiative channels. Observations of target radiation reflect the role of projectile K vacancies through measured target thickness dependences of the target radiation.

The analysis of data[13] for target x-ray production for S ions incident on Cu foils has shown that there is a strong dependence of the K-vacancy-bearing fractions of the beam on target thickness and initial condition of the incident ion. It was observed that the equilibration distance in Cu for the S K shell is approximately 60 μg/cm^2.

In those cases where catastrophic rearrangement of the vacancy populations does not occur upon exit of the ion from the foil into the vacuum, the information about the K-vacancy population of the ion beam is impressed upon the charge-state fractions observed downstream. We propose a model for the charge-state fractions of a heavy-ion beam that has passed through a solid target of thickness X which is based upon a two-component description of the K-vacancy states of the projectile. We include the effects of cascading in modifying the observed charge-state fractions by the use of a simple approximation. Previous work has shown that the charge-state fractions depend upon the foil thickness.[15] Our work will show that the charge-state fractions of heavy ions depend upon the solid target thickness and the microscopic ion-atom interactions which govern the K-shell populations of the projectile. We present experimental results for 54-MeV S ions incident upon C foils and on targets of Al, Ti, and Ni. The results of this work establish the need to view the individual charge-state fractions of a heavy-ion beam moving in a solid in terms of the fundamental interactions which govern the inner-shell populations of the ion.

II. EXPERIMENTAL

The measurements of charge-state fractions for S ions moving in thin self-supporting C foils were made using a 54-MeV S^{8+} ion beam obtained from the model EN tandem Van de Graaff accelerator at Kansas State University. The experimental arrangement is as shown in Fig. 1. The ion beam was passed through carbon prestripping foils of

10- to 20-μg/cm^2 thickness which were placed in the drift tube between the exit of the accelerator and the 90° analyzing magnet. Adjustable slits were placed in front of the prestripping foil in order to define the beam geometry. The target foils were placed in the drift space between the 90° analyzing magnet and the switching magnet. The switching magnet was used to select the charge state of interest after the interaction region.

The target foils were obtained from the Arizona Carbon Foil Co. and were mounted on target frames having a 0.32-cm-diam aperture for the passage of the ion beams. Blank target frames were used to investigate contributions to the charge-state fractions in the beam associated with scattering from the edges of the target frames. No measurable charge-state fractions were observed for other than the incident beam. The beam optics were established at the detection region with a blank target frame in the target position. No adjustments were made in the beam geometry during a set of measurements. Additionally, equilibration charge-state fractions were measured for self-supporting foils of Al (135 μg/cm^2), Ti (240 μg/cm^2), and Ni(180 μg/cm^2).

The ions were charge state analyzed by the second magnet and allowed to impinge upon Au scattering foils of ~300–600 μg/cm^2 thickness. A Rutherford scattering detector was placed on an adjustable mount in the front-scattering hemisphere to detect the scattered ions. During a given set of charge-state fraction measurements, the second magnet was scanned and the number of ions in each charge state was recorded against a monitor which was associated with the number of ions incident upon the target. Two different monitor methods were employed during the experiment.

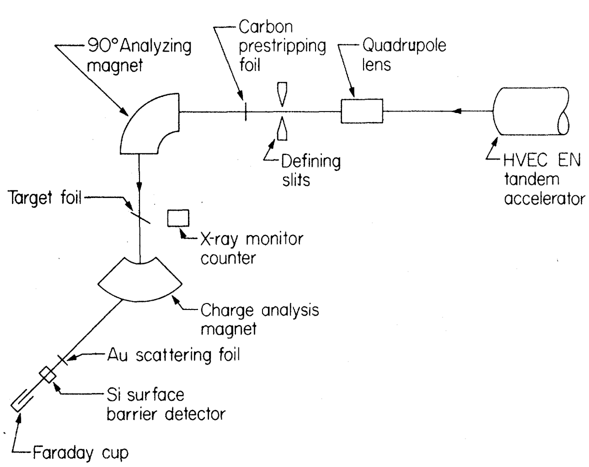

FIG. 1. A diagrammatic representation of the experimental arrangement.

The target current was monitored for each target. In addition, a gas flow proportional counter was employed to monitor the beam x rays arising from the passage of the S beam through the target material. The targets were mounted so that only x rays from the transmitted beam were observed. Both monitor systems worked quite well with a reproducibility of order 5–10%.

A typical set of measurements for the charge-state fractions was made by placing a target of thickness X in the beam. The 90° analyzing magnet was used to select a 54-MeV sulfur beam in either charge state 11^+ or 15^+. The intensities of the charge states leaving the target foil were measured relative to the monitor system, and the charge-state fractions were determined by normalization of each intensity to the total intensity for all states detected. Charge states from 9^+ to 16^+ were observed with the 16^+ ions having an intensity of $\leq 10^{-4}$ times the maximum in the charge-state distribution.

The use of a scattering foil to detect the ions after charge-state selection by the second magnet was chosen because of the small currents associated with the 9^+ and 15^+ charge states. Also the use of a scattering foil facilitated the coverage of a dynamic range in ion intensity which covered more than three orders of magnitude. Direct detection of the ions was investigated but was abandoned from considerations of count rate and accelerator stability. Studies of the scattering-foil–detector geometry were made by scanning the analyzed ions in a given charge state over a small range of changes in the magnetic field of the final analyzing magnet. A distribution of detected ions having a Gaussian shape was observed. For each measurement of the number of ions in a particular charge state, the magnet was adjusted to the maximum intensity in the distribution. An intensity was recorded, the magnet was once again maximized, and a second intensity was recorded. The reproducibility resulting from this procedure was typically within the statistics of the measurement. A Hall probe was used in the final analyzing magnet to monitor the approximate relative magnetic field for each charge state that was analyzed.

Care had to be exercised to assure the purity of the ion beam which was analyzed by the 90° magnet. In the case of S^{15+}, a number of beams having different energies were observed to be passed through both magnets. However, the use of the scattering foil as a detector allowed the identification of the beam component of interest through the energy selection obtained from the Si detector. It is noted that the use of the Faraday cup would not have allowed for the energy discrimination obtained by the scattering-foil technique.

III. MODEL

We propose a model for the charge-state distributions based on factorization of K-shell and higher-shell processes. Consider an ion beam moving in a solid at some energy E_1. The K shell of the ion may exist in one of two states describable in terms of Y_0 and Y_1, i.e., the fraction with no or one K-shell vacancy, respectively. The double K vacancy is neglected in this model at present. Work by Gardner *et al.*[13] shows that the double K-vacancy fraction is small (i.e., $<3\%$) for 54-MeV S ions moving in Cu. The ion may be excited and have i electrons in states other than the K shell. The quantity g_i is defined as the probability that there are i electrons outside of the K shell after the ion emerges from the target foil. The g_i's are determined by collisional processes within the foil, exit-surface interactions, and post-foil relaxation. In order to obtain a tractable model, we assume that the distribution of electrons in shells higher than the K shell is not dependent upon the state of the K shell. We further assume that relaxation of excitations resident in these shells does not depend on whether K vacancies are present in the ion. These assumptions must be only approximately correct, but lead to a rather simple model capable of describing the major features of our data. The g_i's are assumed to be equilibrated for foil thicknesses of $\gtrsim 5\ \mu\text{g/cm}^2$ for a material like carbon. This assumption is based upon geometrical scaling of the scale length for K-shell processes observed in the work of others and on measured cross sections for charge-changing processes in the L shell.[16] The charge-state fractions ϕ_j, where j is the total number of electrons in the ionized atom, are then proposed to be

$$\begin{aligned} \phi_1 &= Y_1 g_0 , \\ \phi_2 &= Y_0 g_0 + Y_1 g_1 \\ \phi_3 &= Y_0 g_1 + Y_1 g_2 , \\ &\cdots , \\ \phi_j &= Y_0 g_{j-2} + Y_1 g_{j-1} . \end{aligned} \tag{3}$$

The fractions Y_0 and Y_1 are determined by the relationships

$$\frac{dY_1(X)}{dX} = \sigma_V Y_0(X) - \sigma_Q Y_1(X) \tag{4}$$

and

$$Y_0(X) = 1 - Y_1(X) ,$$

where σ_V is the vacancy production cross section for the K shell of the projectile and σ_Q is the cross section for quenching the projectile K-shell vacancies. These equations have the familiar solution

$$Y_1(X) = (\sigma_V/\sigma)(1 - e^{-\sigma X}) + A e^{-\sigma X} , \tag{5}$$

where $\sigma = \sigma_V + \sigma_Q$ and A is determined by the initial condition of the incident beam, i.e., $A = 1$ for an ion with charge $Z_1 - 1$ and $A = 0$ for ions with incident charges below $Z_1 - 2$. The heliumlike beam contains a small but unknown fraction of $(1s2s\,^3S_1)$ metastables and hence is excluded from the experiment and analysis.

The expressions for the charge-state fractions as given in Eqs. (3) describe the ion at the target foil. The ions are detected after charge-changing relaxation downstream associated with the filling of K vacancies. In order to bring in considerations of such cascade effects, it is assumed that only nearest-neighbor cascades are important. This is very simple assumption but it allows cascading to be included, if only in the lowest order of approximation. In including cascading in this approximation one then has to account for the radiative decay and Auger decay of the various components contained in the charge-state fractions given by Eqs. (3). The measured charge-state fractions are thus

$$\begin{aligned} \Phi_1 &= Y_1 g_0 \omega_1 + Y_1 g_1 (1 - \omega_2) , \\ \Phi_2 &= Y_0 g_0 + Y_1 g_1 \omega_2 + Y_1 g_2 (1 - \omega_3) , \\ \Phi_3 &= Y_0 g_1 + Y_1 g_2 \omega_3 + Y_1 g_3 (1 - \omega_4) , \\ &\cdots , \\ \Phi_j &= Y_0 g_{j-2} + Y_1 g_{j-1} \omega_j + Y_1 g_j (1 - \omega_{j+1}) , \end{aligned} \tag{6}$$

where ω_j is the K fluorescence yield for the ion with j electrons. These equations can be rewritten in a general form

$$\Phi_j(X) = g_{j-2} + [\sigma_V/\sigma + (A - \sigma_V/\sigma) e^{-\sigma X}](\beta_j - g_{j-2}) \tag{7}$$

by using Eq. (5). It is noted that $g_j = 0$ for $j < 0$. The quantity β_j is

$$\beta_j \equiv g_{j-1} \omega_j + g_j (1 - \omega_{j+1}) \tag{8}$$

and it contains the effects of cascade transitions for the ion. If a more complex assumption of cascading is included, the expression for β_j will be modified to include the additional considerations. However, the form of Eq. (7) will remain intact.

The limiting cases for $\Phi_j(X)$ are given below:

$$\text{Case I: } A = 0;\ X \to 0 , \quad \Phi_j(X) \to g_{j-2} ; \tag{9}$$

$$\text{Case II: } A = 1;\ X \to 0 , \quad \Phi_j(X) \to g_{j-1} \omega_j + g_j (1 - \omega_{j+1}) ; \tag{10}$$

$$\text{Case III: } A = 0, 1;\ X \to \infty , \quad \Phi_j(X) \to g_{j-2} + (\sigma_V/\sigma)[g_{j-1} \omega_j + g_j (1 - \omega_{j+1}) - g_{j-2}] . \tag{11}$$

The Φ_j are quite sensitive to the presence of K vacancies in the beam. In case III the saturation value depends upon σ_V/σ, which is a function of Z_2 as well as Z_1. It is shown later in this work that the equilibrium charge-state fractions for S ions depend on Z_2.

In summary, the two-component model that is proposed for the description of charge-state fractions arising from collisions in a solid target predicts the following: (i) There is a dependence on target thickness for *all* charge-state fractions of an ion beam moving in a solid. This dependence will become negligible for $\sigma_V/\sigma \ll 1$. (ii) The value of Φ_j for vanishingly thin targets is a measure of the equilibrated g_{j-2} for incident ions that do not have K-shell vacancies. (iii) The equilibration value for Φ_j depends upon σ_V/σ and hence upon Z_1 and Z_2.

The present model applies to those ion-target combinations where σ_V/σ is not negligible. For very heavy ions incident upon light foil materials at relatively low velocities, e.g., 30-MeV U on C, the influence of K-shell ionization in the projectile is of little importance. However, considerations similar to those advanced in the proposed model which addresses the effects of K-shell vacancies on charge-state distributions may be appropriate for the description of charge-state distributions for the L shell, M shell, etc. Indeed, the data of Ref. 15 show effects for L-shell vacancies which may be correlated to the basic foundations of the present work for S ions on thin solid targets.

IV. RESULTS AND DISCUSSION

The measured charge-state fractions for 54-MeV S ions on carbon foils ranging in thickness from 4- to 120-μg/cm^2 are given in Fig. 2. The charge-state fractions, Φ_1 through Φ_6, exhibit a thickness dependence which has been fitted with Eq. (7) using the method of least squares. The incident charge states were chosen as 11^+ and 15^+ in order to determine the thickness dependence for ions which had initial conditions of $A=0$ and $A=1$, respectively. The values of the parameters g_j, β_j, $\langle\sigma_V\rangle$, and $\langle\sigma\rangle$ extracted from the model calculations are given in Table I. The intercepts for incident charge state 11^+ were used to determine the values of g_0 through g_5.[17] The values of $\langle\sigma_V\rangle$ and $\langle\sigma\rangle$ were determined by taking the average of the values of these cross sections which had been obtained by fitting each individual set of data for a given incident charge-state and final charge-state fraction. The variations in σ_V taken about the average $\langle\sigma_V\rangle$ were $\leq\pm 10\%$ over six different sets of data. The fits shown in Fig. 2 were made using the common values of $\langle\sigma_V\rangle$ and $\langle\sigma\rangle$.

The values of β_j given in Table I are derived in two ways. The quantities β_j^c represent calculations of the effects of cascading on the Φ_j using Eq. (8). The fluorescence yields used in these calculations were deduced from K x-ray production data for Cl

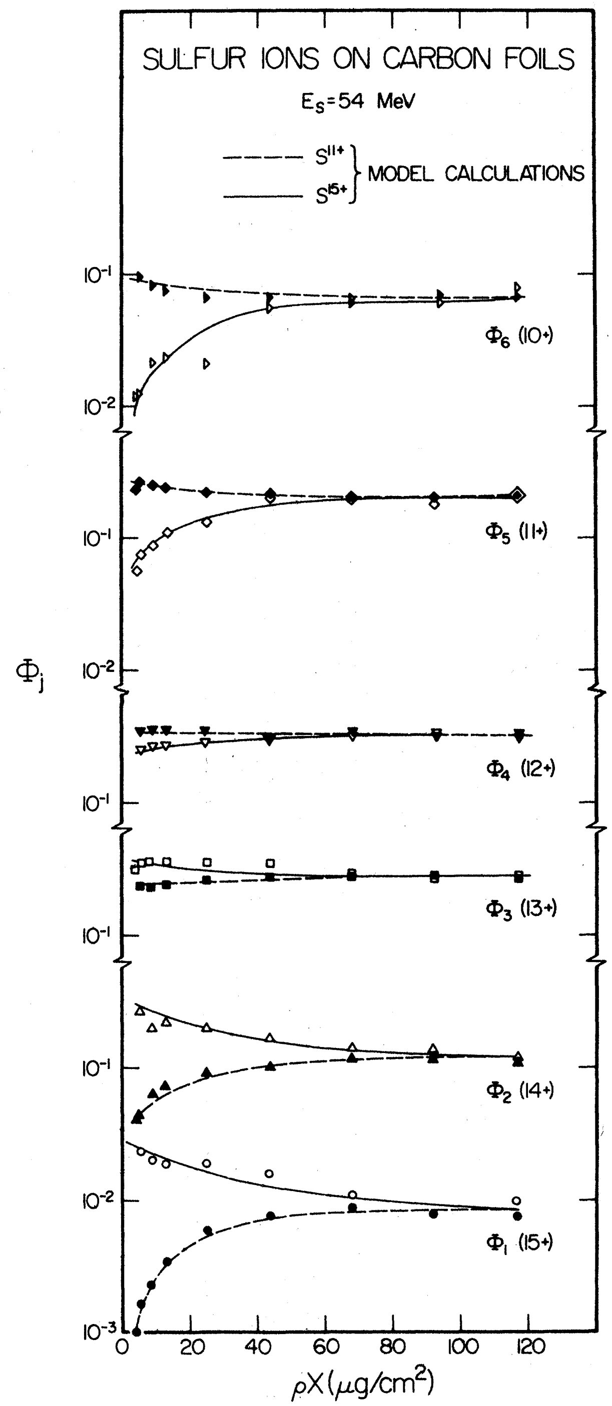

FIG. 2. Experimental results for the measured charge-state fractions Φ_1 through Φ_6 for 54-MeV S ions incident upon carbon foils of varying thickness. The solid and dashed curves are calculated from Eq. (7).

TABLE I. Values of parameters used in calculating the charge-state fractions Φ_j, for $j=1-6$, as a function of the foil thickness. All cross sections are given in units of 10^{-19} cm^2.

j	ω_j [a]	g_j	β_j^f	β_j^c
0	1	0.027	...	...
1	1	0.22	0.027	0.027 [b]
2	1	0.34	0.31	0.32
3	0.7	0.27	0.38	0.40
4	0.4	0.093	0.22	0.18
5	0.26	0.016	0.041	0.037
6	0.2	...	...	...

$\langle\sigma_V\rangle = 2.3$, $\langle\sigma\rangle = 7.3$

[a] ω_j are from Ref. 18.
[b] $\beta_1 \equiv g_0$ as taken from Eq. (8).

ions incident upon H_2 by Macdonald.[18] Variations in β_j^c were investigated by arbitrarily decreasing the values of ω_j by 50%. The changes in β_j^c were $\lesssim 30\%$ using this procedure. The g_j's were taken from the measured intercepts of the S^{11+} data of the present work. The quantities β_j^f represent the values of these parameters which were obtained from the fitting procedure. The agreement between the β_j^f and the β_j^c suggests that the simple approximation of the nearest-neighbor cascades is appropriate for the charge states investigated. It is expected that this simple approximation may not be adequate for systems with large numbers of

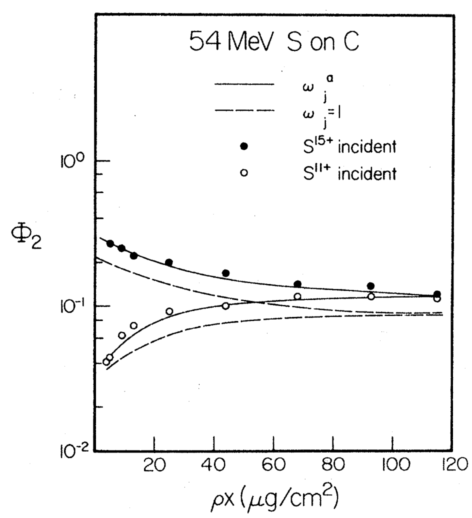

FIG. 3. An evaluation of the model calculation for Φ_2 to assess the effects of cascading on the observed charge-state fractions. Cascading is excluded by setting $\omega_j = 1$. The value of ω_j^a is taken from Table I.

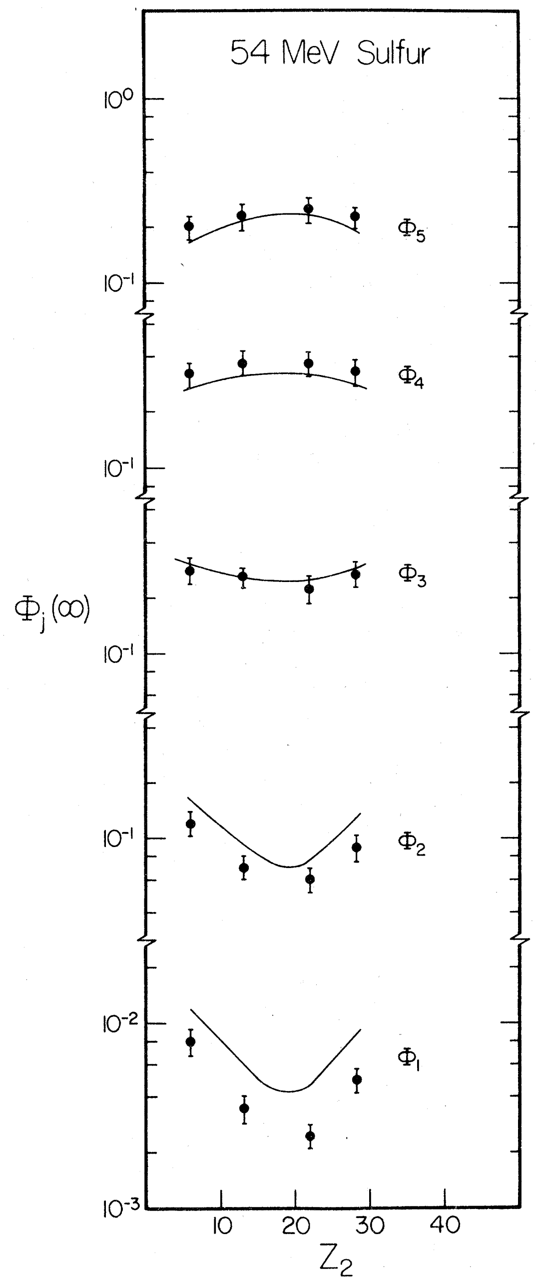

FIG. 4. Experimental results for the equilibration values of Φ_1 through Φ_5 as a function of Z_2 for 54-MeV sulfur ions on targets of C, Al, Ti, and Ni. The solid curves are calculated from Eq. (11).

electrons. However, over the range of present measurements the data support the approach that has been taken.

The model predictions for both incident charge states and all charge-state fractions recorded are in excellent agreement with the experimental data. The thickness dependences are reproduced by Eq.

(7) using a single set of projectile K-vacancy and quenching cross sections. Further $\langle\sigma_V\rangle$ and $\langle\sigma\rangle$ are in agreement with σ_V and σ as reported by Cocke *et al.*[7] for 50-MeV S ions incident on carbon foils.

In order to investigate the importance of the cascading, calculations of the thickness dependence of the charge-state fractions were also performed setting $\omega_j = 1$, $(j = 1, \ldots, 6)$, thus effectively removing the cascading. The values of $\langle\sigma_V\rangle$, $\langle\sigma\rangle$, and g_j were taken from Table I in these calculations; i.e., the data were not refitted to determine new values of these parameters. As the intercepts for the case $A = 0$ determine the g_j's, independent of the ω_j's, and the data for Φ_1 determine σ and σ_V, we do not expect a refitting procedure to change these parameters significantly. The results of eliminating the cascading are shown for Φ_2 in Fig. 3. Similar results are obtained for the other charge states. The effects of cascading as included in Eq. (7) are in agreement with the data. Elimination of the cascade contributions is not supported by the experimental results. This result agrees with the work of Bell *et al.*[8]

Equation (11), case III, gives the equilibrium values $\Phi_j(\infty)$. The role of the target foil material enters into the determination of $\Phi_j(\infty)$ through the cross sections σ_V and σ. Targets of C, Al, Ti, and Ni were used to obtain equilibration charge-state fractions for 54-MeV S ions. The results of the measurements for $\Phi_j(\infty)$ as a function of target atomic number are given in Fig. 4. The model calculations made using Eq. (11), with the (a)-model values of σ_V and σ from Ref. 7, are in excellent agreement with the data from the present work. The depression of the equilibrium K-vacancy fractions near matching target-projectile Z observed in the metastable yields of Ref. 7 appears here as a shift of the charge-state fractions to lower charge for $Z_2 \sim 20$. This effect is due to the large K-vacancy quenching cross section characterizing electron transfer between target and projectile K shell for matching Z.

In performing the calculations for Fig. 4, it was assumed that the g_j's were independent of Z_2. It is possible that the outer shells may achieve a statistical equilibrium which is not strongly dependent upon the structure of the host material. The assumption that the g_j's are independent of Z_2 is an area that is in need of further investigation. We observe a sharp break in the data for the Φ_j's for 54-MeV S ions incident on carbon foils having thicknesses less than 5 μg/cm^2. This characteristic of the data suggests that there is a rapid exponential decay in the thickness dependence which may be associated with the development of the g_j's. As the transfer of electrons from the target surface should be independent of the foil thickness for continuous foils, the rapid variation of Φ_j for $X \lesssim 5$ μg/cm^2 is considered not to be a surface effect such as recently discussed by Veje.[19] The determination of g_j for differing target materials and vanishingly thin targets is complicated by carbon surface contaminants, surface oxidation, and foil continuity problems. It is probable that the techniques employed in ultrahigh vacuum surface studies will have to be employed before a definitive investigation into the properties of the g_j's can result.

V. CONCLUSIONS

The results of the present work establish the role of the ion-target interactions in determining the target thickness dependence of the charge-state fractions for heavy ions moving at high velocities in solid targets. The model presented is successful in predicting the salient features of the data for the charge-state fractions as a function of foil thickness and target atomic number. The role of K-shell vacancies in the projectile in determining the post-foil charge-state fractions is clearly illustrated.

Our results tend to support the BG model to the extent that it is necessary to include post-foil charge-changing processes to explain the data. However, our model is somewhat more specific in that it speaks to the question of describing the individual charge-state fractions in terms of the K-vacancy populations at any distance X within a thin solid target. The individual characteristics of each charge-state fraction are thus defined once the relevant cross sections σ_V and σ, the outer-shell probabilities g_j, and the cascading parameters have been determined. Instead of addressing the question of mean charge state $\bar{q}$ or the width of the charge-state distribution Δq for ions after moving in solids, the model provides information on the individual charge-state fractions. Having the Φ_j allows one to calculate $\bar{q}$ and Δq after the ion has penetrated through a given thickness of a solid foil. The charge-state fractions for an ion passing through the target medium depend critically on the initial K-vacancy population of the incident ion. The overall consistency of the physical parameters derived from beam-foil results, target x-ray investigations, and the present measurements give us confidence that our picture of the development of K vacancies for ions moving in solids is correct.

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