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[16]Recalculation of E_r, Γ, and δ_p with Eq. (4.12) for the elastic case gave improved results for the two smaller couplings. The following values should be compared with the average values found in Table I of Ref. 5: $\lambda_{12} = 1$: $E_r = 90.1347$, $\Gamma = 0.001472$, $\delta_p = -0.2719$; $\lambda_{12} = 10$: $E_r = 91.2162$, $\Gamma = 0.1692$, $\delta_p = -0.1856$; $\lambda_{12} = 20$: $E_r = 94.3809$, $\Gamma = 0.7377$, $\delta_p = 0.0469$.

[17]Two remarks of caution are in order. First, when one partial width is significantly larger than the other (and if the background scattering is small), it turns out that severe cancellation may result in the calculation of either ρ_1 or ρ_2, so that $\rho_2 - \rho_1$ may be far from $\pi/2$. This effect was seen in model calculation *B*; however, as Table III partially indicates, the results obtained from the ρ_α with smaller σ_α are not affected by this difficulty. Second, extreme cancellation was seen when the three roots used were so similar that $S_t^{(n)}$ and $C_t^{(n)}$ $(t = 1, 2)$ were close for all three values of n. This occurred when one of the open-channel M_t (M_1 or M_2) was the same for all three roots used. In this work, the triplets were chosen to avoid this difficulty.

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Si $K\alpha$ X-Ray Spectrum Produced by 30-MeV Oxygen Bombardment*

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$K\alpha$ x-rays of Si were produced by 30-MeV oxygen bombardment on a Si wafer. Nine $K\alpha$ lines are observed with an energy resolution of 2.5 eV at energies of 1739.78 ($K\alpha_{1,2}$), 1750.8 $\pm$ 0.5 ($K\alpha_3$), 1753.1 $\pm$ 0.6 ($K\alpha_4$), 1762.6 $\pm$ 0.5 ($K\alpha_5$), 1766.4 $\pm$ 0.6 ($K\alpha_6$), 1775.3 $\pm$ 0.6, 1778.8 $\pm$ 0.5, 1794.2 $\pm$ 0.6, and 1809.7 $\pm$ 0.8 eV. The intensity pattern is very nearly symmetric and the envelope approximately Gaussian. The energies of these lines are found to agree with Hartree-Fock-Slater calculated energies for $K\alpha$ transitions from Si atoms with initial configurations $(1s)^{-1}(2p)^{-n}$ for $n = 0$, 1, 2, 3, 4, and 5.

I. INTRODUCTION

Characteristic x rays produced by bombarding targets with heavy ions at MeV energies have produced x-ray spectra unlike any previously seen with other means of excitation.[1-6] The K and L x-ray lines obtained with high-resolution Si (Li) detectors are shifted to energies higher than those excited by other than high-energy heavy-ion bombardment. These energy shifts are attributed to a high probability of multiple inner-shell ionization created by atom-ion collisions.[2] Two recent experiments[7,8] using high-resolution crystal spectrometers have resolved some of the structure in the uncharacteristic $K\alpha$ spectra. In the case of Al plus 5-MeV N^+ beams,[7] six $K\alpha$ lines are observed. One of these lines is the normal $K\alpha_{1,2}$ line whereas the other lines agree with Hartree-Fock-Slater (HFS) calculated $(1s \to 2p)$ transition energies for the five possible initial configurations $(1s)^{-1}(2p)^{-n}$, where $n = 1$, 2, 3, 4, and 5. The production of $(2s)$ holes is not manifested in the spectra as distinct peaks due to large Coster-Kronig widths which transfer $(2s)$ holes to the $(2p)$ shell[9] before a $K\alpha$ event can occur. The observed intensity pattern is nearly symmetric and the envelope nearly Gaussian. In the case of Fe plus 30-MeV O^{5+} beams[8] only three lines were observed corresponding to $1s \to 2p$ transitions from initial configurations $(1s)^{-1}$ $(2p)^{-n}$, where $n = 0$, 1, 2. Additional m-shell vacancies are deduced in the latter work.

In the present experiment 30-MeV O^{5+} bombardments on Si are used to observe the Si $K\alpha$ spectrum with an over-all resolution full width at half-maximum (FWHM) of ~2.5 eV. At this bombarding energy the observed spectrum is very similar to that given in Ref. 7. Multiplet structure is observed for three of the $K\alpha$ peaks so that a total of nine

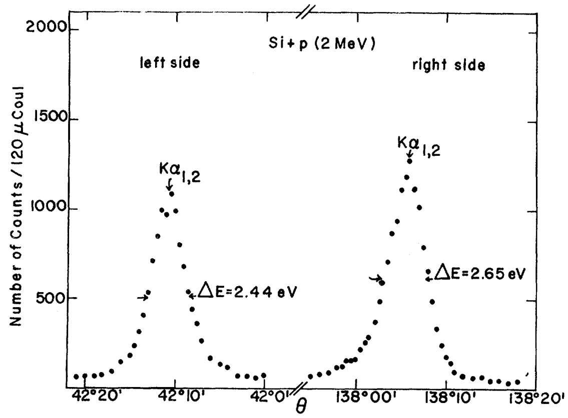

FIG. 1. Si $K\alpha$ spectra taken with a 2-MeV proton beam on the left- and right-hand sides of the spectrometer.

lines are resolved.

II. EXPERIMENTAL PROCEDURE

In the present experiment the 30-MeV O^{5+} beam was produced by the University of Texas tandem Van de Graaff and was used to bombard a thick Si wafer. The amount of oxygen beam on target was kept at approximately 300 nA. The target was thick enough to stop the beam and was positioned at 45° with respect to the incident beam. Spectra were also taken with 5-MeV protons from the tandem and with 2-MeV protons from the KN Van de Graaff. The KN is used in calibration runs.

The x-rays were energy analyzed by means of a Bragg crystal spectrometer[10] which was equipped with a horizontal entrance Soller collimator with angular divergence of 2 min and with a vertical exit Soller collimator with angular divergence of 20 min. An ammonium dihydrogen phosphate (ADP) crystal was used as the analyzer. By measuring the profile on both sides of the spectrometer with 2-MeV protons on Si as shown in Fig. 1, the Bragg angle θ_B was measured[11] to be 42° 2′ 15″ with an estimated error of 1′30″. The crystal $2d$ spacing was measured[12] to be 10.642 ± 0.004 Å using the above value of θ_B and assuming the $K\alpha_{1,2}$ energy to be 1739.78 eV. This energy was obtained from the $K\alpha_1$ and $K\alpha_2$ energies of 1739.98 and 1739.38 eV, respectively, as given by Bearden,[13] and the $K\alpha_2/K\alpha_1$ ratio of 0.5042 given by Scofield.[14] This technique neglects the centroid shift due to the difference in absorption of the $K\alpha_1$ and $K\alpha_2$ x rays. The maximum error due to this effect would be $K\alpha_1 - K\alpha_{1,2} = 0.2$ eV. The uncertainty of 0.004 Å in determining $2d$ leads to an error of ~0.5 eV in the energy of the Si $K\alpha$ lines. This error is in addition to the error in locating the position of each line relative to the $K\alpha_{1,2}$ line.

The spectrometer was situated at 90° with respect to the beam axis and shared a vacuum system common to the beam line. The detector was a gas-flow proportional counter[15] mounted behind the exit collimator of the spectrometer. The counter had a 6-μ Hostaphan foil[15] window and was operated at + 2000 V with a 10–90% mixture of methane argon. At each angular setting of the spectrometer the number of x rays counted was recorded for a given number of μC of beam on the target. The current-integrator pulse output was accumulated in a master scaler with a present count. The master scaler controlled a slave scaler which accepted only pulses near the Si $K\alpha$ pulse height from the flow proportional counter after being amplified and selected by means of a single-channel analyzer. After each counting sequence the new angular setting of the spectrometer was reset manually.

III. RESULTS AND DISCUSSION

The measured Si $K\alpha$ x-ray spectrum obtained with 30-MeV oxygen ions is shown in Fig. 2 and the energies obtained for the peaks are shown in Table I. In the first column of the table the nine observed $K\alpha$ x-ray lines are labeled according to Fig. 2. Column 2 lists the relative intensities and column 3 lists the measured Bragg angles for each peak. All the angles were zero corrected so as to make θ_B agree with the value obtained with 2-MeV protons as described in Sec. II. Column 4 gives the calculated energies of the nine resolved peaks. Peak A has a resolution FWHM of 2.4 eV. As can be seen from Fig. 2 the peaks become broader in going from A to I. Peaks H and I may well be un-

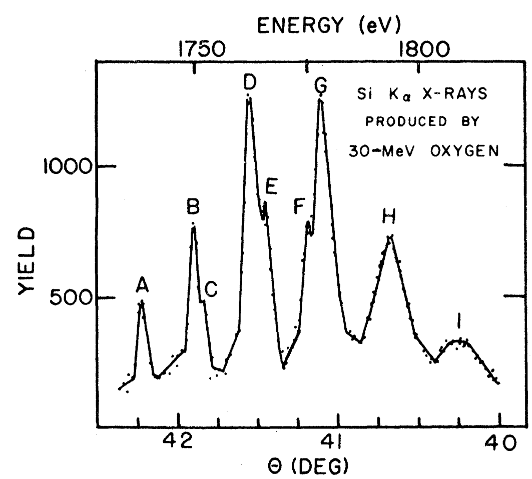

FIG. 2. Nine Si $K\alpha$ satellite lines are resolved in this spectrum produced by 30-MeV oxygen bombardment. The measured spectrometer angle in degrees can be read at the bottom of the figure and the corresponding energy in eV is given at the top of the figure. The yield is the number of counts for a given number of μC of beam on the target.

TABLE I. Si $K\alpha$ lines from 30-MeV oxygen bombardment.

Label[a]	Relative intensity	θ_B [b]	Energy (eV)[c]
A	1.0	42° 2′ 15″	1739.78
B	2.31	41° 42′ 45″	1750.8 ± 0.5
C		41° 38′ 45″	1753.1 ± 0.6
D	4.59	41° 22′ 15″	1762.6 ± 0.5
E		41° 15′ 45″	1766.4 ± 0.6
F	5.16	41° 0′ 45″	1775.3 ± 0.6
G		40° 54′ 45″	1778.8 ± 0.5
H	3.95	40° 29′ 15″	1794.2 ± 0.6
I	1.67	40° 4′ 15″	1809.7 ± 0.8

[a]Labels refer to peaks in Fig. 2.
[b]θ_B for peak A is determined as discussed in Sec. II. All other angles are based on this value.
[c]The energy of peak A is taken from Ref. 13. All other energies are determined relative to this value.

resolved multiplets.

In Table II a comparison of our results to previous experiments is made. Column 3 of this table lists the energies of the Si $K\alpha$ satellites measured by Ford[16] using electron bombardments. The accepted labels of the satellite lines seen by Ford are given in column 4. As can be seen in columns 2–4 of Table II, there are four satellite lines seen in the present work which were not seen by Ford. Column 5 gives the energy separation of the various peaks from the $K\alpha_{1,2}$ line as measured in the present work. Column 6 gives the same information for Ford's results. Very good agreement is obtained between these numbers which gives one confidence that the same lines are being observed in both types of excitation, however, the so-called "satellite lines" dominate the heavy-ion–induced reactions and are very small compared to $K\alpha_{1,2}$ in electron or proton bombardments.

A modified Herman-Skillman HFS self-consistent program[17] was used to calculate x-ray energies for various initial-hole configurations. The energies and the corresponding initial-hole configurations $(1s)^{-1}(2p)^{-n}$ for $n = 0$, 1, 2, 3, 4, and 5 from these calculations are presented in the last two columns of Table II. The agreement of the calculations with the experimental results is excellent.

The data are nearly Gaussian with the centroid of the satellites at $n = 2.89$. The centroid for the Al $K\alpha$ satellites produced with a 5-MeV N^+ beam[7] is at $n = 2.65$. It is interesting that even though the centroid positions do not change appreciably, the ratio of the multiple-hole to single-hole deexcitation is 18:1 for the Si $K\alpha$ data and 37:1 for the Al $K\alpha$ data. At the same time the ratio R of peak B ($K\alpha_3$) to peak A ($K\alpha_{1,2}$) is 2.3 for the Si $K\alpha$ data and 2.4 for the Al $K\alpha$ data. Assuming that the probability of forming peak B $[\sigma(KL)]$ is equal to the probability of knocking out a single $1s$ electron $[\sigma(KL)]$ times the probability of knocking out a single $2p$ electron $[\sigma(L)]$, then

$$R = \frac{\sigma(KL)}{\sigma(K)} \propto \frac{\sigma(K)\sigma(L)}{\sigma(K)} = \sigma(L) .$$

If the assumption is made that the ratio R is due to the energy dependence alone then the experimental ratios given above can be related by

$$\frac{R_{\text{expt}}\,(30\text{ MeV})}{R_{\text{expt}}\,(5\text{ MeV})} = \frac{\sigma(L)\ (30\text{ MeV})}{\sigma(L)\ (5\text{ MeV})} .$$

The left-hand side calculated from experiment is 0.96, whereas the right-hand side has been calculated by Burch[18] for the case of Al L-shell ionization. These calculated cross sections are 23×10^8 b at 5 MeV and 11×10^8 b at 30 MeV which gives a value for the right-hand expression of 0.48. Con-

TABLE II. Comparison of Si $K\alpha$ lines with previous experiments and with calculations.

Lab Label[a]	Energy (eV) Present	Energy (eV) Ford[b]	Designation	$E - E\alpha_{1,2}$ (eV) Present	$E - E\alpha_{1,2}$ (eV) Ford	HFS Calculations Energy (eV)	HFS Calculations Initial configuration
A	1739.8	1744	$K\alpha_{1,2}$	0	0	1739	$(1s)^{-1}$
...	...	1751	$K\alpha'$	...	7	...	...
B	1750.8	1756	$K\alpha_3$	11.0	12		
...	...	1757	$K\alpha_3'$	...	13	1750	$(1s)^{-1}(2p)^{-1}$
C	1753.1	1758	$K\alpha_4$	13.3	14		
D	1762.6	1768	$K\alpha_5$	22.8	24	1763	$(1s)^{-1}(2p)^{-2}$
E	1766.4	1770	$K\alpha_6$	26.6	26		
F	1775.3	...	...	35.5	...	1777	$(1s)^{-1}(2p)^{-3}$
G	1778.8	...	...	39.0	...		
H	1794.2	...	...	54.4	...	1794	$(1s)^{-1}(2p)^{-4}$
I	1809.7	...	...	69.9	...	1812	$(1s)^{-1}(2p)^{-5}$

[a]The labels refer to peaks in Fig. 2. [b]O. R. Ford, Ref. 16.

sidering the uncertainty in the calculated cross sections plus the experimental errors in obtaining these ratios, the disagreement is not too bad. They are within an order of magnitude which gives some confidence in the general ideas presented here.

IV. CONCLUSIONS

The present experiment demonstrates that 30-MeV oxygen bombardment of Si produces $K\alpha$ satellite spectra similar to 5-MeV nitrogen on Al even though the K- and L-production cross sections as a function of energy are varying in a completely different manner. This suggests possibly that atomic rearrangement occurs during the atom-ion collision and that the rearrangement is dominated by strong correlation effects. Another possibility which seems less likely is that the cross sections for K (single K), KL (single K, single L), KLL, $KLLL$, $KLLLL$, and $KLLLLL$ electron knockout are all very similar over the energy range discussed. It is obvious that more data and reaction-mechanism calculations are needed to further understand the high-energy heavy-ion–atom reaction.

For the first time it is shown that the $K\alpha$ satellite transitions due to initial configurations $(1s)^{-1}(2p)^{-n}$ for $n = 1, 2$, and 3 produced by MeV heavy ions are doublets. Two of the doublets occurring at the positions of $(1s)^{-1}(2p)^{-1}$ and $(1s)^{-1}(2p)^{-2}$ configurations have been observed in electron bombardment on Si whereas the other doublet occurring at the position of the $(1s)^{-1}(2p)^{-3}$ configuration was not observed. This latter doublet is in fact the largest structure of the 30-MeV oxygen plus Si spectrum.

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New Classical Model for Proton-Impact Ionization of Atoms

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A new model for ionizing collisions between slow protons and atoms has been proposed. K-shell ionization cross sections of oxygen atoms have been calculated and compared with available experimental data and with the results obtained by Gryzinski's formula. The proposed modification gives very good results for the cross section.

INTRODUCTION

The application of classical binary-encounter theory in the formulation given by Gryzinski[1] has been used successfully to calculate the cross sections for electron-impact ionization of atoms and molecules. The basic idea of this theory is to calculate the differential cross section for a definite