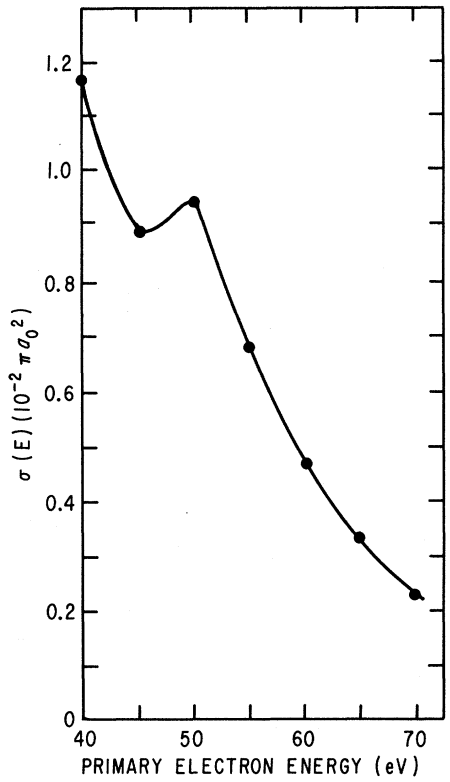

FIG. 3. Total cross section for electron excitation of the 2^3S state of He as a function of primary electron energy.

previously observed states of He^-, $(2s^22p)$ and $(2s2p^2)$, but possibly to the compound states, $2s(2snp \pm 2pns)$. While these states correspond to narrow resonances in Li, they need not correspond to narrow resonances in the isoelectronic sequence of He^-. In a comparison of He and H^- resonances, it has been found[9] that the (+) series of narrow resonances in He corresponds to a single broad resonance in the isoelectronic sequence of H^-. Measurements of the cross sections differential in primary energy and angle for excitation of all the singly excited states of helium over larger energy domain are in progress.

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Energy Shifts and Relative Intensities of K X Rays Produced by Swift Heavy Ions*

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The energy shifts of Fe, Co, Zr, and Sn K x rays produced by 5-MeV/amu He, C, O, Ne and 10 MeV/amu C ions depend nearly linearly on the stopping power for the bombarding ion. The shifts and the $K\beta/K\alpha$ ratios show a projectile energy dependence similar to that predicted for the L-ionization cross section. This suggests that these phenomena can be explained by existing Coulomb excitation theories.

Weak satellites associated with K lines were first discovered by Siegbahn and Stenström,[1] and an explanation involving multiple inner-shell ionization was proposed by Wentzel.[2] More recently the observation of energy shifts in the $K\beta$ lines of Cu and Ni induced by 15-MeV O bombardment has been reported by Richard *et al.*[3] using a Si(Li) detector for measuring the x-ray energies. They ascribe the shifts to multiple inner-shell ionization, an explanation which has been verified by Bragg spectrometer experiments in which the measured lines were resolved into satellites cor-

responding to 1, 2, 3, etc. vacancies in the L shell.[4-6] Other measurements on K energy shifts have been made[7,8] for a variety of targets at several projectile energies. The available data suggest that the energy shift in the K lines is related to the L-ionization cross section as predicted by the plane-wave Born approximation[9] (PWBA) or the binary encounter model[10] (BEM). Similar measurements have been made by Der *et al.*[11] for the L x rays of Ni, Cu, and Zn induced by bombardment with 8- and 20-MeV O ions. They noted shifts in L-x-ray energies which decreased as the projectile energy increased and they pointed out that this is consistent with the expected decrease in cross section for the production of M vacancies when the projectile velocity is greater than the electronic orbital velocity.

If the phenomenon of multiple ionization can be described in terms of simple Coulomb excitation, it is to be expected that (a) the energy shift observed at a given ion velocity should be proportional to Z^2, where Z is the projectile charge; (b) that for a given projectile the shift at sufficiently high energies should be inversely proportional to the projectile energy, in the same way as the electronic stopping power; and (c) that an energy shift due primarily to L vacancies would have a maximum in the region of $E/\lambda U_L \approx 1$, where E is the projectile energy, λ is the ratio of projectile mass to the electron mass, and U_L is an average binding energy for L electrons in the target. The aim of the present experiment was to check these predictions.

Beams of 5-MeV/amu He, C, O, and Ne ions from the Oak Ridge isochronous cyclotron were used with targets of Fe, Co, Zr, and Sn to study the projectile Z dependence of the K-x-ray energy shifts. The same targets were also bombarded with 10-MeV/amu C ions. The dependence of the shifts on the projectile energy was investigated using 0.625- to 2.84-MeV/amu O beams from the Oak Ridge Tandem Van de Graaff accelerator on targets of Ti and Fe.

The targets were placed normal to the beam, and the x rays viewed by a 12-mm^2 Si(Li) detector with an overall system resolution of 250 eV at 6 keV. For the cyclotron and tandem experiments the detector was placed at the angles 150° (cyclotron) and 43° (tandem), respectively, to the beam direction, and 50 and 12 cm from the target, respectively. X rays from the target were viewed directly through the 0.0125-mm Be window of the detector for the cyclotron runs, while at the tandem an additional 0.0125-cm Mylar window was employed. The beam currents were such that the count rate was always less than 1000 Hz, and generally less than 100 Hz.

TABLE I. Measured target thicknesses.

Target	Thickness (μg/cm^2)
Ti	100
Fe	428
Co	936
Zr	580
Sn	689

Except for Ti, the targets were self-supporting foils, whose thicknesses were measured by the Rutherford scattering of 5-MeV/amu projectiles at an angle of 11.25°. The Ti target was evaporated onto a 40-μg/cm^2 C backing, the thickness being measured with a crystal-oscillator film-thickness monitor. Table I shows the targets and their measured thicknesses. The estimated uncertainty in the measurements is 10%.

The energy calibration of the system was measured using a pulser in conjunction with standard x-ray sources of ^{55}Fe, ^{57}Co, and ^{241}Am. In regions remote from the calibration energies the absolute accuracy was estimated to be ± 10 eV; near to these energies this improved to ± 2 eV. The detector efficiency calibration was made using the same standard sources. Interpolation to other energies was made using a theoretical curve calculated from the detector characteristics supplied by the manufacturer and the x-ray cross section compilation of McMaster *et al.*[12] The theoretical efficiency curve was adjusted downwards by approximately 15% to fit the experimental data points. This difference was presumably due to a reduction of the effective area of the detector caused by incomplete charge collection near the edges of the crystal.

Except for the $K\beta$ lines from Zr and Sn, peak positions and areas were extracted from the spectra using a computer code, assuming the peaks to be Gaussian in form and the background to be either linear or quadratic in channel number. Although these assumptions, particularly the first, are not necessarily justified, such an analysis does provide reliable estimates of relative areas and positions. In the case of the $K\beta$ lines of Zr and Sn, the peak areas were extracted by hand and no attempt was made to estimate the average peak positions due to the relatively poor statistics coupled with the fact that the $K\beta_1$ and $K\beta_2$

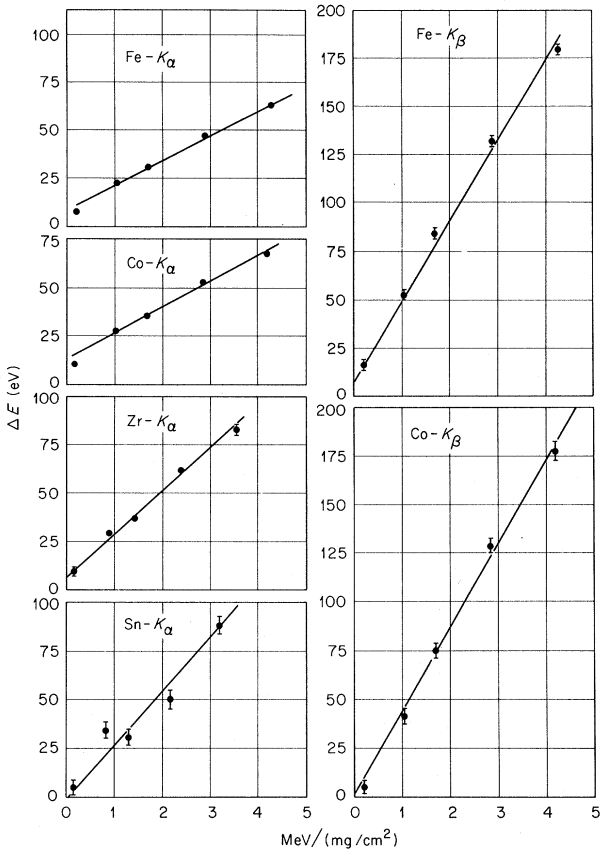

FIG. 1. K-x-ray energy shifts measured with 5-MeV/amu He, C, O, and Ne projectiles, and 10-MeV/amu C projectiles. The data are shown as a function of the stopping power of the projectile in the target material.

components were partially resolved.

$K\beta/K\alpha$ ratios for Fe and Sn were estimated from the peak areas and corrections applied for the energy dependence of the detector efficiency, for absorption in the Mylar window where appropriate, and for self-absorption in the target, taking into account the fact that the large energy shifts were generally sufficient to raise the $K\beta$ energy above the K absorption edge.

The measured energy shifts induced by 5-MeV/amu He, C, O, and Ne ions and 10-MeV/amu C ions are shown in Fig. 1, plotted against the stopping power of the target material for the appropriate projectile. An almost linear relationship is evident for each of the x-ray lines considered. In this energy region the electron stopping power is roughly proportional to AZ^2/E, where A, Z, and E are the projectile mass, charge, and energy, respectively. If we accept the explanation that the shifts are mainly due to L vancancies

TABLE II. $E/\lambda U_L$ for $E=5$ MeV/amu.

Target	$E/\lambda U_L$
Fe	3.7
Co	3.3
Zr	1.2
Sn	0.66

produced at the same time as a K vacancy, then the linear behavior for the 5-MeV/amu data points merely reflects the Z^2 scaling law for L-ionization cross sections, while the 10-MeV/amu C points imply that the L-ionization cross section varies as $1/E$. The $1/E$ dependence holds for projectile velocities larger than the electron orbital velocity, a condition which may be expressed in the notation of Garcia[10] as

$$E/\lambda U_L > 1. \quad (1)$$

The value of $E/\lambda U_L$ for 5-MeV/amu particles on Fe, Co, Zr, and Sn is shown in Table II. Condition (1) is seen to be satisfied for all targets except Sn, and indeed for this case the 10-MeV/amu data point does not follow the trend defined by the 5-MeV/amu data.

The $K\alpha$ and $K\beta$ shifts for Ti and Fe which were measured as a function of the energy of the bombarding O ion are shown in Fig. 2, plotted against $E/\lambda U_L$. The solid lines have been drawn to guide the eye. The form of the energy dependence is similar to that of the L-ionization cross sections predicted by the PWBA or the BEM, except that

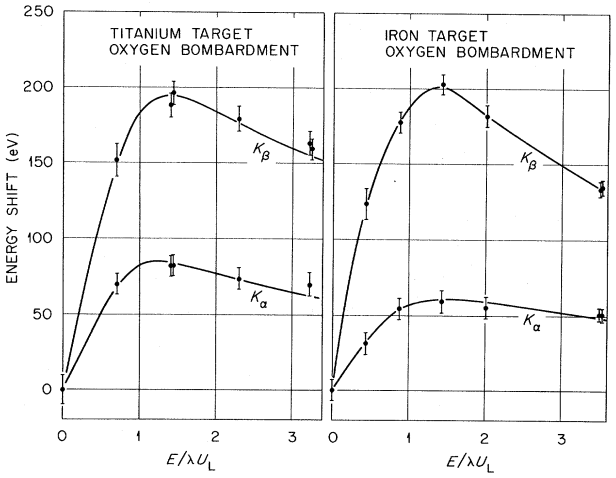

FIG. 2. K-x-ray energy shifts as a function of the O bombarding energy. The errors indicated at $E/\lambda U_L = 0$ reflect the uncertainty in the absolute energy calibration.

the maximum occurs at $E/\lambda U_L \approx 1.3$, rather higher than expected. This probably reflects the fact that the projectiles have, on the average, impact parameters smaller than the Bohr radius of the L shell as they must also have produced a K vacancy. One effect of such small impact parameters is to increase the effective nuclear charge seen by L electrons,[13] resulting in an effective increase in U_L.

The influence of M vacancies on the energy shifts, at least for the Fe $K\alpha$ lines, has been shown to be small.[6,14] Relativistic Hartree-Fock-Slater calculations[14] indicate that the average shift per L vacancy is approximately 25, 55, and 65 eV for the Fe $K\alpha$, Fe $K\beta$, and Sn $K\alpha$ lines, respectively. Thus the K x-ray shifts induced by the 5-MeV/amu Ne ions correspond to an average of two to three L vacancies for Fe, dropping to approximately one L vacancy in the case of Sn.

Burch, Richard, and Blake[6] have done calculations showing the influence of L and M vacancies on the $K\beta/K\alpha$ ratio for Fe. They show that the presence of vacancies in the L shell and $3p$ subshell has a marked effect on the ratio, as might be expected from the simple assumption that the $K\beta/K\alpha$ ratio is proportional to the $3p$ subshell population and inversely proportional to the number of electrons in the L shell. Our measurements of the Fe $K\beta/K\alpha$ ratio, shown in Fig. 3, show very similar systematics to the energy-shift data, at least for $E/\lambda U_L \gtrsim 1$. This indicates that the dominating influence is again the production of L vacancies, and suggests a rather small probability for the production of vacancies in the $3p$ subshell. From the calculations in Ref. 6, we estimate the $K\beta/K\alpha$ ratio for 32.5-MeV O bombardment of Fe ($E/\lambda U_L = 1.4$) to correspond to an average of $\lesssim 1$ $3p$ vacancy, if the energy-shift data at that energy is interpreted to correspond to two to three L vacancies. For all E with $E/\lambda U_L > 1$, the influence of $3p$ vacancies is expected to remain small, as both L and M ionization cross sections will scale roughly as AZ^2/E (or dE/dx). However, for $E/\lambda U_L < 1$, the relative importance of the $3p$ vacancies is expected to increase, as the M-ionization cross section increases, while the L-ionization cross section decreases rapidly. This effect would reach a maximum in the region of $E/\lambda U_M \approx 1$ ($E/\lambda U_L = 0.07$), where U_M is the ionization energy of the $3p$ subshell, and might result in a $K\beta/K\alpha$ ratio rather lower than the value obtained from an unperturbed atom. A hint of such behavior is evident in the Fe data for low O bombarding energies.

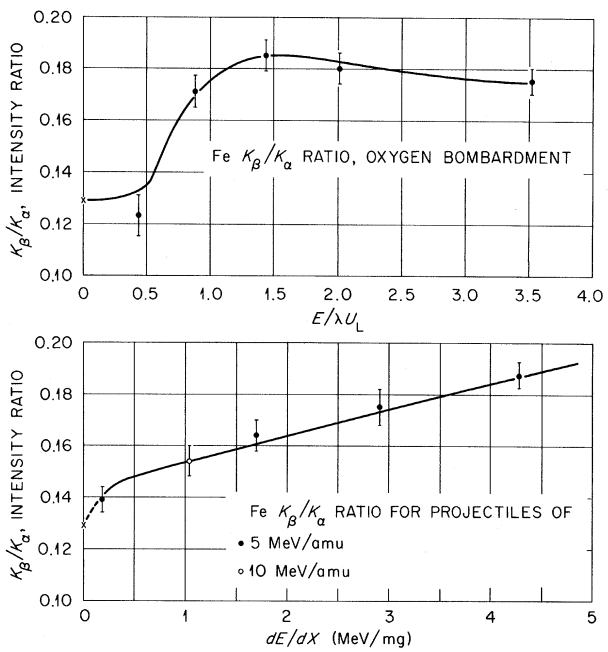

FIG. 3. Fe $K\beta/K\alpha$ intensity ratios. Lower curve, 5- and 10-MeV/amu data as a function of the stopping power of the incident ion in the target material. Upper curve, ratio as a function of bombarding energy for O projectiles. The value at $dE/dx = 0$ and $E/\lambda U_L = 0$ is taken from Ref. 15.

Tin $K\beta/K\alpha$ ratios were obtained only with the 5- and 10-MeV/amu projectiles, and these results showed no AZ^2/E dependence. The average of the five data points is 0.240 ± 0.015, close to the normal value of 0.2226 estimated by Hansen, Freund, and Fink.[15] This probably indicates that for this target the effect due to the production of L vacancies is approximately canceled by that due to M vacancies in this energy range.

In summary, both the energy shifts and the $K\beta/K\alpha$ ratios reported in the present work show similar systematic behavior with respect to the energy and charge of the incident projectile. These systematics can be qualitatively understood within the framework of existing Coulomb excitation theories, and show no evidence for a molecular promotion mechanism.[16] If the Coulomb excitation theories are formulated to extract the impact-parameter dependence of the ionization cross sections, as has been done in the case of Au L x rays,[17] it seems likely that a quantitative description of multiple-ionization phenomena may be achieved.

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Scattering of CsF by Electrons*

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Absolute differential and total cross sections for the scattering of CsF by 0.6- to 6.5-eV electrons have been measured using the molecular-beam recoil technique. The first-Born-approximation differential cross section is used as the theoretical model to fit the data. The experimental differential cross sections rise more sharply near 0° than predicted. Total cross sections derived from our measurements are a factor of 1.5 to 4 smaller than the first-approximation results.

We report absolute total and differential cross sections for the scattering of CsF by 0.6- to 6.5-eV electrons, measured by the molecular-beam recoil technique. To our knowledge these are the first absolute, single-collision measurements on a molecule of significant polarity, and therefore a first test for features of the theory.

Given the 7.9-D dipole moment of the CsF molecule, one expects the scattering to be described by an electron–permanent-dipole interaction. For a $^1\Sigma$ diatomic with a point dipole moment and a set of rigid-rotor internal energy levels, the first Born approximation (FBA) to the differential cross section is[1]

$$\frac{d^2\sigma}{d\omega^2}=\begin{cases}\frac{4}{3}\left(\frac{me\mu}{\hbar^2}\right)^2\frac{k'}{k}\frac{J_>}{2J+1}|\vec{k}'-\vec{k}|^{-2} & \text{for } J\to J\pm1,\\ 0 & \text{for } J\not\to J\pm1.\end{cases}$$

Note the extraordinary prediction that the scattering is entirely inelastic. More exact theories have not been evaluated for CsF, so this form is used in our analysis.

When the electron energy greatly exceeds the rotational spacing, the angle dependence can be approximated,

$$|\vec{k}'-\vec{k}|^{-2}\approx\tfrac{1}{2}k^{-2}(1-\cos\theta+\delta)^{-1}.$$

For CsF, $\delta=2.6\times10^{-10}(J_>/E)^2$. The differential cross section is extremely sharply forward peaked. Averaging over the J distribution (1000° K) and integrating over all angles,

$$\sigma(\text{Å}^2)=7024/E+(930/E)\ln E.$$

An interaction of this magnitude should dominate the scattering.

The many-to-one nature of the laboratory to center-of-mass transformation in our experiment prevents a direct inversion of lab measurements to produce a c.m. differential cross section. Instead, the molecular scattering is compared with theory by assuming a c.m. differential cross section with an undetermined constant as a factor, transforming the form into lab coordinates, and then fitting the constant by least