1, and thus can be responsible for the deviation in the lead region. Our experimental result is not in contradiction with such an approach.

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Heavy-Ion-Produced High-Resolution Si-*K*-X-Ray Spectra from a Gas and Solid

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Si-$K\alpha$-x-ray spectra produced by 45-MeV Cl-ion bombardment using thin solid Si and SiH_4 targets are measured. The Si satellite lines shift in energy and change in relative intensity between the solid and gas spectra indicating that different electronic states are produced in the two collisions. The effective fluorescence yield varies by a factor of 2 between the two systems affecting interpretation of comparisons of heavy-ion-induced x-ray-production cross sections.

High-resolution x-ray spectra produced by high-energy heavy-ion bombardment have previously been studied using both gas[1] and solid[2] targets, but x-ray spectra from the same element in solid and gaseous form have not been investigated. In this Letter we report measurements of the high-resolution spectra of Si produced by 45-MeV Cl projectiles in a gas and in a thin solid target. The x-ray satellite lines are observed to shift to higher energy in the gas with respect to the solid. The large shift is consistent with calculated energies of transitions in Si ions having no M-shell electrons present. An enhancement of the relative intensities of the more highly ionized states is observed in the gas spectra compared with the solid. Single-hole L-shell decay rates are too small to explain the differences in terms of filling of the L-shell vacancy before K-x-ray emission.

With use of the observed relative intensities, an average fluorescence yield, $\bar{\omega}$, for the collision in the gas and in the solid can be obtained. The absence of M-shell electrons during the decay in the gas in addition to the larger amounts of relative intensity in the higher multiple-ionization peaks in the gas will increase the average fluorescence yield in the gas collision with respect to the solid case. The change is estimated to be a factor of 2 for the system studied here. This change in fluorescence yield can significantly alter comparison of low-resolution x-ray-production cross sections in solid and gas targets.[3]

In this experiment targets of silane (SiH_4) gas and thin solid silicon are bombarded by 45-MeV Cl^{+7} ions obtained from the Kansas State University EN tandem Van de Graaff accelerator. A differentially pumped gas cell[1] is used to confine the target gas at a constant pressure of 0.11 Torr. Thin solid Si targets (~20 $\mu g/cm^2$) evaporated on to 20-$\mu g/cm^2$ carbon backings can be inserted in the gas cell so that the geometry is the same for solid and gas targets. The x rays are observed at 90° to the beam axis using a 4-in. curved-crystal spectrometer[4] equipped with an EDdT crystal ($2d = 8.808$ Å). The x-ray spectra are obtained by recording the number of x rays detected for a preset amount of beam current and stepping the spectrometer in constant wavelength intervals.

Spectra of the Si-$K\alpha$ satellite structure produced in a gas and solid are shown in Fig. 1. The spectra are calibrated using the known wavelengths[7] of the $K\alpha_{1,2}$ and $K\beta$ lines observed in a 2-MeV p + Si spectrum. The peaks labeled KL^n in the solid-Si spectrum (curve c) are the satellite lines originating from states having initially one K-shell vacancy and n L-shell vacancies. The peak identifications are consistent with those made by McWherter *et al.*[5] In curves a and b Si x rays produced in the silane gas are shown. The spectrum in curve a is obtained by passing the Cl^{+7} beam directly through the gas cell, while in curve b a 20-$\mu g/cm^2$ C prefoil is inserted, raising the mean charge of the beam to ~12.2.[8] The change in relative intensity of the satellite spectrum in a gas target has been observed previously in Ne.[1] No change in the solid-Si spectrum is observed when the prefoil is inserted.

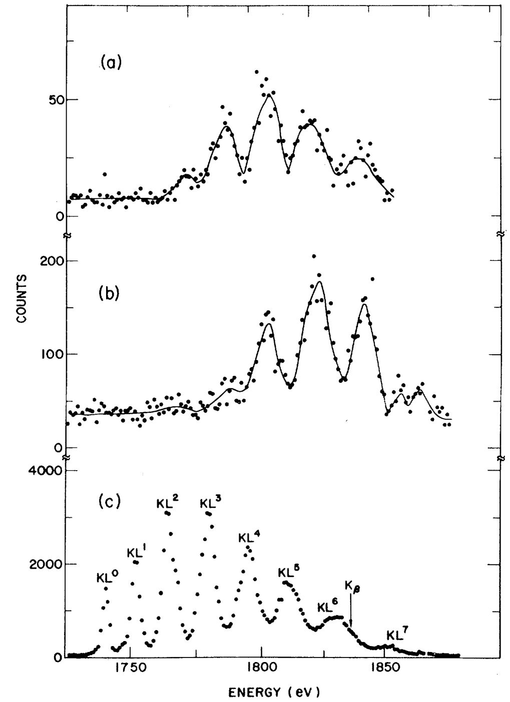

FIG. 1. High-resolution spectra of Si-$K\alpha$ x rays. Spectra from SiH_4 gas produced by 45-MeV Cl^{+7}, curve a, and by 45-MeV $Cl^{\langle +12\rangle}$, curve b, which is prepared by inserting a prefoil in the beam. Curve c is an x-ray spectrum from a thin solid Si sample produced by 45-MeV Cl.

The centroid energies of the satellite peaks are given in Table I. The estimate of the error is ± 0.5 (± 1) eV for the solid- (gas-) target data. The centroid energies of the Si-$K\alpha$ satellites for 35-MeV O bombardment reported by McWherter *et al.*[5] is also given. In Table II the relative intensities, R_{KL^n}, of the x-ray peaks corresponding to one K-shell vacancy and n L-shell vacancies are given. The error in the extraction is 15% for the prominent peaks in the spectra and larger for the smaller peaks in the gas spectra.

Comparison of the gas- and solid-target data show large differences. The centroid energies of the satellite peaks from the gas are shifted to higher energy with respect to the solid targets. These shifts are in agreement with calculated energy shifts,[6] presented in Table I, assuming complete ionization of the M shell of Si in the gas. The energies of KL^7 observed in the $Cl^{\langle +12\rangle} + SiH_4$ spectrum agree with the He-like transitions $(1s2p)^3P_1$-$(1s^2)^1S_0$ and $(1s2p)^1P$-$(1s^2)^1S_0$ measured in Si beam-foil spectra,[9] providing further evidence that all M-shell electrons are removed in the gas collisions. Energy shifts in the solid are not observed for the various projectiles. In Si the M shell comprises the valence shell so that electrons from neighboring atoms are readily available to fill M-shell holes created in the collision. The plasmon lifetime in Si (~4×10^{-17} sec),[10] which is a measure of the valence-shell

TABLE I. Centroid energy (eV) of Si-K x rays.

	p+Si, 2 MeV	O+Si, 35 MeV[a]	Cl+Si, 45 MeV	Cl^{+7}+SiH_4, 45 MeV	$Cl^{(+12)}$+SiH_4, 45 MeV	ΔE	
						Expt.	Calc.[b]
KL^0	1740	1739.4	1740				3.4
KL^1	1751	1750.5 1753.1	1751				4.8
KL^2	1764	1762.8 1766.3	1764	1770	1769	5	6.3
KL^3		1778.4	1779	1785	1786	7	8.0
KL^4		1793.5	1795	1802	1802	7	9.7
KL^5		1808.8	1810	1817	1821	11	11.4
KL^6			1830	1840	1841	11	13
KL^7							
^3P-^1S					1855		
^1P-^1S					1864		
$K\beta$	1836						

[a] Taken from Ref. 5.

[b] Calculated energy shift due to removal of all M-shell electrons using a Hartree-Fock computer code (see Ref. 6). The value for KL^6 was obtained by extrapolation.

response time, is almost 40 times shorter than the K-hole lifetime ($\sim 1.5\times 10^{-15}$ sec),[11] supporting this explanation.

The relative intensities also change between the gas and the solid, as given in Table II. For n greater than three, R_{KL^n} is larger in the $Cl^{(+12)}$ + SiH_4 collision than in the Cl + solid-Si case. This effect could possibly be due to differences in L-shell excitation between the two collision systems, or due to filling of the L shell in the solid by M electrons before K-x-ray emission. The filling cannot occur in the gas since the M-shell electrons are removed in the collision. The effect of L-shell filling can be estimated using single-hole L-shell filling rates and scaling them by the number of L-shell vacancies, but the rates are too small to explain the difference in the relative intensities between the solid and gas spectra. Calculations of L-shell rates in the solid in the presence of K-shell holes and other L-shell holes are needed before these differences in relative intensities can be better understood.

TABLE II. Relative intensities of the Si-x-ray satellite peaks.

	Cl^{+7} + SiH_4, 45 MeV	$Cl^{(+12)}$ + SiH_4, 45 MeV	Cl + Si(Solid), 45 MeV
R_{KL^0}			0.04
R_{KL^1}			0.08
R_{KL^2}	0.04	0.02	0.18
R_{KL^3}	0.27	0.05	0.21
R_{KL^4}	0.30	0.22	0.19
R_{KL^5}	0.25	0.38	0.16
R_{KL^6}	0.14	0.27	0.11
R_{KL^7}		0.06	0.03

The vacancy-production cross section, σ_v, is related to the x-ray-production cross section, σ_x, by the formula $\sigma_v = \sigma_x/\bar{\omega}$. $\bar{\omega}$ is a function of the collision system for heavy ions and can be calculated by[1]

$$\bar{\omega}^{-1} = \sum_n R_{KL^n}/\omega_n \,, \qquad (1)$$

where ω_n is the fluorescence yield of the multiply ionized states KL^n. $\bar{\omega}$ will differ for the gas- and solid-Si measurements because of changes in ω_n as well as the observed variations in R_{KL^n}. ω_n will in general increase in the gas because the KLM and KMM Auger channels will be closed as a result of M-shell ionization. By scaling the rates calculated for the defect configurations of Al,[12] the fluorescence yield in Si is found to increase by less than 10% for ω_0 and by more than 100% for ω_6 and ω_7. Using Eq. (1) and the relative intensities in Table II, $\bar{\omega} = 0.074$ for Cl + Si(solid) and $\bar{\omega} = 0.144$ for $Cl^{(+12)}$ + SiH_4. Therefore, a variation by a factor of 2 could be observed in σ_x between gas and solid measurements although σ_v would remain constant. Such fluorescence-yield effects must be included in interpreting low-resolution measurements.

In a recent Letter, Datz *et al.*[3] have reported low-resolution measurements of σ_x for the K shell of Si in a gas and a solid produced by an 86-MeV Ar projectile. In the gas, σ_x is a function of the charge state of the incident projectile. From comparisons of σ_x in the gas and in the solid, the mean charge of Ar is found to be ~ 11. In this analysis $\bar{\omega}$ is implicitly assumed to be the same in the gas and the solid. In this paper it is shown that $\bar{\omega}$ can change by a factor of 2 since Cl and Ar projectiles are expected to produce similar amounts of multiple ionization. Adjusting the data for the factor of 2 change in $\bar{\omega}$, the mean charge of Ar in the foil is ~ 14 which agrees with the mean charge measured emerging from the solid.

In summary, we have observed a shift in energy and a change in relative intensities of the Si-$K\alpha$ satellite peaks from gas and solid targets when bombarded by 45-MeV Cl ions. The shift of the satellites to higher energy in the gas is attributed to removal of all of the M-shell electrons during the collision. The change in relative intensities between the gas and the solid cannot be explained in terms of L-shell filling by M-shell electrons if single-hole rates are used. Unless better estimates of these rates are much greater than the present values, the amount of multiple L-shell ionization created in the collision is greater in the gas target than in the solid. Both effects will produce a higher $\bar{\omega}$ in the gas than in the solid, which can affect interpretations of low-resolution cross-section data.

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Spatially Resolved and Stark-Broadened X-Ray Lines from Laser-Imploded Targets

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We report the first observation of spatially resolved x-ray lines from laser-irradiated spherical targets. The lines are found to emanate mainly from inside the critical layer but the density they all indicate is not much higher than critical. These results are relevant to the study of heat conductivity and the laser ponderomotive force.

The transfer of absorbed laser energy into super-critical layers of an irradiated target has been shown recently to be very complicated. In particular, heat flow may be inhibited by magnetic fields[1] or be nonclassical[2] and the density profile may be modified by the laser ponderomotive force.[3] We show here that x-ray-line spectroscopy with spatial resolution can be a very useful tool for studying such effects. The targets used in these experiments, spherical glass shells, contain a variety of species (silicon, oxygen, sodium, magnesium) and the comparison of their spectra forms the basis for the present method. Additional information was gained by comparing such measurements with the emission at twice the laser frequency, which was spatially[4] and temporally[5] resolved. The results indicate a plateau (or "upper shelf") in the density profile ex-