of a minimum. We have also had private communication from Professor M. C. R. McDowell whose theoretical treatment of the analogous H^{--} indicates a possibility of stability.

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EVIDENCE FOR A "RADIATIVE AUGER EFFECT" IN X-RAY PHOTON EMISSION

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A broad x-ray emission structure with several maxima has been found on the low-energy side of the $K\alpha_1\alpha_2$ line in Mg, Al, Si, and S. It is interpreted as a radiative $K \rightarrow L^2$ transition resulting in the simultaneous emission of a photon and an L-shell electron.

Usually an x-ray inner-hole state decays either through a radiative or a nonradiative transition. However, other decay modes are possible. Bloch[1] suggested that an atom may be able to emit an x-ray photon and a valence-shell electron simultaneously instead of undergoing a "forbidden" quadrupole transition. Here we report observation of yet another possible decay mode, one in which a photon and an inner L-shell electron are emitted simultaneously instead of the dipole allowed $K\alpha$ line. Following Bloch we call this the "radiative Auger effect," but we might also call it the "atomic internal Compton effect" from its analogy to nuclear γ emissions involving the simultaneous ejection of an atomic electron.[2]

In the course of our search[3] for a many-body structure situated on the low-energy tail of the $K\alpha$ line in Al metal we extended our measurements to energies below the expected range for the many-body effects. Here we found a broad structure with several "bumps," the intensity of the highest peak being about 0.05% of the intensity of the $K\alpha$ line. A similar structure has also been found in compounds, but here we limit our discussion to measurements on the elements investigated so far, namely, Mg, Al, Si, and S.

The plane-crystal spectrometer equipment used has been described previously[4] with the exception of a new vacuum chamber which allows an improved angular resolution. The specimens were excited by the radiation from a chromium-anode x-ray tube. The fluorescent radiation from Mg was recorded with a potassium acid phthalate crystal ($2d = 26.64$ Å), that from Al with an ammonium dihydrogen phosphate crystal ($2d = 10.648$ Å), and that from Si and S with an ethylene diamine tartrate crystal ($2d = 8.808$ Å). In the cases of Al, Si, and S the spectra were also obtained with the potassium acid phthalate crystal in order to make sure that there were no extra reflections involved due to the analyzing crystal.[5] As an example of the new structure we show in Fig. 1 records of the low-energy side of the S $K\alpha$ line. The energies of the peaks labeled E_1, E_2, A, B, C, and D were determined relative to the energy of the $K\alpha$ line from at least three independent measurements. The energy of the $K\alpha$ line was taken from the table of Bearden.[6]

The measured peak energies are given in Table I, where we have also compared the energies of the maxima A, B, C, and D with the known KLL Auger electron energies of the elements.[7] The energies of the peaks agree closely with the known Auger energies corresponding to various terms of the final state in the intermediate coupling. Note also that the peaks at A, B, C, and D have greater half-widths than the $K\alpha$ peak. All this is consistent with the following interpretation: Instead of the initial K hole being filled with emission of either a full-energy $K\alpha$ photon or a full-energy Auger electron, there is a simultaneous emission of a lower energy photon $\hbar\omega$ and excitation of an L-shell electron. In Fig. 1(b) the peaks E_1 and E_2 correspond to transitions in which the L-shell electron has been excited into bound states whereas each of A, B, C, and D represents the approximate beginning of a continuous band of x-ray energies. Within each of these bands the energy $\hbar\omega$ of the photon satis-

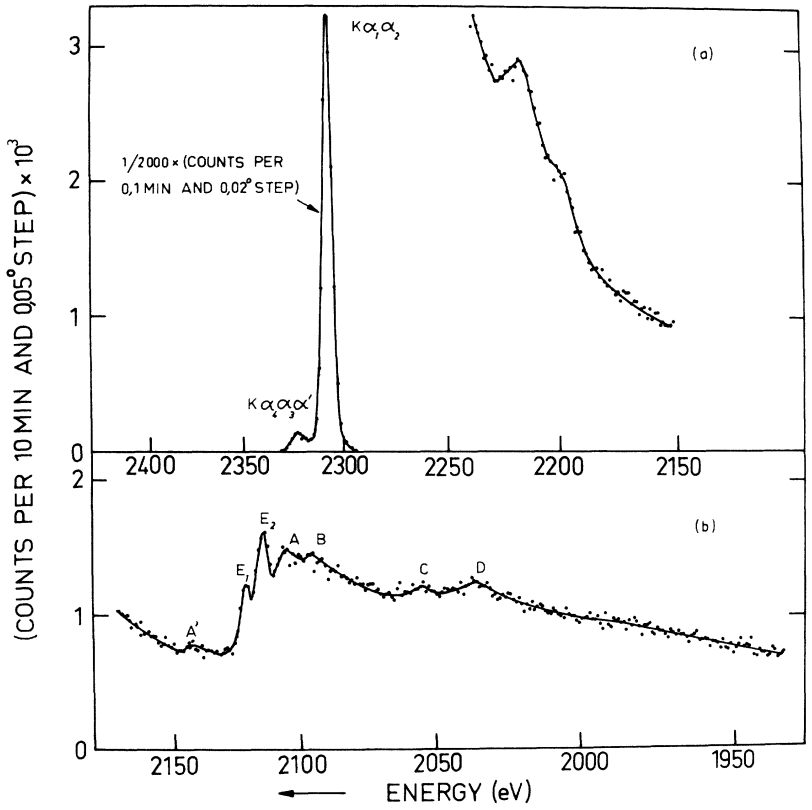

FIG. 1. The low-energy side of the S $K\alpha_1\alpha_2$ line. (a) Two unidentified peaks. (b) The peaks identified in this Letter. The spectra shown in (a) and (b) were recorded from separate samples, the counting rates being slightly different in the region of overlap.

fies the energy-conservation relation

$$\hbar\omega + E_{\mathrm{kin}}(L) = E(KLL), \tag{1}$$

where $E_{\mathrm{kin}}(L)$ is the kinetic energy of the ejected L electron and $E(KLL)$ is the full Auger electron energy. As $E_{\mathrm{kin}}(L)$ varies from zero to $E(KLL)$ we get a continuous band of photon energies extending from an edge at $\hbar\omega = E(KLL)$ toward lower energies. The different bands correspond to different energy terms of the final, doubly ionized atom, each band consisting of a

Table I. Exciton and Auger energies for the $K \rightarrow L^2$ transition in some elements. The energies E_1, E_2, A, B, C, and D are from this work and the "ESCA" energies from Ref. 7. "ESCA" denotes electron spectroscopy for chemical analysis.

	Exciton energy (eV)		Auger energy (eV)							
			$2s^2 2p^4$					$2s\,2p^5$		
			^1D		^1S		^3P		^1P	
Element	E_1[a]	E_2[a,b]	A	ESCA	B[a]	ESCA	C[c]	ESCA	D[c]	ESCA
Mg			1182 ±2	1179		1172	1150 ±3	1151	1128 ±5	1135
Al	1395 ±1		1389 ±2	1387	1381 ±2	1379		1354		1336
Si	1620 ±1	1614 ±1	1607 ±3	1611	1596 ±4	1602	1573 ±3	1574	1554 ±2	1554
S	2121 ±1	2114 ±1	2106 ±2	2107	2096 ±4	2096	2056 ±5	2058	2037 ±2	2034

[a]The spectrum of Mg has been recorded with a rather low resolution. Hence only one broad peak with the maximum denoted by A has been found.

[b]In the spectrum of Al the exciton peak E_2 and the maximum A do not appear separately.

[c]In the spectrum of Al a broad peak situated between about 1370 eV and 1330 eV has been found but it is overlapped by the Cr $K\alpha$ line in the fourth order.

continuum of photon energies beginning at an edge that corresponds to an energy term.

The maximum at A correspons to the strongest line $1s(^2S_{1/2}) \rightarrow 2s^2 2p^4(^1D_2)$ in the Auger spectrum. The ratio of the integrated intensity of the whole $K \rightarrow L^2$ spectrum to that of the $K\alpha$ line decreases slightly when the atomic number Z increases from 12 to 16, the average value being 0.007. The observed decrease is obviously a consequence of the decrease in the Auger electron yield with increasing Z. In view of the high Auger yield in this region of Z values the $K \rightarrow L^2$ structure should be detectable for Z values higher than 16. Related structures may also be found in other regions of the x-ray spectrum. Thus, Cady and Tomboulian[8] supposed that the low-energy tail of the L-emission bands in Na, Mg, and Al is due to a radiative Auger effect. Some low-energy satellite lines of the $K\alpha$ and $K\beta$ lines for elements in the range of Z from 33 to 44 observed by Hulubei[9] and Hulubei, Cauchois, and Manescu[10] were interpreted as $K \rightarrow LM$ and $K \rightarrow M^2$ transitions, but it is not clear whether these satellites show any bandlike structure.

The shape of the x-ray bands observed by the authors is similar to the shape of the x-ray Raman bands found by Suzuki[11] to result from the inelastic scattering of x rays by K electrons in light elements. The analogy between Suzuki's results and ours is clear if we imagine our radiative $K \rightarrow L^2$ Auger effect to be an internal Raman or modified Compton effect where the photon which is inelastically scattered by an L electron is created within the scattering atom itself. This latter scattering can be distinguished from the kind observed by Suzuki, which, in our experiment, would be the ordinary Raman scattering of a $K\alpha$ photon emitted from one atom by another atom. In ordinary Raman scattering energy conservation requires that the energy of the scattered photon $\hbar\omega$ satisfy, instead of (1), the relation

$$\hbar\omega + E_{\mathrm{kin}}(L) = \hbar\omega(K\alpha) - E(L) > E(KLL). \qquad (2)$$

Here $\hbar\omega(K\alpha)$ is the energy of a $K\alpha$ photon and $E(L)$ is the binding energy of an L electron. It should also be noted that the ordinary Raman effect produces a singly ionized atom whereas the radiative Auger effect produces a doubly ionized atom; so the multiplet structures are different in the two effects. Actually, according to Eq. (2) the peak denoted by A' in Fig. 1(b) may correspond to S $K\alpha$ rays inelastically scattered by $L_{\mathrm{II,\,III}}$ electrons. We have also found evidence in our spectra for some other faint peaks on the high-energy side of the $K \rightarrow L^2$ band as shown in Fig. 1(a) but neither of the energy relations (1) and (2) fits these peaks.

The shape of the $K \rightarrow L^2$ band also closely resembles the shape of the energy spectrum for L shake-off electrons ejected from neon during the K photoionization as observed by Krause, Carlson, and Dismukes.[12] The cross sections for both processes depend upon the behavior of the continuum wave function near the threshold for the ionization of the L electrons. However, the shake-off cross section is determined by a monopole matrix element whereas the radiative Auger cross section is determined in second order by a dipole matrix element. No complete theory of the radiative Auger effect exists but we are currently working on it.

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