Energy Shift of Characteristic X Rays Induced in Collisions Between 15- to 60-MeV I Ions and Mo, Yb, and Au Targets

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X rays emitted in collisions between heavy atomic particles were analyzed with a highly resolving Si(Li) detector. L and M x-ray spectra are shown for the collision systems I → Mo, Yb, and Au at 17.6-, 34.0- and 57.0-MeV ion energy. The L x rays of both colliding particles are shifted to higher energies compared with photon-induced characteristic x rays.

The x-ray emission induced by U^{235} fission-fragment bombardment of heavy target atoms was studied by Specht in 1965.[1] He reported an energy shift for the collision-induced radiation compared with the photon-induced characteristic x rays. Because of the inherent resolution of the proportional gas-flow counter used, Specht was not able to observe structure in the L-radiation energy spectrum. In order to resolve the energy structure of L x rays induced in collisions between heavy particles, a Si(Li) detector was used in the present work. Such experiments were also proposed by Burch and Richard.[2]

15- to 60-MeV single-component I beams (up to about 10 nA) were produced in the model FN tandem accelerator at the University of Cologne. The beam is incident on thin Mo, Yb, and Au targets (about 100-300 $\mu g/cm^2$)[3] at an angle of 45°. The emitted x rays were detected outside the vacuum chamber by a 30-mm^2 Si(Li) detector[4] placed perpendicular to the beam direction. The solid angle was 7×10^{-4} sr; the system resolution was 260 eV (full width at half-maximum at 6.4 keV and 1000 counts/sec). The count rate was always less than 1000 counts/sec. The intensity of the emitted x rays was reduced by absorption in the targets themselves, in a 12-μm Hostaphan window, in about 5 mm of air, and in the 2-mil Be window of the Si(Li) detector. The energy scale was calibrated using a Co^{57} source.

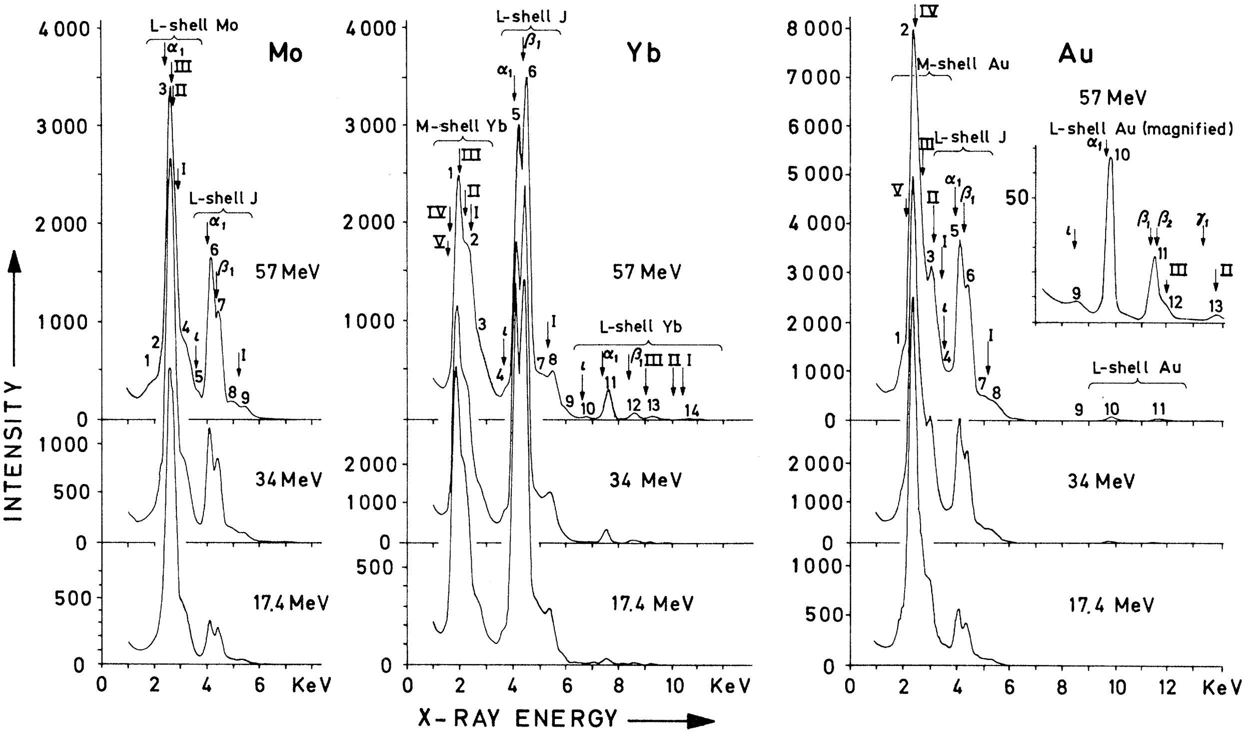

FIG. 1. Collision-induced x-ray spectra for 17.4-, 34.0-, and 57.0-MeV I-ion bombardment on Mo, Yb, and Au targets. Roman numerals indicate the different (photon) absorption edges. The channel width of the multichannel analyzer was 25 eV.

Figure 1 shows the x-ray spectra induced in collisions between 17.4-, 34.0-, and 57.0-MeV I ions and Mo, Yb, and Au target atoms. In Fig. 2 the L radiation of Yb alone is shown using an expanded scale. The different peaks in each spectrum are characterized by serial numbers. The energy positions of the photon-induced characteristic x rays and of the absorption edges are marked by arrows.^{5}

From the spectra we see the following:

(1) The L-radiation components of both colliding particles are shifted to higher energies compared to photon-induced x rays. The measured peak positions and the energy shifts at 57.0 MeV are summarized in Table I. The position uncertainty is approximately 25 eV (= channel width). In column 4 of the table, the photon-induced reference peaks are given.

(2) The L radiation of both colliding particles contains components with an energy considerably beyond the corresponding L_{I} absorption edge.

(3) The energy structure of the M radiations of Yb and Au and the L radiation of Mo may be influenced by the self-absorption in the target material in the region of the absorption edges. Less influence on the energy structure by edge absorption may be expected for the L radiation of Yb and Au. In the case of the iodine L radiation, no edge absorption can occur.

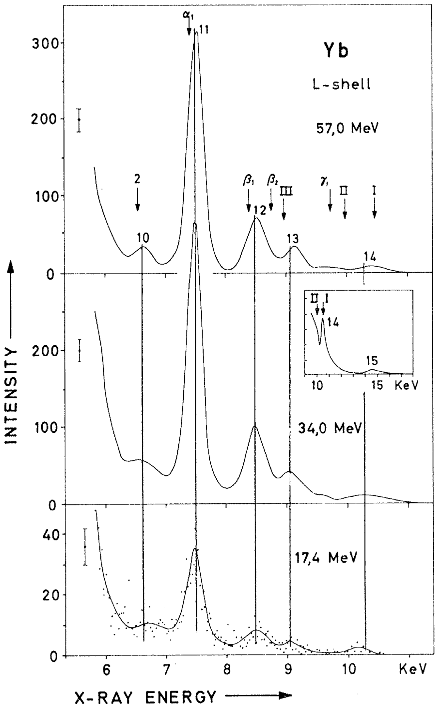

FIG. 2. Collision-induced x-ray spectra of the Yb L shell for 17.4-, 34.0-, and 57.0-MeV I-ion bombardment. Roman numerals indicate the different (photon) absorption edges. The channel width of the multichannel analyzer was 25 eV.

(4) The energy shift depends on the nuclear charge of the emitting atom and on the bombarding energy. For the Yb L radiation the energy dependence on the shift may be seen from Fig. 2; in the case of Au, this effect was not studied in detail, and for Mo this effect may be falsified by the target absorption. For the bombarding particles only a very weak energy dependence of the shift is observed. For the $L\alpha_1$ line of 17.4-MeV I in Yb, e.g., the shift is approximately 35 eV smaller than at 57 MeV.

Several effects may cause the L-line shifts: (1) the loss of *outer electrons*, (2) the production

Table I. Energy positions and energy shifts for different components of the collision-induced x-ray spectra shown in Figs. 1 and 2 at 57.0 MeV. The peak numbers are identical with the peak serial numbers in the spectra. The shift is the difference between the measured energy position of a component and the energy of the corresponding reference peak (photon-induced characteristic x rays; column 4).

target material	peak number	position [keV]	reference peak	shift [eV]
Mo	1	1.80	-	-
	2	2.12	Mo L_l	~100
	3	2.60	Mo $L_{\alpha 1}$	300
	4	3.20	-	-
	5	3.60	I L_l	~100
	6	4.09	I $L_{\alpha 1}$	150
	7	4.40	I $L_{\beta 1}$	190
	8	4.95	(I $L_{\beta 2}$)	(450)
	9	5.35	(I $L_{\gamma 1}$)	(450)
Yb	1	1.85	-	-
	2	2.20	-	-
	3	2.85	-	-
	4	3.60	I L_l	100
	5	4.10	I $L_{\alpha 1}$	160
	6	4.40	I $L_{\beta 1}$	190
	7	~5.10	(I $L_{\beta 2}$)	(600)
	8	5.40	(I $L_{\gamma 1}$)	(600)
	9	~6.00	-	-
	10	6.65	Yb L_l	100
	11	7.53	Yb $L_{\alpha 1}$	120
	12	8.52	Yb $L_{\beta 1}$	120
	13	9.12	Yb $L_{\beta 2}$	350
	14	10.45	-	-
	15	~14.6	-	-
Au	1	1.90	-	-
	2	2.37	-	-
	3	3.01	-	-
	4	3.60	I L_l	~100
	5	4.09	I $L_{\alpha 1}$	150
	6	4.38	I $L_{\beta 1}$	160
	7	4.96	(I $L_{\beta 2}$)	(450)
	8	5.40	(I $L_{\gamma 1}$)	(400)
	9	~8.5	Au L_l	-
	10	9.75	Au $L_{\alpha 1}$	40
	11	11.50	Au $L_{\beta 1}$	60
	12	11.99	-	-
	13	13.80	(Au $L_{\gamma 1}$)	(420?)

of a certain amount of *M-shell vacancies*,[6,7] and (3) a double *L-shell ionization*. From energy-level calculations,[8] shifts caused by the loss of outer electrons are expected to be too small to explain the measured values. For each successively removed $3d$ electron we expect average shifts of the $L\alpha_1$ and $L\beta_1$ lines of Mo, I, Yb, and Au of about 5, 14, 19, and 21 eV, respectively. These values are estimated from an extrapolation of the calculations given in Ref. 8. For a double L-shell ionization of Mo, I, Yb, and Au we expect, respectively, shifts of approximately 130, 170, 240, and 290 eV for the $L\alpha_1$ lines and shifts of about 140, 200, 300, and 380 eV for the $L\beta_1$ lines. These values are estimated from simple satellite energy calculations.[5] From a comparison of all these values with our measured shifts we may conclude the following: A multiple L-shell ionization may be important only for the main components of Mo and partially for the small high-energy components of the other elements. For the main components of I, Yb, and partially of Au, we expect M-shell vacancies to give the largest contribution to the shifts. The M electrons may be removed to highly excited (autoionizing) states; their decay may cause the high-energy components beyond the absorption edge. Energy-shift measurements seem to be a useful method to determine excitation and ionization states.[2] Further experiments and more detailed calculations are desirable.

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Plasmon Effects in Field Ion Emission

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The observed oscillatory structures in the energy distribution of field-emitted ions are interpreted as due to discrete energy losses from multiple excitations of surface plasmons in the metal tip. The shape of the loss spectrum and its dependence on field strength agree with experiment. Plasmon losses are shown to influence the ion-energy distribution in field desorption of evaporation and may also affect the ultimate mass resolution of the "atom-probe" microscope.

In the large electric fields required to ionize, desorb, or evaporate an atom from the metal tip of a field ion microscope,[1] the outgoing ion acquires several tens of electron volts of kinetic energy within a few angstroms from the tip surface. Typically, singly ionized evaporated atoms will be accelerated to 50 eV within 10 Å from the tip surface in an applied field of 5 V Å^{-1}. Thus the ion reaches the energy threshold for possible excitation of collective plasma modes in the metal (typical energy ~10 eV) within a few angstroms from the position where it originated.

It is known, from electron energy-loss spectroscopy,[2] that charged particles of sufficiently high energy are capable of exciting collective plasma modes in matter, thereby losing discrete amounts of energy equal to the plasmon quantum $\hbar\omega_k$. Whereas the electric fields accompanying bulk-plasma oscillations are confined to the interior of the metal, surface plasmons[3] generate fields which can extend far outside the sample and can therefore couple to and be excited by energetic charged particles traveling near the surface.

In this Letter we present a model for the ion–surface-plasmon coupling in the physical situation of field ion microscopy. The results of this study strongly suggest that the observed structure[4] in the energy distribution of field-emitted