X-ray Emission Wavelengths of Argon, Krypton, Xenon, and Curium

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The wavelengths of the L series of argon, krypton and xenon, the K series of argon, and the M series of curium were measured by means of wavelength dispersive X-ray microanalysis. The specimens for the investigations were TiC layers which had been HF sputtered under reduced argon pressure by the PVD method, krypton and xenon implanted zeolites, and a curium doped borosilicate glass. The obtained relative intensities of the X-ray emission lines were normalized to the maximum intensity of the line of the respective series.

The qualitative and quantitative analysis of argon, krypton, and xenon in solids is becoming increasingly important in thin film physical vapour deposition (PVD) sputtering experiments under reduced argon atmosphere, implantation studies of noble gases in bulk materials, and fission gas analysis in irradiated nuclear fuels. The analysis of curium is of interest for the characterization of the chemical behaviour of this α-particle emitting short-lived actinide in nuclear fuels and wastes. The identification of these elements by X-ray spectroscopy requires precise knowledge of the wavelengths and intensities of the X-ray emission spectra which have favourable regions for X-ray microanalysis between 200 pm and 6 nm.

The X-ray emission spectra of the most intensive lines of the K and L series of argon, krypton and xenon were reviewed in [1]. The M series of the actinides uranium, neptunium, plutonium and americium were refined [2] and the L series of technetium was complemented [3]. In this study, the X-ray emission lines of the K series of argon, the L series of argon, krypton and xenon, and the M series of curium were measured in the wavelength range between 200 pm and 6 nm. As a spin-off result the chemical shift of the Kα and Kβ_1 lines of aluminium in zeolite was investigated.

Argon was implanted during the biased magnetron sputtering of a 5 µm thick TiC layer on a hard material substrate under reduced argon pressure. The quantitative X-ray microanalysis yielded 6 at.% Ar, uniformly distributed in the TiC layer. Krypton and xenon were incorporated in magnesium and calcium substituted type 5A zeolites (Bayer AG) at temperatures up to 650 °C and noble gas pressures up to 1400 bar with concentrations of 0.165 g Kr and 0.195 g Xe per zeolite [4]. The krypton and xenon concentrations were inhomogeneously distributed in the zeolite kernels. Curium was dissolved in form of 1.7% Cm-244 dioxide in molten borosilicate glass. The excellent homogeneity was checked by α-autoradiography. This sample is used as Cm standard for quantitative X-ray microanalysis. The Kr, Xe and Cm samples were embedded into an araldite resin, and the cylindrical cuts were polished with diamond paste down to 0.25 µm grit. The Ar implanted TiC layer was used without any further treatment. The wavelengths and the relative intensities of the X-ray emission lines were measured with the crystal spectrometers of two X-ray microanalyzers. The Ar L series was diffracted on an advanced lead stearate crystal [5] and the Kr L series on a thallium phthalate crystal ($2d = 10.0$ and 2.5745 nm) in the Cameca Camebax Microbeam instrument, take-off angle $\alpha = 40°$. The Xe L and Cm M series were diffracted on the $10\bar{1}1$ plane of a quartz crystal ($2d = 668.62$ pm) in the α-γ shielded Jeol JRXA50 instrument, take-off angle 35°. The counts were measured by pulse counting in 0.4 pm steps widths. Experimental details are given in [2, 3].

Results

The X-ray L spectra of argon, krypton and xenon and the M spectrum of curium are illustrated in Figs. 1 to 4. The wavelengths were calibrated by external and interal standards in the samples, e.g. gold of the coat-

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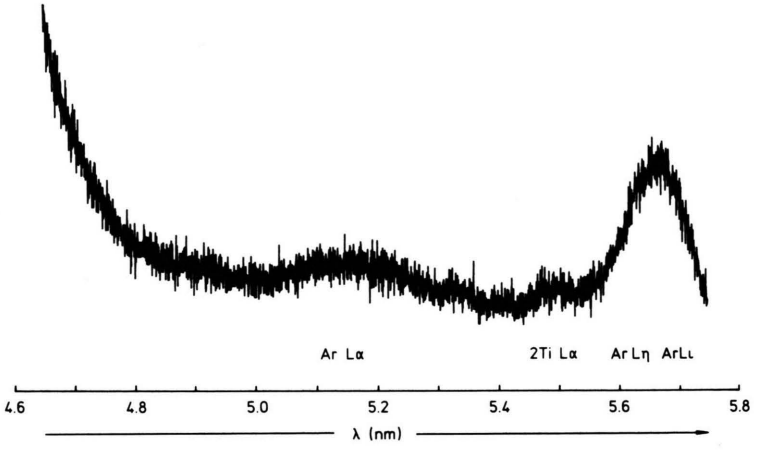

Fig. 1. X-ray spectrum of the L series of argon.

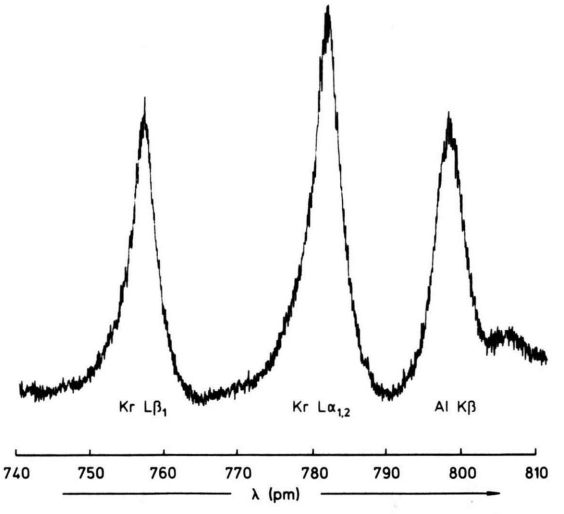

Fig. 2. X-ray spectrum of the most intensive lines of the L series of krypton.

Table 1. Wavelengths and relative intensities of the L series of the X-ray emission lines of argon, krypton and xenon; maximum relative intensity = 100%.

Line	Transition	Argon		Krypton		Xenon	
		λ in nm	rel. int.	λ in pm	rel. int.	λ in pm	rel. int.
$L\gamma_{2,3}$	$L_I N_{II,III}$	–	–	–	–	233.8	2
$L\gamma_1$	$L_{II} N_{IV}$	–	–	–	–	246.1	9
$L\beta_{2,15}$	$L_{III} N_{V,IV}$	–	–	–	–	262.8	20
–	$L_{II} N_{III}$	–	–	724.1	1	–	–
$L\beta_3$	$L_I M_{III}$	–	–	726.0	2	274.9	9
$L\beta_4$	$L_I M_{II}$	–	–	–	–	278.7	5
$L\beta_1$	$L_{II} M_{IV}$	–	–	757.2	50	280.74	50
$L\alpha_{1,2}$	$L_{III} M_{V,IV}$	5.15	< 10	781.9	100	301.72	100
$L\eta$	$L_{II} M_I$	5.62	20	860.8	1.5	313.1	< 1
$L\iota$	$L_{III} M_I$	5.66	100	894.0	4	340.7	< 1

ing, calcium of the zeolites, and titanium of the argon implanted layer. The wavelengths and the relative intensities of the L series of argon, krypton and xenon are presented in Table 1; those of the K series of argon in Table 2; the $M\alpha_1$ and $M\beta$ X-ray emission lines of curium are compiled together with the other light actinides in Table 3. The standard errors are smaller than 0.1 pm for the Xe L and Cm M series due to the excellent spectral resolution $\Delta\lambda/\lambda = 0.0013$ of the quartz crystal. The standard errors range between 0.1 and 0.5 pm for the Kr L series, depending on the intensity of the lines by use of a TAP crystal with a spectral resolution $\Delta\lambda/\lambda = 0.006$. The standard errors are 10 pm for the Ar $L\iota$ and Ar $L\eta$ lines and 30 pm for the Ar $L\alpha$ line by use of a lead stearate crystal with a spectral resolution $\Delta\lambda/\lambda = 0.03$ [4]. The relative intensities were measured by counting of the net pulses and were normalized to $K\alpha_1 = 100\%$, $L\alpha_{1,2} = 100\%$ and $M\alpha_1 = 100\%$ of the respective series. The most intensive line of the Ar L series is the $L\iota$ line.

The wavelengths of the Al K series were determined by use of the zeolite. The wavelength of the measured

Table 2. Wavelengths and relative intensities of the K series of the X-ray emission lines of argon; maximum relative intensity = 100%.

Line	Transition	Bearden [1]	This work	
		λ in pm	λ in pm	rel. int.
$K\beta_5$	$KM_{IV,V}$	–	387.7 ± 0.1	2
$K\beta_1$	KM_{III}	388.60	388.56 ± 0.05	17
$K\alpha_1$	KL_{III}	419.180	419.23 ± 0.05	100
$K\alpha_2$	KL_{II}	419.474	–	–

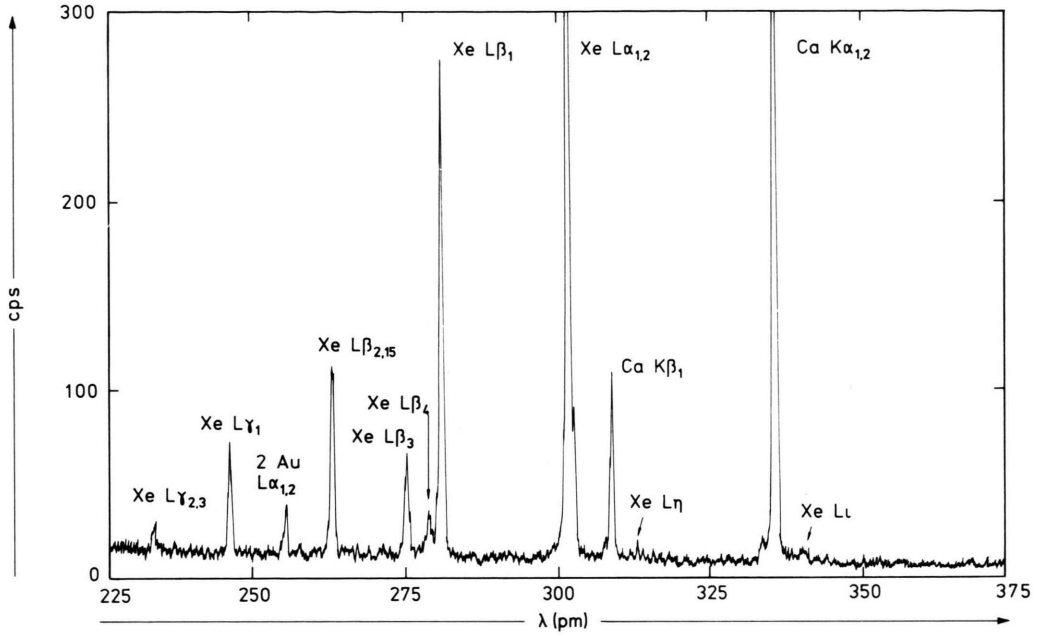

Fig. 3. X-ray spectrum of the L series of xenon.

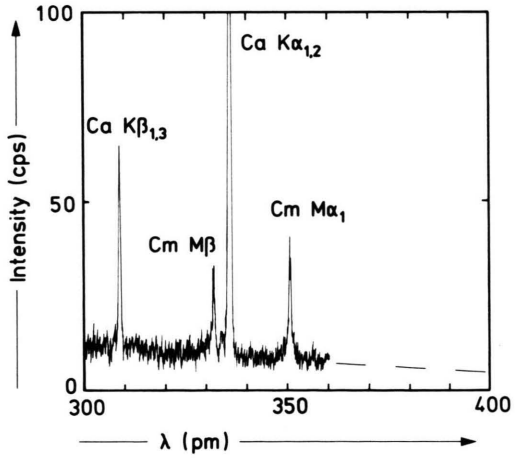

Fig. 4. X-X-ray spectrum of the most intensive lines of the M series of curium.

Al $K\alpha_1$ line is $\lambda = 833.8$ pm compared to that of elemental aluminium, $\lambda = 833.934$ pm [1]; the wavelength of the measured Al $K\beta$ line is $\lambda = 798.5$ pm compared to that of elemental aluminium, $\lambda = 796.0$ pm [1].

Table 3. Wavelengths and relative intensities of the $M\alpha_1$ and $M\beta$ X-ray emission lines of the light actinides; maximum relative intensity of $M\alpha_1 = 100\%$.

Element	$M\alpha_1$	$M\beta$		Ref.
	λ in pm	λ in pm	rel. int.	
Thorium	413.8	394.1	–	[1]
Protactinium	402.2	382.7	–	[1]
Uranium	391.0	371.6	180	[2]
Neptunium	380.0	360.8	72	[2]
Plutonium	370.1	351.0	67	[2]
Americium	360.2	341.3	64	[2]
Curium	350.7	331.7	48	–

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