PRAMANA
— journal of
physics

Vol. 40, No. 1,
January 1993
pp. 59–64

Measurement of angular distribution of M shell fluorescent X-rays excited by 5·95 keV photons in thorium

K S KAHLON*, K L ALLAWADHI and B S SOOD
Physics Department, Punjabi University, Patiala 147 002, Punjab, India
* Physics Department, LIET, Longowal, Distt. Sangrur 148 106, Punjab, India

MS received 19 October 1991

Abstract. The differential cross-sections for the emission of M shell fluorescent X-rays from Th by 5·95 keV photons at eight angles ranging from 50° to 120° have been measured. The differential cross-section is found to decrease with increase in the emission angle showing anisotropic spatial distribution of M shell fluorescent X-rays. The present results contradict the predictions of the calculations of Cooper and Zare [1] that the atomic inner shell vacancy states produced in photoionization are not aligned but confirm those of Flugge *et al* [2] and Scofield [3] that the vacancy states with $J > 1/2$ are aligned. The integral M shell fluorescent emission cross sections have been determined from the measured angular distribution coefficients and compared with theoretical integral cross-sections calculated by using theoretical values of M subshell photoionization cross-sections, fluorescence yields and coster kronig transition probabilities available in literature. The experimental and theoretical values of integral cross-sections show a reasonable agreement.

Keywords. Fluorescent X-rays; M-shell; angular distribution.

PACS No. 32·80

1. Introduction

Our recent experiments [4–7] have shown that, subsequent to photoionization of K and L shell electrons, the emission of the Kα, Kβ, Lβ and Lγ groups of fluorescent X-ray lines is isotropic while that of Ll and Lα groups is anisotropic in spatial distribution. The results contradict the predictions of the calculations of Cooper and Zare [1] that the atomic inner shell vacancy states produced in photoionization are not aligned but confirm those of Flugge *et al* [2] and Scofield [3] that the vacancy states with $J > 1/2$ are aligned. The radiation emitted on the decay of unaligned and aligned vacancy states have isotropic and anisotropic spatial distribution respectively.

In order to provide a further check on the theoretical calculations we have extended our earlier measurements of the angular distribution of K and L shell fluorescent X-rays to M shell X-rays. The differential cross-sections for the emission of M shell X-rays from Th by 5·59 keV photons at eight different angles varying from 50° to 120° at intervals of 10° have been measured. The energy of the incident photons is chosen to be lower than the L3 subshell photoionization threshold energy of Th so that its K and L shell electrons are not ionized and transfer of vacancies from K and L subshells to M subshells is prevented. Thus the population distribution of the vacancies among various M subshells produced directly by the photoionization of M subshell electrons is not disturbed by the transfer of vacancies from K and L subshells to various M subshells. It may, however, be noted that the initial M subshell vacancy distribution produced by the direct photoionization gets disturbed when some of the vacancies in lower M subshells are shifted to higher M subshells through coster kronig transitions prior to M subshell X-ray emission since coster kronig transitions are known to be faster than X-ray emission. The method of measurement alongwith the experimental set-up used for measurements and analysis of experimental results are discussed here.

2. Method of measurement and experimental set-up

The method of measurement and experimental set-up were similar to the ones described in detail earlier [4]. Briefly, the method of measurement of differential cross-section for the emission of M shell fluorescent X-rays from Th by 5·95 keV photons at angle θ consisted of measuring the absolute yield of M shell X-rays emitted at angle θ from Th target of known thickness when it was irradiated with 5·95 keV photons of predetermined flux. 5·95 keV X-rays obtained after K capture in ^{55}Fe radioisotope of strength ~ 100 mCi were collimated to fall on target of Th with thickness 54·3 mg/cm^2. The M shell X-rays emitted from the target at angle θ following the photoionization of M shell electrons in the target were counted with a Si(Li) detector X-ray spectrometer. The Si(Li) detector was fixed at one position on a graduated circular turn table, while the ^{55}Fe source and Th target were moved together with respect to the detector by putting both of them on a movable arm capable of rotation about an axis through the centre of the circular turn table. The angle of incidence of 5·95 keV photon beam on the target was fixed at 45° while the angle of emission of X-rays from the target was varied from 50° to 120° and the M X-ray emission intensity was measured at eight angles at intervals of 10° with an angular spread of $\pm 4°$ which had to be increased from its previous values of $\pm 2°$ used in our earlier measurements to get the desired statistical accuracy in counting rates in reasonable counting time. Circular target of Th of 4 cm in diameter was cut from 99·99% pure metallic foil. Si(Li) detector with active diameter 10 mm, sensitive depth 4·66 mm and Be window thickness 0·0254 mm was coupled to nuclear data 76 multichannel analyser system to analyse and count M X-rays. The resolution of the X-ray spectrometer was ~ 170 eV at 5·95 keV. A typical M X-ray spectrum of Th taken at emission angle of 90° is shown in figure 1. The various M X-ray lines of Th are not resolved due to the limited resolution of the spectrometer but fall under one composite peak. However the composite M X-ray peak is well resolved from the peak due to scattering of the incident radiation from the target. The differential cross-section for the emission of X-rays at angle θ is given by

$$\frac{\mathrm{d}^{\theta}\sigma(M)}{\mathrm{d}\Omega} = N_x^{\theta}(M)\frac{A}{Nt}\frac{1}{\beta^{\theta}(M)}\frac{4\pi}{S_r a_r \omega_1 \omega_2^{\theta} \varepsilon^{\theta}(M)} \tag{1}$$

where various terms have the same meaning as explained earlier but stand for M shell instead of Li group of L subshell X-rays. $Nx^{\theta}(M)$ was measured with a statistical accuracy of $\sim 1\%$ from the total number of counts observed under the peaks in the spectra taken at various angles. The values of the term A/Nt which are essentially reciprocal of the number of atoms per unit area of the target, and the term $\beta^{\theta}(M)$ that takes care of the absorption of the incident and emergent X-rays in Th were determined from the physical parameters of the target and the absorption coefficients of the incident and the emitted photons in Th target respectively. The values of the

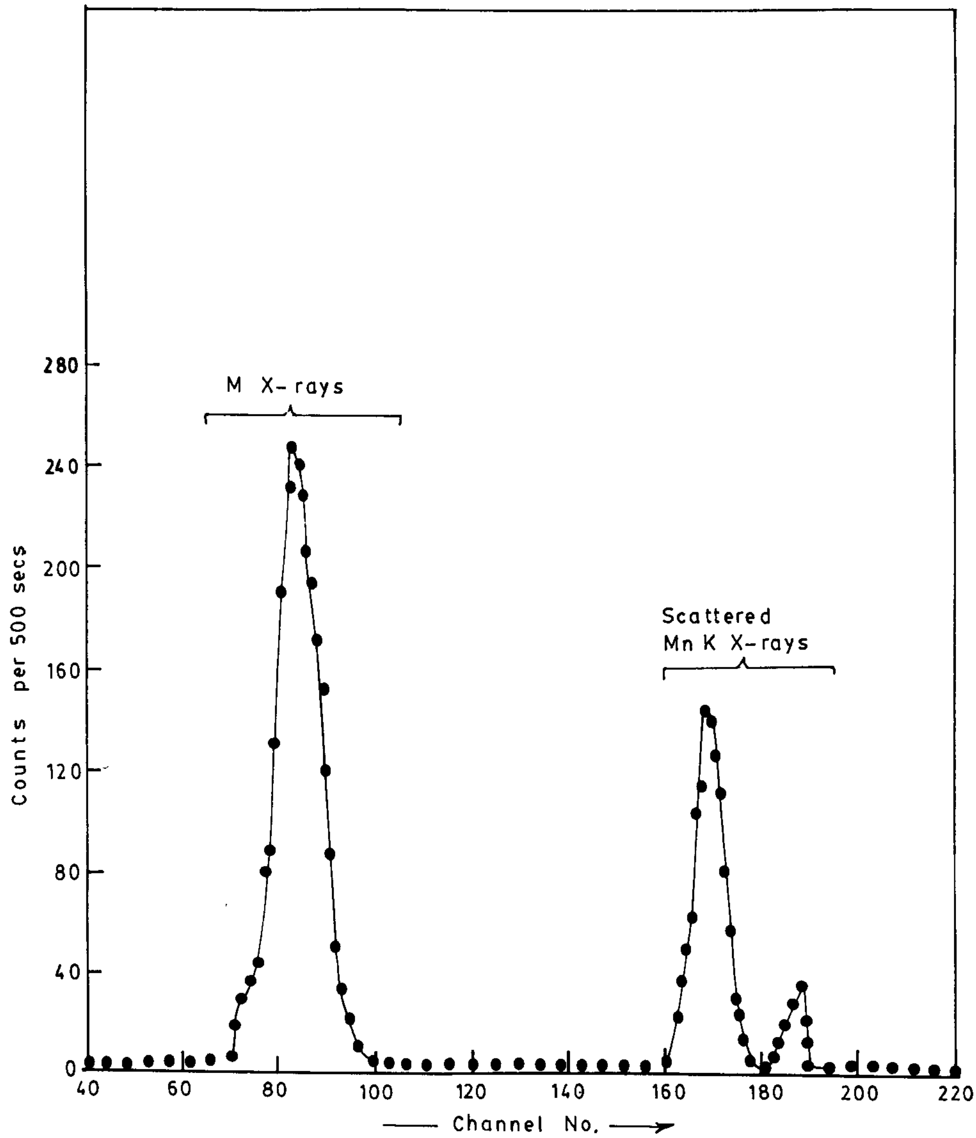

Figure 1. Energy convergence profile in a typical pathological case of orbital optimization in OGM when shifting is used (a–c) and when shifting is withdrawn after a few iterations (a–b).

factor $[4\pi/S_r a_r \omega_1 \omega_2^\theta \varepsilon^\theta(M)]$ which contains terms relating to the ^{55}Fe source strength, source target and target detector solid angles and detector efficiencies were determined with an accuracy of $\sim 3\%$ in a separate experiment in terms of the known K X-ray emission cross-sections in elements $16 \leqslant Z \leqslant 23$ using the same method as explained earlier [4].

3. Results and discussion

The measured values of the differential cross-sectons for emission of M X-rays at different emission angles are shown in table 1. To our knowledge no other experimental

Table 1. Measured differential cross-sections for the emission of Th M X-rays.

Angle of emission	Differential cross sections in b/atom		
	I	II	III
50	1213 ± 96	1189 ± 94	1087 ± 86
60	1078 ± 86	1054 ± 83	952 ± 75
70	884 ± 71	860 ± 68	758 ± 60
80	848 ± 70	824 ± 65	722 ± 57
90	736 ± 59	712 ± 56	610 ± 48
100	675 ± 58	651 ± 52	549 ± 43
110	610 ± 54	586 ± 46	484 ± 38
120	570 ± 48	546 ± 43	444 ± 35

Column I: Differential cross-section for emission of M1, M2, M3, M4 and M5 subshell X-rays.
Column II: Differential cross-sections for emission of M3, M4 and M5 subshell X-rays.
Column III: Differential cross-sections for emission of M3, M4 and M5 subshell X-ray when the vacancies transferred from M1 and M2 subshells are excluded.

or theoretical cross-sections are available for comparison with present results. The errors in the present measurements are ~ 7–8% and are due to counting statistics and uncertainties involved in calculation and or measurement of other parameters used for the determination of the cross-section from equation 1. The differential cross-section is found to decrease by a factor of ~ 2 when the emission angle increase from 50° to 120° showing that the M X-ray lines emitted under the composite M X-ray peak have anisotropic distribution.

In our earlier experiments the observed isotropic spatial distribution of fluorescent X-rays lying under the Kα, Kβ and Lγ peaks and anisotropic distribution of X-rays under the Ll and Lα peaks respectively were straightaway taken to confirm the predictions of the theoretical calculations of Flugge *et al* [2] that only vacancy states with $J > 1/2$ are aligned since Kα, Kβ and Lγ peaks originate only from transitions to $J = 1/2$ states while Ll and Lα peaks arise only from transitions to $J = 3/2$ state in K and L X-ray emission spectra. In the present experiment even though the peaks due to transitions to $J = 1/2$, 3/2 and 5/2 respectively in M X-ray emission spectra are not resolved because of the limited resolution of the currently available energy dispersive X-ray spectrometers and it is not possible to study the angular distribution of X-rays under the individual peaks yet the observed anisotropy of the M X-rays under the composite peak can be taken to confirm our earlier results [6] since more than 85% contribution to the composite peak is made by M3, M4 and M5 subshell X-rays with $J = 3/2$, 3/2 and 5/2 respectively. Assuming the vacancies produced in the photoionization of M1 and M2 subshells to be unaligned their contribution to X-ray emission under the composite M X-ray peak was calculated from the relation $1/4\pi[\sigma(M_1) + \sigma(M_2)]$ and subtracted from the measured differential cross-section at each angle. σ(M1) and σ(M2) are M1 and M2 subshell X-ray production cross-sections which were calculated from the theoretical values of M1 and M2 subshell photoionization cross-section and fluorescence and coster kronig yields available in literature. The differential cross-sections after subtraction of the contributions of M1 and M2 subshell X-rays produced by the direct photoionization of M1 and M2 subshells are given in column II of table 1. Since some of the vacancies created directly by photoionization of M1 and M2 subshell electrons are also transferred to M3, M4 and M5 subshells through coster kronig transitions, the differential cross sections for the emission of X-rays due to the filling of vacancies created only by the photoionization of M3, M4 and M5 subshell electrons were calculated by subtracting from the cross section in column II the cross sections for the emission of X-rays due to filling of the unaligned vacancies which were transferred from M1 and M2 subshells to M3, M4 and M5 subshells through coster kronig transitions and are listed in column III of table 1. The differential cross-sections for the emission of X-rays due to the filling of transferred vacancies from M1 and M2 subshells to M3, M4 and M5 subshells were calculated using relations discussed in detail earlier [8]. It is seen that the ratio of differential cross-sections at 50° and 120° for Th increases from 2·13 to 2·45 when the contributions of both the directly created and transferred M1 and M2 subshell vacancies are taken into account. The observed increase in ratio of $d^{50}\sigma(M)/d^{120}\sigma(M)$ indicates greater spatial anisotropy and it indirectly justifies the validity of the assumption that the M1 and M2 subshell vacancies are not aligned.

Representing the differential M X-ray emission cross section by a legendre

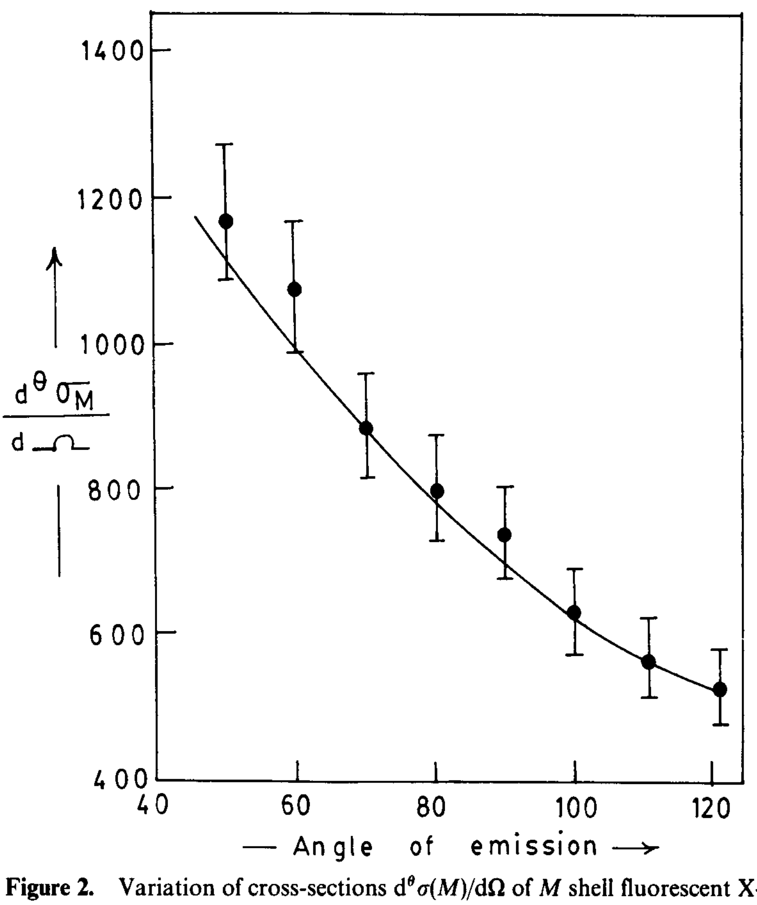

Figure 2. Variation of cross-sections $d^{\theta}\sigma(M)/d\Omega$ of M shell fluorescent X-rays of Th with angle of emission θ. Φ, experimental points; full curve, fitted curve drawn with measured $a0$, $a1$ and $a2$ coefficients.

polynomial sum

$$\frac{d^\theta \sigma(M)}{d\Omega} = \sum_l a_l P_l(\cos\theta), \tag{2}$$

the observed cross-sections are fitted to the relation

$$d^\theta \sigma(M)/d\Omega = a_0 + a_1 \cos\theta + a_2 \cos^2\theta. \tag{3}$$

The values of the coefficients $a0$, $a1$ and $a2$ are 693, 473 and 281 respectively. The experimental and fitted cross-sections are shown in figure 2. Since the theoretical values of angular distribution functions for the emission of M shell X-rays are not available in literature, the integral cross-section was determined from the measured angular distribution coefficients and for comparison with theory using the relation

$$\sigma_M = 2\pi \int_0^\pi \sum_{n=0}^{2} a_n \cos^n\theta \sin\theta \, d\theta. \tag{4}$$

The value of the integral cross-section determined from the measured angular distribution coefficients is found to be 10317 ± 820 b/atom. The value of the integral cross-section calculated from the theoretical values of M subshell photoionization cross section, fluorescence and coster kronig yields using the relations explained earlier [8] is 9526 b/atom.

Since the current knowledge of M subshell coster kronig transition probabilities and fluorescence yields needed in the calculations of M shell integral cross sections is inadequate the agreement between the experimental and theoretical values of the integral cross-sections is reasonable.

Acknowledgements

The authors (BSS and KSK) gratefully acknowledge the award of emeritus fellowship from University Grants Commission, India, and senior research fellowship from Council of Scientific and Industrial Research, India, respectively.

References

[1] J Cooper and R N Zare, *Atomic collision processes* (Gordan and Breach, New York, 1969) **XIC 317**
[2] S Flugge, W Mehlhorn and V Schmidt, *Phys. Rev.* **A29**, 7 (1972)
[3] J H Scofield, *Phys. Rev.* **A14**, 1418 (1976)
[4] K S Kahlon, K Shatindra, K L Allawadhi and B S Sood, *Pramana – J. Phys.* **35**, 105 (1990)
[5] K S Kahlon, H S Aulakh, N Singh, R Mittal, K L Allawadhi and B S Sood, *J. Phys.* **B23**, 2733 (1990a)
[6] K S Kahlon, H S Aulakh, N Singh, R Mittal, K L Allawadhi and B S Sood, *Phys. Rev.* **A43**, 1455 (1991)
[7] K S Kahlon, N Singh, R Mittal, K L Allawadhi and B S Sood, *Phys. Rev.* **A**, (1991a) (accepted)
[8] K S Mann, N Singh, R Mittal, K L Allawadhi and B S Sood, *J. Phys.* **B23**, 2497 (1990)