K-AND L-SHELL IONIZATION IN ALPHA DECAY

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ABSTRACT

The probabilities per α particle of shake-off in the K and L shells of ^{210}Po have been determined by α-X ray coincidence experiments. The results $P_K = (2.3 \pm 0.2) \times 10^{-6}$ and $P_L = (6.2 \pm 0.3) \times 10^{-4}$ are simultaneously compared with other experimental results and with the latest theoretical predictions. The number of Pb L X-rays arising from shake-off in the α decay of ^{210}Po is $(2.3 \pm 0.1) \times 10^{-4}$ per α decay and the agreement with other results is satisfactory.

1 — INTRODUCTION

The shell ionization of an atom can be produced during the α-decay of its nucleus by the emerging α-particle. The outgoing α spectrum associated with the ejected electron from a particular shell will have a maximum energy equal to the α-particle initial energy less the binding energy of the electron. The X-rays for each shell of the daughter element result either from the contribution of the 'shake-off' phenomenon, in which the atomic electron is excited into the continuum, or of the 'shake-up', in which the atomic electron is excited to an unoccupied bound state. The latter effect is the smallest of the two and, in this context, can be neglected. The degrees of ionization of the K-and L-shells are given by the ionization probabilities P_K and P_L which are the probabilities to create vacancies in those shells. The best way to determine experimentally these probabilities is by doing either X-ray-α coincidences or X-ray-electron coincidences in a pure α-emitter. The theory of the 'shake-off' phenomenon was first treated by Migdal [1], Feinberg [2], Levinger [3] and lately by Hansen [4], Scott [5], Watson [6], Law [7]; agreement between the results is unsatisfactory. The latest experimental results [8-13] seem to favour Hansen's theoretical interpretation.

On the other hand, in the same experimental results [9] P_L values obtained by X-ray-α coincidences and X-ray-electron coincidences are not in agreement. Fischbeck and Freedman [9] have raised the possibility that some electrons may be captured by the He^{++} ions and emerge like He^{+}. As most of the detectors do not distinguish He^{++} from He^{+}, the number of X-ray-α coincidences is not changed by the existence of the phenomenon but the number of X-ray-electron coincidences will be affected by the capture of the electron. So far, however, the errors in the P_L values do not allow us to reach definitive conclusions. The work reported here – a measurement of the ionization probabilities of the K-and L-shells of ^{210}Po – was undertaken because there are important discrepancies between theoretical and experimental results and some more values for P_L can contribute to choose the correct theoretical approach. On the other hand, our value for P_L determined by L X ray-α coincidences is absolutely necessary to investigate the possibility of electron capture by He^{++}, which is one of our objectives. This phenomenon is now being studied and we hope to say something more later on.

2 — EXPERIMENTAL PROCEDURE

2.1 — *X-ray side*

The K X-ray energy range goes from 73 keV to about 87 keV and so they were recorded in a coaxial Ge(Li) detector which has a volume of 22.5 cm^3, a full width at half maximum (FWHM) 2.4 keV for a 1.33 MeV γ-ray. The source-to-detector distance was variable and we have worked with a solid angle $\Delta\Omega_x = (2.10 \pm 0.17) \times \times 10^{-1}$ sr.

The L X-ray energy goes from 10.5 keV to about 14.8 keV and they were recorded in a solid state detector of hyperpure Ge which has an active diameter of 6 mm, an active depletion depth of 5 mm, a full-width at half maximum of 225 eV for a 5.9 keV and a 5 μm thick beryllium window. The working solid angle was $(4.51 \pm 0.24) \times \times 10^{-4}$ sr.

2.2 — α-*Side*

The ^{210}Po α-particles with an energy of 5.306 MeV were recorded in a surface barrier detector, of 50 mm² surface area, of 100 μm depletion depth and a resolution of 17 keV for an 5.486 MeV energy.

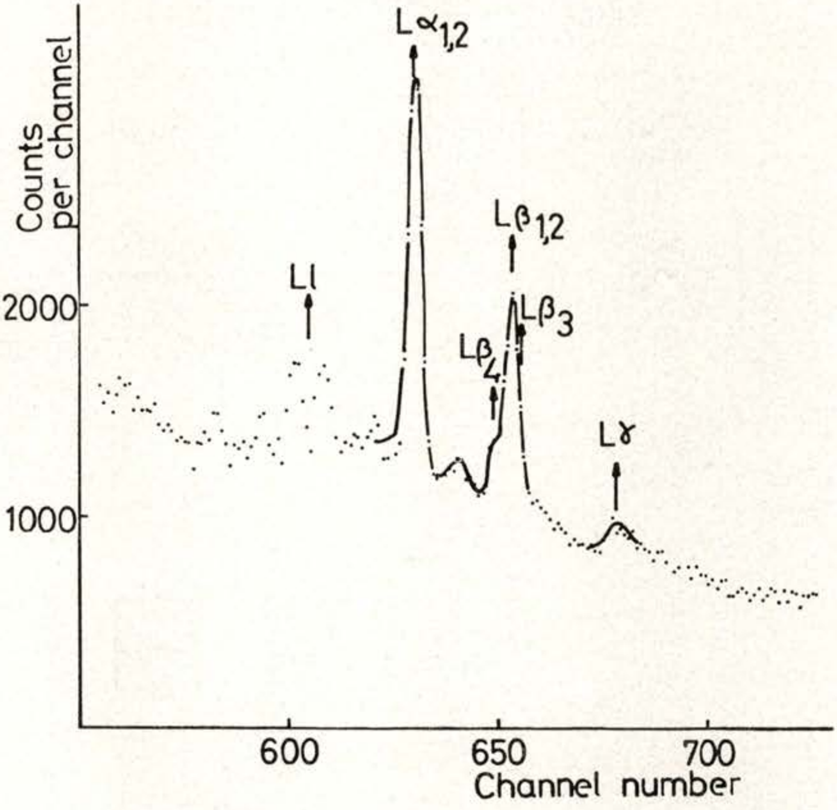

Fig. 1 — The Pb L X-ray spectrum.

This detector and the ^{210}Po source were housed in a small vacuum chamber which has a very thin mica window for the X-ray detection.

2.3 — *Source preparation*

The ^{210}Po was purchased from Radiochemical Centre (Amersham, England). The ^{210}Po activity was deposited by evaporation onto a mylar film. The source diameter was about 2 mm and its thickness was controlled to minimize the α-particle energy loss. The source purity was confirmed by the L X-ray spectrum shown in Fig. 1.

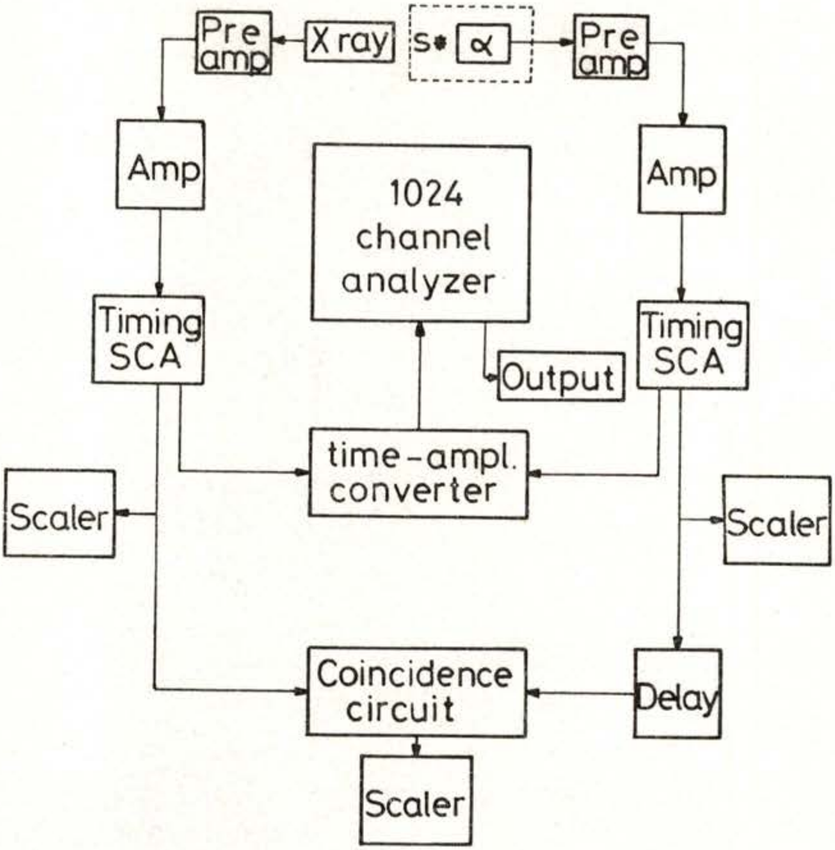

Fig. 2 — Block diagram of the electronic system.

2.4 — *Electronic setup*

The experimental results were obtained with a conventional coincidence installation associated with an Ortec time-amplitude converter according to the block diagram shown in Fig. 2. The X-ray spectra and the α spectrum were controlled daily in a 1024 multichannel analyser.

3 — RESULTS

3.1 — K-shell ionization probability P_K

The coincidence rates obtained with the ^{210}Po source were measured by the coincidence unit and by the time-amplitude converter (TAC) for a total run time of about 31 days. The spectrum of the KX-rays in coincidence with α-particles and registered in the TAC is shown in Fig. 3.

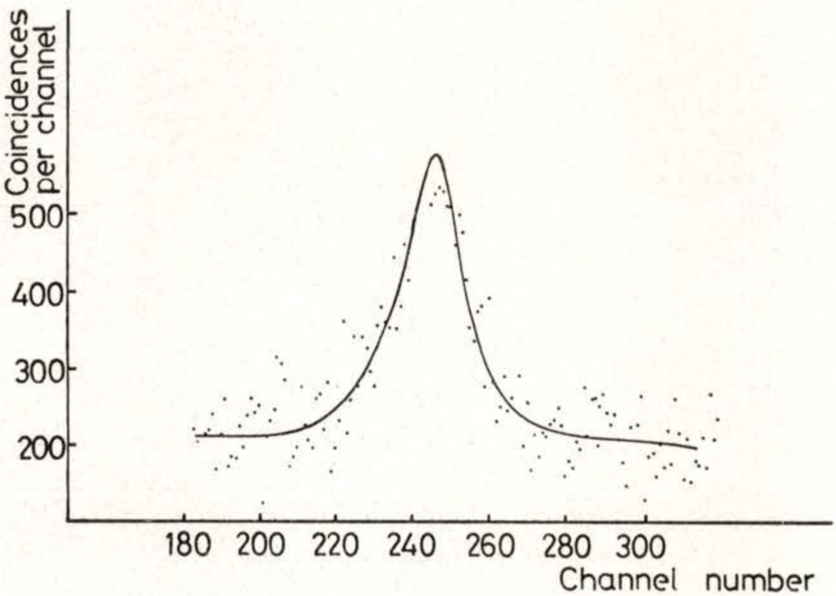

Fig. 3 — K X-ray-α particle coincidence spectrum registered in the TAC.

The ionization probability P_K, that is, the probability to create a vacancy in the K-shell, was determined from the expression:

$$N_c = N_\alpha \, \Delta\Omega_\alpha \, \varepsilon_\alpha P_K \, \omega_K \, \Delta\Omega_x \, \varepsilon_x \tag{1}$$

where N_c is the number of coincidences per time unit, N_α is the number of α particles per time unit, ε_α, ε_x are the α-particle and the X-ray detector efficiencies and ω_K is the fluorescence yield of the

K-shell. Using the value of N_e taken from Fig. 3, the value of $\Delta\Omega_x$ referred in 2.1 and the value $\omega_K = 0.972 \pm 0.008$ [16] we determined

$$P_K = (2.3 \pm 0.2) \times 10^{-6}$$

3.2 — *L-shell ionization probability P_L*

The spectrum of L X-rays in coincidence with the α-particles is shown in Fig. 4. From this spectrum and from an expression similar

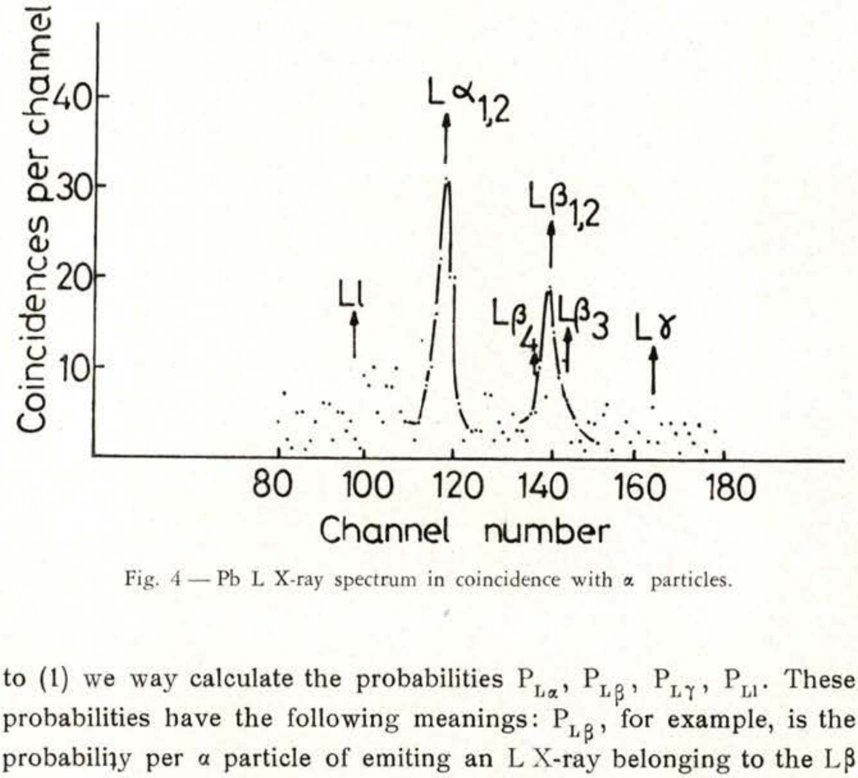

Fig. 4 — Pb L X-ray spectrum in coincidence with α particles.

to (1) we way calculate the probabilities $P_{L\alpha}$, $P_{L\beta}$, $P_{L\gamma}$, P_{Ll}. These probabilities have the following meanings: $P_{L\beta}$, for example, is the probabiliły per α particle of emiting an L X-ray belonging to the Lβ peak. To have good statistics we performed three runs of about 17 days each and the results shown below are the average value of these runs. The single L X-rays and the α spectra were controlled daily. The results for the L X-rays of Pb, expressed for α decays of ^{210}Po, are:

$$P_{L\alpha} = (1.09 \pm 0.08) \times 10^{-4}$$

$$P_{L\beta} = (0.95 \pm 0.07) \times 10^{-4}$$

$$P_{L\gamma} = (0.18 \pm 0.03) \times 10^{-4}$$

$$P_{LI} = (0.06 \pm 0.01) \times 10^{-4}$$

Therefore the total number P_{LX} of Pb L X-rays arising from shake-off in the α-decay of ^{210}Po is

$$P_{LX} = (2.3 \pm 0.1) \times 10^{-4}$$

Assuming that the fluorescence yield in the L shell is $\bar{\omega}_L = 0.37$ [16] we found for the ionization probability P_L the value

$$P_L = (6.2 \pm 0.3) \times 10^{-4}$$

This probability can also be written in terms of the P_{L_I}, $P_{L_{II}}$, $P_{L_{III}}$ subshell probabilities and these values can be deduced from the expressions

$$P_{L\alpha} = [P_{L_{III}} + P_{L_{II}} f_{23} + P_{L_I} (f_{13} + f_{12} f_{23})] \, \omega_3 \, F_{3\alpha},$$

$$P_{L\beta} = [P_{L_{III}} + P_{L_{II}} f_{23} + P_{L_I} (f_{13} + f_{12} f_{23})] \, \omega_3 \, F_{3\beta} +$$

$$+ (P_{L_{II}} + P_{L_I} f_{12}) \, \omega_2 \, F_{2\beta} + P_{L_I} \, \omega_1 \, F_{1\beta},$$

$$P_{L\gamma} = (P_{L_{II}} + P_{L_I} f_{12}) \, \omega_2 \, F_{2\gamma} + P_{L_I} \, \omega_1 \, F_{1\gamma},$$

where f_{12}, f_{13} and f_{23} are the values of the Coster-Kronig yields, ω_1, ω_2 and ω_3 are the values of the subshell fluorescence yields and F_{ij} is the fraction of radiative transitions in the L_j peak connected with filling a vacancy in the L_i subshell. The radiative rates are taken from Scofield tables [15] and the f_{ij} and ω_i from Bambynek et al tables [16]. By solving the previous system of equations we may write P_{L_I}, $P_{L_{II}}$, $P_{L_{III}}$ in terms of $P_{L\alpha}$, $P_{L\beta}$, $P_{L\gamma}$. Thus, for example, $P_{L_I} = a \, P_{L\alpha} + b \, P_{L\beta} + c \, P_{L\gamma}$ and the coefficients a, b, c, depend on the f_{ij}, ω_i, F_{ij} parameters. Unfortunately the coefficients a, b, c can be of different signs and therefore they can generate large uncertainties in the P_{L_I}, $P_{L_{II}}$, $P_{L_{III}}$ values and consequently in the

P_L value. For this reason we have chosen to evaluate P_L from the total photon yield per α particle, P_{LX}, using the mean L-shell fluorescence yield $\bar{\omega}_L = 0.37$.

4 — DISCUSSION

In tables I, II, and III, we have summarized the theoretical and latest experimental results and compared them with our values.

TABLE I — Theoretical and experimental K-electron emission probability per α decay.

Theory	Reference	Experiment	Method	Reference
2.5×10^{-6}	1	$(2.0 \pm 0.5) \times 10^{-6}$	α-KX coinc.	8
2.02×10^{-6}	4	$(1.65 \pm 0.16) \times 10^{-6}$	α-KX coinc.	10
1.81×10^{-6}	7	$(2.6 \pm 0.5) \times 10^{-6}$	α-KX coinc.	9
2.24×10^{-6}	7	$(2.5 \pm 0.7) \times 10^{-6}$	Elect-KX coinc.	9
2.34×10^{-6}	7	$(2.3 \pm 0.2) \times 10^{-6}$	α-KX coinc.	This work
2.88×10^{-6}	7			

The results of ref. 7 are obtained with different approximations for the α-nucleus potential.

TABLE II — Theoretical and experimental L-electron emission probability per α decay

Theory	Reference	Experiment	Method	Reference
1.13×10^{-4}	1	$(2.83 \pm 0.45) \times 10^{-4}$	α-LX coinc.	9
5.9×10^{-4}	4	$(3.05 \pm 0.46) \times 10^{-4}$	Elect-LX coinc.	9
1.29×10^{-4}	7	$(8.6 \pm 2.2) \times 10^{-4}$	α-LX coinc.	8
2.74×10^{-4}	7	$(7.23 \pm 0.65) \times 10^{-4}$	α-LX coinc.	16
1.27×10^{-4}	7	$(6.2 \pm 0.3) \times 10^{-4}$	α-LX coinc.	This work
2.69×10^{-4}	7			

The P_K value is very close to the other experimental values and the agreement with the theoretical results is quite satisfactory.

The unexpected value of $(2.83 \pm 0.45) \times 10^{-4}$ for P_L obtained by Fischbeck and Freedman [9] is not reinforced by our result. This seems, in fact, to confirm the experimental results obtained by many

TABLE III — Theoretical and experimental L-total photon yield per α decay

Theory	Reference	Experiment	Reference
1.83×10^{-4}	4	$(2.93 \pm 0.44) \times 10^{-4}$	14
0.477×10^{-4}	7	$(3.2 \pm 0.8) \times 10^{-4}$	8
1.01×10^{-4}	7	$(3.03 \pm 0.19) \times 10^{-4}$	9
0.470×10^{-4}	7	$(2.37 \pm 0.21) \times 10^{-4}$	10
0.995×10^{-4}	7	$(2.6 \pm 0.4) \times 10^{-4}$	12
		$(2.3 \pm 0.1) \times 10^{-4}$	This work

The results of ref. 7 are obtained from table II assuming $\bar{\omega}_L = 0.37$.

other authors and the theoretical value calculated by Hansen [4]. The recent theory due to Law [7] is not confirmed by our experimental result. Since our values have been obtained by α-L X coincidences, the electron capture hypothesis can not be discussed. This will be a matter for study in the near future. On the other hand, as the values of P_{L_I}, $P_{L_{II}}$, $P_{L_{III}}$ depend strongly on the theoretical model, an experimental set of accurate values for those subshell probabilities will be important to test those models.

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