INELASTIC INTERACTIONS OF GAMMA RAYS WITH K-SHELL ELECTRONS

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ABSTRACT. The technique of the absolute intensity measurement of K-shell fluorescent radiation by a NaI(Tl) crystal has been employed to measure the cross-sections of the inelastic interactions of 280, 662 and 1250 keV gamma rays with K-shell electrons in lead and gold. The X-rays efficiency of the detector has been measured experimentally by comparing the ratio of gamma rays and X-rays following internal conversion from Au^{198} and Hg^{203} sources. For 280 keV gamma rays the measured cross-sections agree with the known photo-electric cross-sections showing that the X-rays are produced essentially through the photo-electric interaction. For 662 and 1250 keV the measured cross-sections are somewhat higher than those of photo-electric interaction indicating the contribution of the Compton scattering from K-shell electrons, the integrated cross-section of which is estimated to be equal to that from free and stationary electrons.

INTRODUCTION

The inelastic interactions of gamma rays with K-shell electrons of the target atoms result in K-vacancies which emit fluorescent X-rays or eject Auger electrons. The processes of interactions are, (i) Photoelectric effect and (ii) Compton scattering from bound electrons. The number of K-vacancies created, which is equal to the K-shell X-rays emitted divided by the K-shell fluorescence yield, is a measure of the cross-sections of these interactions. The measurement of the number of X-rays emitted when a target is irradiated with a known flux of gamma rays thus provides a method to obtain information about the cross-sections of these processes.

The experiments performed to determine the cross-sections of inelastic interactions of 280, 662 and 1250 keV gamma rays with K-shell electrons in Pb and Au by measuring the absolute yield of the K-shell fluorescent X-rays are described and an effort has been made to interpret the results in terms of the cross-sections of the above mentioned processes.

EXPERIMENTAL ARRANGEMENT AND PROCEDURE

The experimental set-up used is shown in fig. 1. Gamma rays of energies 280, 662 and 1250 keV were obtained from radioactive sources of Hg^{203}, Cs^{137} and Co^{60} respectively. The targets of the gold and lead in the form of circular foils (2.5 cm dia) were used. The thickness of the target could be varied by changing the number of foils. With one element measurements were made by using targets of thicknesses t, $2t$, $4t$ etc. The fluorescent X-rays emitted from the target were counted with a single channel spectrometer with a 2.5 cm dia × 2.5 cm height NaI(Tl) crystal. Direct radiation from the source was prevented from

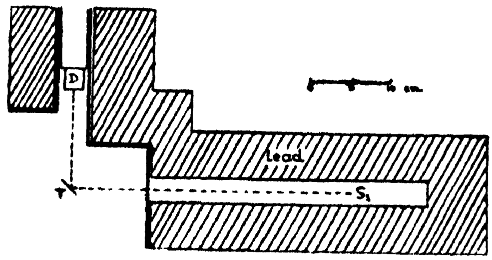

Figure 1. Experimental arrangement.

reaching the counter by graded shielding consisting of lead, tin, copper and aluminium. Source and detector were also shielded by graded absorbers to prevent scattering from walls and surroundings to the detector. The graded shielding had to be used for preferential absorption of fluorescent X-rays produced in the lead shielding. The energy spectrum of radiation emitted from the lead target in the fluorescent X-rays region is shown in fig. 2. It contains a prominent K-

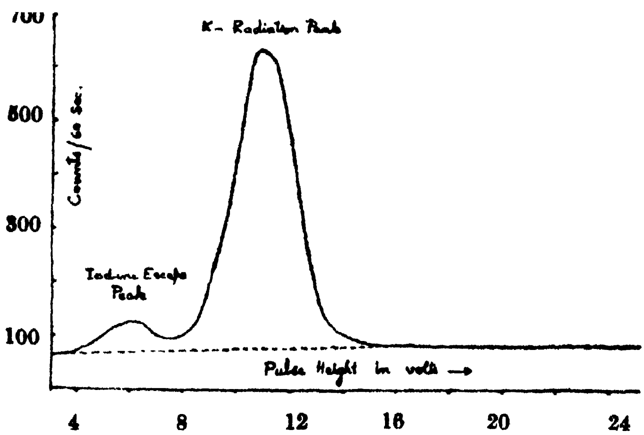

Figure 2. Spectrum of K-radiation when lead is irradiated with 280 keV gamma rays. Dotted curve is the spectrum taken with an equivalent aluminium.

shell X-rays peak. The spectrum taken with an equivalent aluminium target is also shown. The spectrum without any target in position showed a general background lower than that with Al target indicating that only those fluorescent X-rays which are emitted from the target and are of interest in the present investigations are recorded in the counter.

The measurement of the cross-section for the creation of K-vacancies consisted of determining the number of K-shell fluorescent X-rays emitted from the target, the source strength, the number of atoms per cc. of the target, the scatterer-detector and source-scatterer solid angles. The number of X-rays emitted from the target was calculated by measuring the area under the photo-peak of the X-rays spectrum and taking into account (i) the effective detection efficiency of the X-rays under the photo-peak in the experimental set-up used and (ii) the absorption of the incident gamma rays and the emitted X-rays in the target. Both these factors were determined experimentally as discussed later. The effective efficiency accounts for (i) the absorption of X-rays in the air between the target and the detector (ii) the absorption of X-rays in the crystal package, (iii) the iodine escape peak in crystal (Crouthamel, 1960) and (iv) photo-peak efficiency, corresponding to the fraction of X-rays which lose their full energy in the crystal. The source strength was determined in terms of the area under the photo-peak of the gamma rays under investigation, the absolute strength being not needed. The source-target solid angle was calculated from the known geometry, while the scatterer-detector solid angle was determined experimentally by replacing the scatterer with a weak source of the energy under investigation and comparing this weak source with the actual source used in the main experiment. Assuming isotropic distribution of X-rays, the cross-section for the creation of K-vacancies is given by

$$\sigma = \frac{N_1}{N_2} \cdot \frac{S_2}{S_1} \cdot \frac{\epsilon_\gamma}{\epsilon_K \omega_K} \cdot \frac{4\pi}{\omega_1 \rho t \beta} \qquad \ldots \quad (1)$$

where N_1/N_2 is the ratio of the counting rates due to the K-shell X-rays and the small source placed at the position of the target, S_2/S_1 is the ratio of the strengths of the weak and actual source, ϵ_γ is the photo-peak efficiency of the detector for gamma rays, ϵ_k is the effective detection efficiency of X-rays as defined above, ω_1 is the source-scatterer solid angle, ρ is the number of atoms per cc. of the target, t is the thickness of the target, β is the correction that accounts for the absorption of the incident gamma rays and emitted X-rays and ω_K is the K-shell fluorescence yield. S_2/S_1 was measured with an accuracy of 2 per cent by comparing the counts in the gamma ray photo-peaks of the two sources. Two sources of intermediate strength were used to avoid corrections due to source-detector geometry. The value of ϵ_γ, the gamma ray photo-peak efficiency, was taken from the tables of Crouthamel (1960) and graphs of Leutz *et al* (1965). The sequence of taking observations was arranged so as to minimize the effects of drifts in electronics and source decays.

DETERMINATION OF EFFECTIVE EFFICIENCY OF THE DETECTOR

Au^{198} decays by β emission to 412 keV level in Hg^{198} which de-excites by gamma ray emission or electron conversion. The K-shell conversion results in

K-vacancies in Hg and emit X-rays or Auger electrons. The *K*-conversion coefficient is defined as

$$\alpha_K = \frac{N_K \epsilon_\gamma}{N_\gamma \epsilon_K} \frac{1}{\omega_k}$$

where N_γ and N_K are the counting rates due to gamma rays and *K*-shell *X*-rays respectively and the other terms have been defined earlier. Knowing the value of $\alpha_K = 0.0302 \pm 0.0004$ (Suba Rao, 1966), $\epsilon_\gamma = 0.231$ (Crouthamel, 1960; Leutz *et al*, 1966) and measuring N_K and N_γ from the spectrum obtained by placing an Au^{198} source at the position of the target, the value of $\epsilon_K\ \omega_K$ was calculated to be 0.85 ± 0.04 for the 70.8 keV Hg *X*-rays in the present experimental arrangement. The analysis of the Au^{198} spectrum to determine N_γ and N_K is shown in fig. 3.

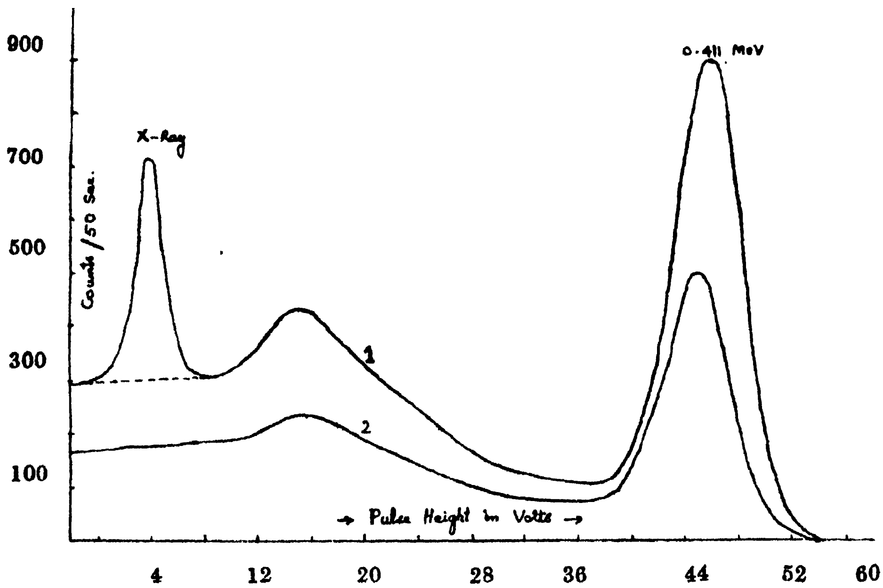

Figure 3. Pulse height distribution of Au^{198} spectrum. Curve 1 direct spectrum and curve 2 with graded absorber to absorb *X*-rays.

Similar measurements were also made for Tl *X*-rays using a Hg^{203} source which decays to 280 keV level in Tl and a value of 0.82 ± 0.04 was found for $\epsilon_K \omega_K$. The value of $\epsilon_K \omega_K$ was also determined by measuring the coincidence rate between β rays feeding 412 keV level and *X*-rays following internal conversion in Hg^{198}. The ratio of the β-*X* coincidence rate and β count rate is given by

$$N_{\beta X}/N_\beta = \omega_K\ \epsilon_K\ \omega_2 \qquad (2)$$

The target was replaced by the small Au^{198} source in the main experimental arrangement and a plastic scintillator was used for counting β rays. The β-ray counter was biased at 500 keV so that the internal conversion electrons are not counted. Coincidence count rate was again measured by placing a graded X-rays absorber before the NaI(Tl) crystal. This counting rate corresponds to 412 keV gamma rays which are counted in X-rays channel. Subtraction of this normalized counting rate from the first gave the true counting rate. Solid angle ω_2 was measured from the geometry of experimental set-up. The value of $\epsilon_K \omega_K$ as determined above came out to be $82 \pm .06$.

The value of ϵ_K for gold and lead X-rays is expected to be the same as that for Hg and Tl and ω_K also does not vary more than 0.05 per cent in the Z range for 79 to 82. Therefore a mean value of 0.83 ± 0.04 is used in eq. (1) for $\epsilon_K \omega_K$.

ABSORPTION OF INCIDENT GAMMA RAYS AND EMITTED X-RAYS IN THE TARGET

It can be shown (Shute *et al*, 1960) that the effective thickness of a target of real thickness t when the absorption of the incident gamma rays and emitted X-rays is taken into account is given by

$$t_{eff} = \frac{1 - \exp\left[-(\mu_K + \mu_\gamma)t/\cos\theta\right]}{\mu_K + \mu_\gamma} \quad \dots \quad (3)$$

where θ is the angle that the incident gamma rays and emitted X-rays make with the target and μ_γ and μ_K are the linear absorption coefficients for gamma rays and X-rays. The value of $\mu_\gamma + \mu_K$ was determined experimentally by measuring the ratio of the counting rates under the photo-peak with target of thickness t and $2t$ respectively. The ratio is given by

$$R = 1 + \exp\left[-(\mu_K + \mu_\gamma)t/\cos\theta\right] \quad \dots \quad (4)$$

The value of R was determined with an accuracy of 0.5 per cent and $\mu_\gamma + \mu_K$ was determined to be 2.85, 2.45 and 2.41 for 280, 662 and 1250 keV gamma rays respectively for lead and 2.88, 2.63 and 2.59 for gold.

RESULT AND DISCUSSIONS

About ten independent runs were made with each target at one gamma ray energy and the results are shown in column 3 of table 1. The errors given are due to the statistics of the counting rate and the uncertainties involved in the comparison of source strengths, the determination of $\epsilon_K \omega_K$ and estimation of other corrections. The calculated (Grodstein, 1957) K-shell photo-electric cross-sections are given in column 4. Column 5 gives the difference between the measured inelastic cross-sections and the calculated K-shell photo-electric cross-sections and should give the contributions of K-shell electron Compton scattering and the secondary processes, e.g. K-shell excitation or ionization of the target atoms by photo- and Compton electrons. Column 6 gives the calculated Compton scattering cross-section for two electrons if assumed free and at rest after the formula given by Klein and Nishina. It is seen from the table that at 280 keV the measured cross-section agrees fairly well with the calculated K-shell photoelectric cross-section showing that for low energy gamma rays and high-Z elements the K-shell fluorescent X-rays are produced essentially through photoelectric interaction and this method can be used to measure the K-shell photoelectric cross-sections of low energy radiation in high-Z elements.

TABLE 1

K-shell interaction cross-sections of 280, 662 and 1250 keV gamma rays with gold and lead.

Gamma ray energy in MeV	Element	σ(exp.) in barns	σ(NBS) in barns	σ(exp)$-\sigma$(NBS) in barns	σ_c in barns
0.280	Au	82.6 ± 5.5	83.4	—	0.73
	Pb	95.1 ± 6.0	95.5	—	0.73
0.662	Au	11.4 ± 0.9	10.6	0.8 ± 0.9	0.51
	Pb	13.4 ± 1.0	12.4	1.0 ± 1.0	0.51
1.25	Au	3.7 ± 0.5	2.9	0.8 ± 0.5	0.38
	Pb	4.2 ± 0.5	3.7	0.6 ± 0.5	0.38

The contribution of K-shell Compton scattering cross-section as given in column 5 increases with gamma ray energy and at 1.25 MeV it is about 20 per cent if the contributions of secondary processes being second order effects are neglected. The data available on Compton scattering of gamma rays from bound electrons (Motz *et al*, 1961; Verma *et al*, 1962) are quite scanty. Our earlier experiments (Anand *et al*, 1964) on small angle scattering of low energy gamma rays have shown that for small values of momentum transfer involved in scattering, the Compton scattering cross-section from bound and moving electrons is less than that from free and stationary electrons. The experiments on large angle scattering (Motz *et al.* 1961; Verma *et al.* 1962) of high energy gamma rays, however, show that the situation is reversed at large values of momentum transfer and the Compton scattering from bound electrons becomes more intense than that from free electrons. No information is yet available about the integrated Compton cross-section from bound electrons where the momentum transfer may vary from zero to some maximum value depending upon the energy of the gamma rays. From the data so far available it may be guessed that the integrated Compton scattering cross-section from the bound electrons may be either less than, or equal to, or greater than that from free electrons depending upon the maximum value of the momentum transfer which in turn depends upon the energy of gamma rays. At 662 and 1250 keV the integrated Compton scattering cross-section from K-shell electrons as shown in column 5 of table 1, may be taken to be equal to that from free and stationary electrons. Large uncertainties present in these values do not allow us to draw any precise conclusion. However, at still higher energies where the photo-electric cross-sections become comparable with the Compton scattering cross-section from K-shell electrons it may be of interest to perform similar experiments to see if for still larger values of momentum transfer the overall Compton scattering cross-sections for bound electrons is more than that from free electrons.

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