INCOHERENT SCATTERING OF 662 keV GAMMA RAYS BY K-SHELL ELECTRONS IN GOLD

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1. INTRODUCTION

The differential cross section for the incoherent scattering of photons by electrons, the Compton scattering, has been derived by Klein and Nishina[1] assuming that the electron is initially free and at rest. This implies that the Klein-Nishina equation is applicable to the case where the atomic binding energy of the struck electron is negligible compared to the kinetic energy which this electron is to acquire as the Compton recoil electron. In such cases the Klein-Nishina equation is in excellent agreement with experimental data.

Du Mond[2-5] and his coworkers first reported the influence of the electron binding. They investigated the line of secondary photons detained in the Compton scattering of X-rays in medium heavy elements and observed a line-broadening and a slight defect of the Compton shift. Sujkowski and Nagel[6] have measured the cross sections for the incoherent scattering of 662 keV gamma rays from K-electrons in lead. They found that at the scattering angles of 28°, 68° and 132.5° the cross sections are 0.29, 0.87 and 1.0 of the corresponding Klein-Nishina cross sections. Motz and Missoni[7] also observed a decrease of the cross section at small scattering angles, but at large angles they found it to be larger than the Klein-Nishina predictions. The increase they found at 110° was by a factor of 1.2 and 1.4 for tin and gold, respectively.

The incoherent scattering of photons by bound electron assuming hydrogen ground state type of wave function for the initial state has been solved exactly, in the nonrelativistic limit[8]. Several approximations have been applied to take into account the complex states of electrons in atoms[9-10]. In this analysis of experimental data Motz and Missoni[7] also calculate the cross sections for the scattering by K-electrons assuming a momentum distribution in a shell of radius corresponding to the K-shell binding energy.

2. THEORY

The process is treated in an impulse approximation assuming the outgoing electron wave to be unperturbed. The initial electron distribution is described by the wave function $u(\vec{p})$, where $\vec{p}$ is the electron momentum in its bound state. The incoming photon with a momentum $\hbar\vec{k}$ interacts with the electron of momentum $\vec{p}$ and is scattered as in a collision with a free electron with the same momentum. The outgoing photon of momentum $\hbar\vec{k}'$ is emitted only if the electron acquires sufficient amount of energy to be released from its bound state, i.e. $\hbar ck - \hbar ck' > B$, where B is the binding energy of the electron.

The cross section for this process can be derived in the impulse approximation. The result is

$$d\sigma(\vec{k},\vec{p};\vec{k}') = |u(\vec{p})|^2 \, d^3\vec{p} \quad d\sigma_F(\vec{k},\vec{p};\vec{k}') \ ,$$

where $d\sigma_F(\vec{k},\vec{p};\vec{k}')$ represents the Klein-Nishina cross section for the scattering of a photon of momentum $\hbar\vec{k}$ on a moving electron with momentum $\vec{p}$ that results in the scattered photon of momentum $\hbar\vec{k}'$. In the case of scattering by free electrons, the final electron energy and momentum are determined by energy and momentum conservation laws. In the calculation of the above cross section it is assumed that the electron as it leaves the atom after interaction does not change its direction. Its final energy is calculated taking into account the binding in the initial state $E = \hbar ck - \hbar ck' - B$. The cross section amounts to the product of the $d\sigma_F$ and of the probability to encounter an electron of momentum $\vec{p}$. Some theoretical cross sections calculated using eq. (1) are shown in Fig. 1.

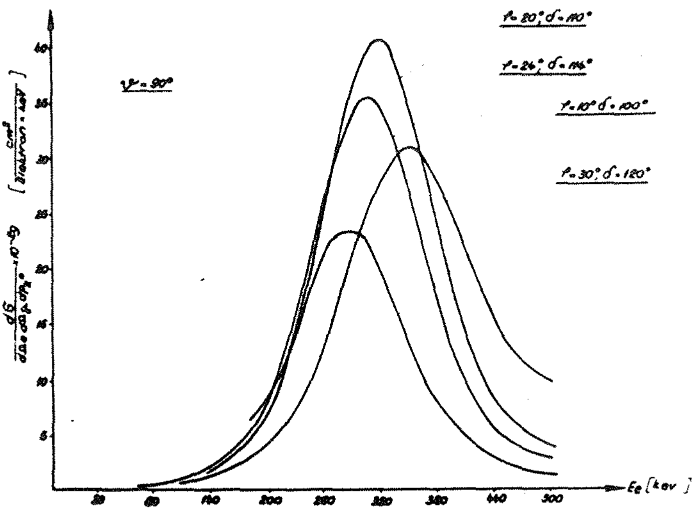


Fig. 1. The theoretical electron-energy dependence of the differential cross sections. θ and φ are photon and electron scattering angles, respectively, and δ is the angle between $\vec{k}'$ and $\vec{p}'$, where $\vec{p}'$ = momentum of scattered electrons.

3. METHOD OF THE MEASUREMENT

The experimental arrangement is shown in Fig. 2. A ^{137}Cs source of 5 Ci was used as the gamma ray source. It was placed in a lead shield. Through the collimator a narrow beam of 662 keV photons was directed into the evacuated scattering chamber. In the centre of the chamber were placed scatterers of 2 cm x 2 cm of 5 mg/cm^2 gold foil or of aluminium for background. The scattered

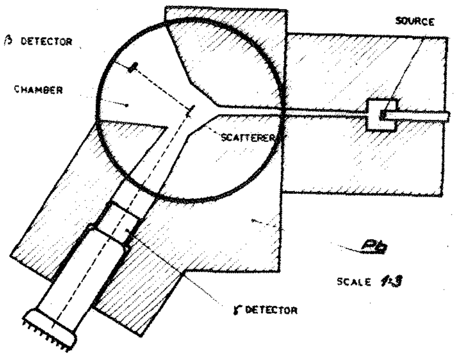


Fig. 2. Experimental arrangement.

electrons were detected in a 15 mm diameter x 1 mm Li-drifted semi-conductor detector. Its resolution was about 20 keV. The scattered photons were detected in a 38 mm diameter x 51 mm NaI(Tl) scintillator. Its resolution for 662 keV gamma rays was 7%. The X-rays were detected also in a NaI(Tl) crystal, but of 38 mm diameter x 12 mm. A tripple coincidence with the resolving time $2\tau = 80$ ns was used. Identification of the real events and a separation from the accidental coincidences was made by the application of two-dimensional analysis of gamma counter and electron counter pulses in triple coincidence with KX-ray pulses.

The differential cross sections were calculated from the expression

$$\frac{d\sigma}{d\Omega_\gamma \, d\Omega_e \, dE_e} = \frac{n_k}{2\Phi n \, \Omega_\gamma \Omega_e} \; \frac{1}{\omega_X \, \epsilon_\gamma \, \epsilon_e} ,$$

where n_k is the number of counts per unit time per channel, Φ the flux of incoming photons per unit time and area, n the number of atoms in the scatterer, Ω_γ and Ω_e the solid angles subtended by the gamma counter and electron counter, E_e the energy width of one channel, ε_γ and ε_e the efficiency of the gamma ray and the electron detector, respectively, and ω_X the total efficiency of the KX-ray detector which takes into account the solid angle, and was adjusted to be 0.04 ± 0.003.

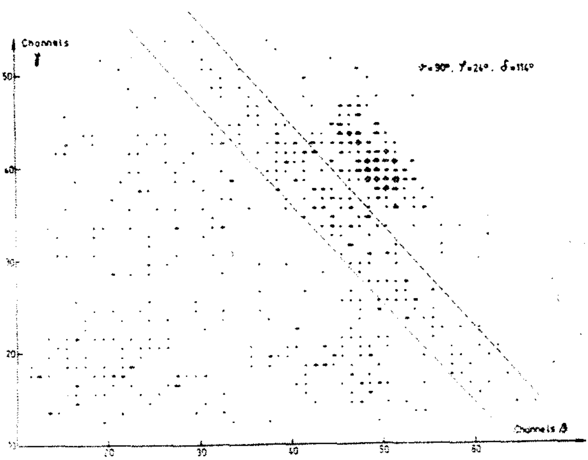


Fig. 3. The experimental two-dimensional energy spectrum obtained with 100x100 pulse-height analyzer. Each point presents one coincident event. The exposure was 36 hours.

The display of two-dimensional spectra obtained with the gold scattered at angles $\theta = 90^{o}$, $\phi = 24^{o}$ are shown in Fig. 3. The dashed line represents the expected locus of events $E_e + \hbar ck' = \hbar ck - B_K$, where B_K is the K electron binding energy in gold. A spectrum, number of events per energy interval of $E_e + \hbar ck'$ is shown in Fig. 4. The upper peak is due to accidental coincidences of X-rays and coincident Compton scat-

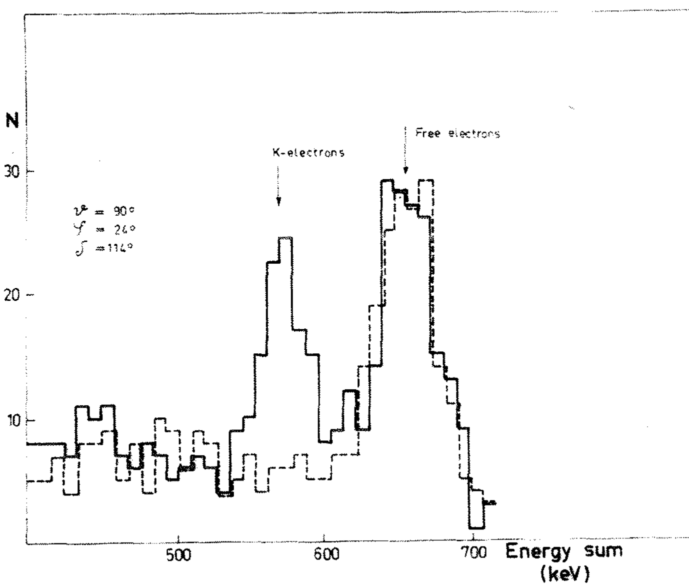
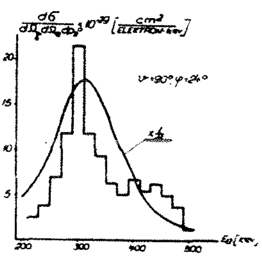
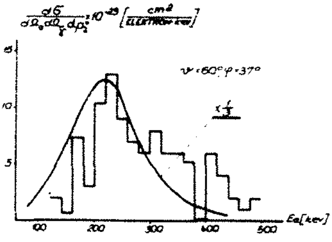


Fig. 4. The number of total and chance coincidence events as a function of the energy sum. The chance coincidences are presented with dashed lines.

tered photons and electrons that were loosely bound. The lower peak is due to the scattering by K-electrons from gold. The accidental coincidences were measured with an aluminium scatterer with the same electron density per unit area.

The dependence of the measured differential cross section obtained for two sets of angles is shown in Fig. 5 and Fig. 6. The background due to accidental coincidences was subtracted. For comparison also are shown the calculated differential





Figs. 5 and 6. The electron-energy dependence of the differential cross section for the Compton scattering by K-shell electrons in gold for incident photon energy E_{γ}^{0} = 662 keV.

cross sections reduced by a factor of 1/2 and 1/3 respectively. The multiple scattering of electrons is very pronounced in the present measurements, and it may be the cause of the discrepancy. A rough estimate of the corrections due to multiple scattering gave factors of roughly 2, but a rather more elaborate calculation is required to find the expected distribution taking into account finite angles and multiple scattering.

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