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# A crossover phenomenon in the photoelectric effect

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**Abstract.** The angular distribution of photoelectrons emitted from the K shell of lead and platinum by 483 keV linearly polarized photons has been studied. At forward emission angles the photoelectrons are emitted predominantly in the plane of polarization of the photons, but at an emission angle of 72° a crossover effect is observed and the preferred plane of emission is orthogonal to the polarization plane of the photons. Although the crossover effect is expected from theoretical considerations it is observed to occur at a smaller emission angle than predicted by theory.

## 1. Introduction

Photoelectrons ejected from the K shell by low-energy linearly polarized photons are emitted predominantly in the plane of polarization of the photons (Kirkpatrick 1931). At higher photon energies relativistic effects are important and calculations (Sauter 1931, Sauter and Wuster 1955) predict that a crossover effect occurs. At forward emission angles the photoelectrons should be emitted predominantly in the polarization plane, but at high photon energies photoelectrons emitted at large angles with respect to the photon direction should be predominantly in the plane orthogonal to the photon polarization plane. Hereford and his collaborators (Hereford and Keuper 1953, McMaster and Hereford 1954) investigated this phenomenon and observed a crossover effect. However, Brini *et al.* (1957) found no evidence for a crossover effect in the photon energy range studied by McMaster and Hereford (1954). Later independent calculations made by two groups (Pratt *et al.* 1964, Hultberg *et al.* 1968) are claimed to be accurate over a wide range of photon energy and target atomic number. The predictions of both groups for photoelectric total cross sections and the angular distributions of photoelectrons emitted by unpolarized photons are in good agreement with the experimental results. Both calculations predict a crossover effect in the case of linearly polarized photons with energies in the few hundred keV region. The emission angle at which the crossover is predicted to occur depends on the photon energy and the atomic number of the target. Predictions (Hultberg 1969 private communication) are available at specific photon energies and target atomic numbers and a direct comparison between theory and experiment is possible. This work reports experimental investigations of the crossover effect with linearly polarized 483 keV photons and photoelectric targets of lead and platinum.

## 2. Procedure

The K shell photoelectron emission was investigated with linearly polarized photons obtained by the Compton scattering of a collimated beam from a 1200 Ci $^{60}Co$ source. A description of the experimental arrangement has been given (Logan 1970) and a simplified diagram of the experimental arrangement is given in figure 1. The vertical collimated beam was scattered by a $\frac{3}{8}$ inch diameter × $\frac{3}{8}$ inch brass cylinder suspended directly below the source. After collimation by a 3 inch long $\frac{1}{2}$ inch diameter tungsten alloy collimator the polarized Compton scattered beam entered through a plastic window into the evacuated enclosure containing the photoelectric target. The target was placed normal to the incident photon beam and was about 6 inches from the brass scatterer. Although it is not shown in figure 1, extensive lead

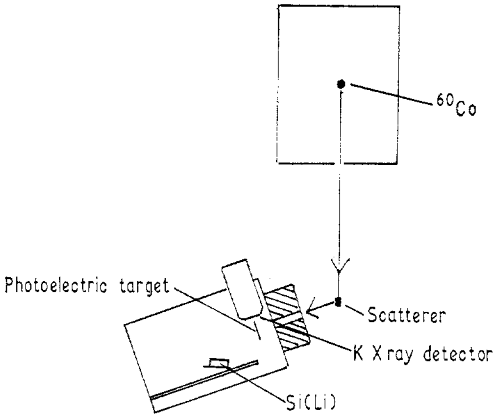


Figure 1.

shielding was placed around the apparatus to reduce the effects of direct leakage from the $^{60}$Co source and from the photons Compton scattered from the exit collimator of the source. The energy of the Compton scattered beam was measured with a scintillation counter. In principle the two gamma ray energies in $^{60}$Co could give a complex energy structure to the scattered beam but the energy spreads introduced by the kinematics of the Compton effect and the angular spread of the Compton scattering angle blurred this out and no detailed energy structure was considered. The mean energy of the beam was 483 keV, the energy spread about 75 keV and the degree of linear polarization was calculated to be 2·4 (the ratio of the intensity with polarization perpendicular to the scattering plane $I_{90}$ to the intensity with polarization parallel to it $I_0$).

Lead and platinum were used as photoelectric targets. The lead targets were made by evaporation onto a Mylar backing and the platinum target was unbacked 0·0 001 inch thick foil. The ratio $R$ of the number of K shell photoelectrons emitted in the polarization plane to the number emitted in a plane orthogonal to this was measured for different values of the photoelectron emission angle. The photoelectrons were detected with two 2 cm$^2$ × 1 mm Si(Li) detectors mounted at equal emission angles, one in the polarization plane and the other in a plane orthogonal to this. The resolution (FWHM) of the detectors was measured to be about 40 keV for the 365 keV conversion electrons of a $^{113}$Sn source. Selection of K shell photoelectrons was made by requiring a microsecond coincidence with K X rays detected in $\frac{1}{4}$ inch × 1 inch diameter NaI(TI) crystals located near the photoelectric target. Only one Si(Li) detector and one of the two scintillation detectors are shown in figure 1.

Gated spectra from the two silicon detectors were recorded simultaneously in multichannel analysers. Background and recoil Compton electron contributions to the spectra were estimated by using a rhodium foil target of the same electron density as the platinum target and leaving the single channel analyser associated with the scintillation detectors set to select the platinum K X rays. No photoelectrons are detected in such an arrangement. A spectrum was also accumulated without any photoelectric target in position. This procedure was carried out at all the detector positions and, in the electron energy range of interest, no differences were observed between the spectra obtained with the rhodium target and the spectra obtained without any target in position. This shows that contributions from Compton recoil electrons were not important. Most of the background was in true coincidence and was attributed to photons Compton scattered from the scintillation detectors into the regions near the silicon detectors. In the case of the platinum target the background corrections were made by subtracting the spectra obtained with the rhodium foil, and in the case of the lead targets corrections were made by subtracting the spectra accumulated with a Mylar backing as target. A typical spectrum has been given (Logan 1970). Only energy regions in the spectra corresponding to electrons depositing energies compatible with K shell emission were used in the analysis.

## 3. The experimental results and uncertainties

The results are tabulated in table 1. The angular spreads in the emission angles were $\pm 13^\circ$ at $25^\circ$, $\pm 19^\circ$ at $32^\circ$ and $+17^\circ/-14^\circ$ at $72^\circ$. The azimuthal angular

**Table 1**

| Target | Target thickness (mg cm$^{-2}$) | Mean photo-electron emission angle (deg) | $R$ |
|---|---|---|---|
| Lead | 2·1 | 25 | 2·3 ±0·9 |
| Lead | 2·1 | 32 | 2·1 ±0·5 |
| Lead | 2·1 | 72 | 0·89 ±0·16 |
| Lead | 4·2 | 25 | 1·21 ±0·21 |
| Lead | 4·2 | 32 | 2·9 ±0·9 |
| Lead | 4·2 | 72 | 0·70 ±0·08 |
| Lead | 10·0 | 25 | 1·16 ±0·09 |
| Lead | 10·0 | 32 | 1·45 ±0·09 |
| Lead | 10·0 | 72 | 0·81 ±0·06 |
| Platinum | 5·4 | 72 | 0·58 ±0·16 |

spreads were $\pm 18^\circ$ at the two forward emission angles and $\pm 15^\circ$ at the $72^\circ$ position. These angular spreads allow for the diameter and the angular spread of the polarized photon beam and are extreme limits as they correspond to the circumferences of the circular-geometry silicon detectors.

The uncertainties for $R$ in table 1 are statistical standard deviations. Other uncertainties can be produced by multiple scattering of the electrons in the target, different detector efficiences, target nonuniformities and geometrical misalignments. The effects of the electron scattering are discussed in § 4. The other uncertainties were investigated by recording the photoelectron spectra produced by the unpolarized gamma rays from radioactive sources. When the sources were on the geometrical axis of the system the two detection efficiences were within 2% of each other. As an added precaution the $72^\circ$ data are the average of two measurements made with the detector positions interchanged. Target nonuniformities which could be important in the case of the lead targets were investigated by rotating the targets. No non-uniformities were detected within a statistical accuracy of a few per cent. Contributions due to possible geometrical misalignments were investigated by displacing the source from the geometrical axis. Uncertainties due to misalignments are less than $\pm 0 \cdot 03$ at forward angles and less than $\pm 0 \cdot 05$ at the 72° position.

## 4. The effects of electron scattering

The scattering of the photoelectrons inside the targets distorts the true angular distribution of the photoelectrons. Scattering corrections have been applied to the angular distribution of photoelectrons emitted by unpolarized photons (Hultberg and Erman 1968). The situation in this work is different from measurements involving unpolarized photons as the photoelectrons are predicted to have some polarization (Hultberg *et al.* 1968) and this may make the scattering more complicated. An experimental investigation of multiple scattering effects was made by using targets with different thicknesses. Although the statistical accuracy is poor for the thinner targets, the forward angle data show evidence of some attenuation for thicker targets. The data obtained at an emission angle of 72° do not show an attenuation effect. A more pronounced attenuation at forward angles can be expected from the geometry of the apparatus. The electron scattering will distort all the data but will be particularly serious when electrons originally incident towards one counter are scattered so severely that they have a high probability of being detected in the other counter. The probable scattering angles of electrons in a gold medium in this energy range have been calculated by Walter *et al.* (1950) and are given in table 2. The

**Table 2**

| Mean photoelectron emission angle (deg) | Angular separation of the silicon detectors (deg) |
|---|---|
| 25 | 34 |
| 32 | 44 |
| 72 | 84·5 |

**Table 3**

| Target thickness ($mg\ cm^{-2}$) | Probable scattering angle (deg) |
|---|---|
| 2 | 19 |
| 4 | 26 |
| 5 | $\sim 30$ |
| 10 | $> 30$ |

angular separation of the two silicon detectors varies with the emission angle and values are given in table 3. As can be seen from the data in table 2 and table 3 the asymmetry values at forward angles can be considerably attenuated by the electron scattering. However, the angular separation of the two silicon detectors at the emission angle of 72° is large enough to prevent appreciable attenuation of the asymmetry.

In the case of the lead targets a Mylar backing was used and backscattering from the Mylar must be considered as the energy resolution of the system was insufficient to discriminate against this. Checks were made by recording the spectra produced by the 365 keV conversion electrons from a $^{113}$Sn source placed in front of a Mylar backing. The silicon detectors were operated at low temperatures in these measurements and a resolution (FWHM) of 5 keV was achieved. Comparison of the spectra obtained with and without the Mylar backing showed that backscattering from the Mylar was negligible in the energy range of interest.

## 5. The theoretical predictions

The calculations of Hultberg *et al.* (1968) are in good agreement with those of Pratt *et al.* (1964) and predictions (Hultberg 1969 private communication) are available for specific experimental conditions. Both calculations describe the angular distributions of K shell photoelectrons emitted by linearly polarized photons by a parameter $C_{10}(\theta)$. The ratio $R(\theta)$ can be written in terms of $C_{10}(\theta)$ and the degree of linear polarization $I_{90}/I_0$ and is given by

$$R(\theta) = \frac{(1+C_{10})I_{90}+(1-C_{10})I_0}{(1-C_{10})I_{90}+(1+C_{10})I_0}.$$

The $R(\theta)$ function for a lead target is given in figure 2. The expected distribution

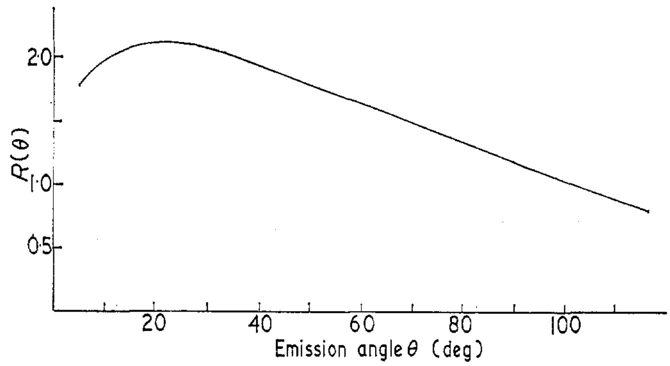


Figure 2.

for platinum is very similar to this. The predicted emission angle at which crossover occurs is 101° in the case of platinum and 103° in the case of lead.

## 6. Summary

All the data obtained at the emission angle of 72° indicate that a crossover effect occurs but the crossover is observed at a smaller angle than that predicted by theory. It is believed that the data are distorted by the electron scattering in the photoelectric target. This may give an apparent angular shift of the $R(\theta)$ distribution and some of the discrepancy between the predicted crossover emission angle and the experimental results may be due to this. However, the results obtained with different targets at 72° are consistent and it does not seem probable that multiple scattering will simulate a crossover if none exists.

The results are in qualitative agreement with those of McMaster and Hereford (1954) but they observed a crossover at a higher photon energy and

Hereford and Keuper (1953) did not observe a crossover with 511 keV photons. No discrimination was made against photoelectrons from higher atomic shells in either experiment and, although McMaster and Hereford (1954) do not quote their target thickness, Hereford and Keuper (1953) used 0·01 inch lead targets. Scintillation counters were used to detect the photoelectrons and it seems unlikely that the energy resolution would be sufficient to prevent electrons produced deep inside the foil from being detected. These electrons may have been scattered extensively and the data could be considerably distorted. Brini *et al.* (1957) used an improved experimental arrangement as they had a thinner photoelectric target (16 mg $cm^{-2}$ lead target) and a coincidence requirement to select K shell photoelectrons. The discrepancy between their results and those of this work is not understood.

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