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Measurement of differential incoherent scattering cross-sections of 145 keV photons from K-shell electrons

V B Acharya and B S Ghumman

Department of Physics, Punjabi University, Patiala-147002

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Abstract. Differential cross-sections for incoherent scattering of 145 keV photons from K-shell electrons of tin, silver and molybdenum have been measured at 110° to investigate the effect of electron binding on differential cross-sections in the low energy region. The incoherent scattered photons are selected in coincidence with X-rays which follow the vacancies caused by the ejection of the electrons NaI(Tl) scintillators are used for the detection of scattered photons and emitted X-rays The experimental results are compared with the available theoretical data

1. Introduction

Compton scattering is one of the basic processes of interaction between gamma rays and matter. The recent general interest in Compton scattering is manifold. First, it is a probe of electron-momentum distribution; secondly, it is a means of determining the polarization of photons produced in nuclear reactions and thirdly, it has provided a test of quantum electrodynamics. Compton scattering generally refers to a case in which a photon is scattered from an electron initially free and at rest; and is described by Klein-Nishina formula. However, the effect of electron binding has to be considered for low energy photons and inner shell electrons, where the incident energy is comparable with the binding energy of the electron. The atomic binding effects are most significant for K shell electrons and Compton scattering from these electrons produces significant deviations from the Klein-Nishina values.

There have been some attempts to obtain scattering cross-sections for bound electrons using non-relativistic treatment based on either atomic form factor approximations (Bloch 1934, Schnaidt 1934) or incoherent scattering function approach (Shimizu *et al* 1965), Sujkowski and Nagel 1961). The validity of these calcula- tions requires the photon energy to be appreciably larger than the binding energy of the electron. Relativistic theories are available only for an energy of 662 keV.

There have been some investigations by Motz and Missoni (1961), Sujkowski and Nagel (1961), Pingot (1968, 1969), Spitale and Bloom (1977) and Murty *et al* (1977) reporting the differential Compton scattering cross-sections by K-shell electrons of various atomic targets. Most of these measurements are confined to 662 keV photons from Cs^{137}. The present work was motivated by a desire to investigate the effect of electron binding on differential scattering cross-sections in the low energy region. In this paper we present experimental results on differential incoherent scattering cross-sections for *K*-shell electrons in tin, silver and molybdenum at a scattering angle of 110° for 145 keV photons.

2. Experimental Arrangement

When a photon is scattered incoherently by an electron in the *K*-shell, the electron is ejected and *K* X-ray is omitted with a certain probability defined by the *K*-shell fluorescent yield. The measurement of the intensity of the scattered photons in coincidence with the *K* X-rays enables us to distinguish between the photons incoherently scattered by *K*-shell electrons and photons scattered by free or more loosely bound electrons

The experimental arrangement is shown schematically in figure 1. A narrow beam of 145 keV photons is obtained by placing ^{141}Ce radioactive source at the end of a lead collimator. The target foil is viewed by two detectors, one sensitive to characteristic X-rays emitted from the target and the other to the scattered gamma rays. The scattered photons are detected by 51 mm dia. $\times$51 mm. thick NaI(Tl) scintillator. This detector is shielded by 80 mm thick lead and 60 mm long collimator is placed before it The *K* X-rays emitted from the target are detected by another scintillator with 44·4 mm dia.$\times$2 mm thick NaI(Tl) crystal. The X-ray detector is placed perpendicular to the scattering plane to minimize detector to detector scattering. Movable lead shielding is used to prevent the gamma ray and the X-ray detectors from directly viewing the source slit. The gamma ray and the X-ray detectors subtend solid angles of 0·03 and 0·08 steradians respectively at the target foil The inside surface of the source slit and all surfaces of lead shielding in view of the target and dectors are covered with a graded *Z* absorber. This absorber consists of 2 mm tin, 1 mm iron and 0·8 mm of aluminium with tin facing the wall. Its thickness is sufficient to absorb 76·5 keV X-rays which are emitted from the lead shielding. A slow-fast coincidence set up of 30 n.sec resolving time is used for recording events.

In addition to the desired coincidences between the photons scattered from the *K*-shell electrons and X-rays which follow the ejection of the electrons, other events may contribute to the recorded counting rate. These consists of (i) *K*-shell photoelectrons may ionize the target atoms and the characteristic X-rays produced be detected in gamma detector; (ii) Compton electrons may produce *K* X-rays during slowing down process; (iii) photo and Compton electrons producing bremsstrahlung radiation in the target; (iv) multiple scattering of photons from air, target holder and other surroundings; (v) detector to detector scattering; (vi) cosmic ray background and (vii) the false coincidences. Many of these effects can be accounted for by replacing the target with aluminium foil of equivalent thickness (containing same number of electrons per cm^2 as the target and then recording the coincidence rate).

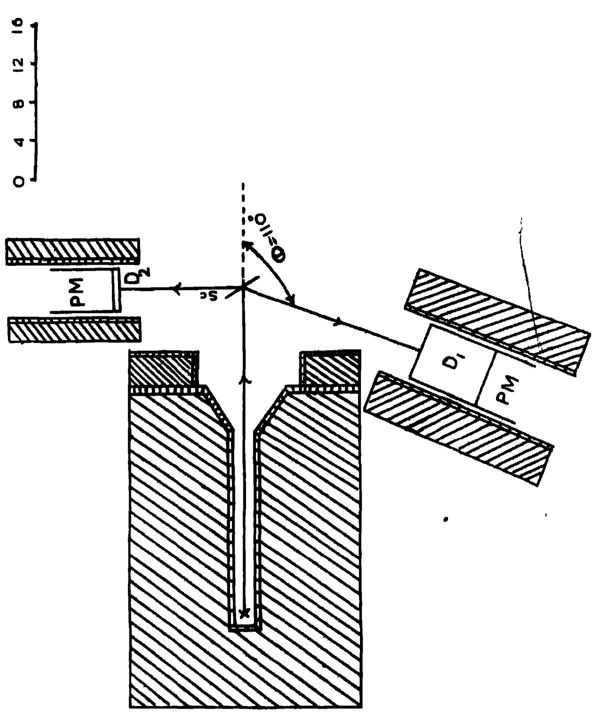

Figure 1. Experimental set up. X—source of 145 keV photons, D_1—gamma ray detector, D_2—X-ray detector, S_c—Scatterer.

Determination of Compton scattering cross-section from K-shell electrons requires an absolute measurement of incident photon flux at the target and the detector efficiency. To avoid these measurements the bound electron cross-section is determined relative to the cross-section due to a stationary and free electron which is given by Klein-Nishina formula.

3. Results and discussion

The experimental results for the K-shell to free electron scattering cross-section ratio for 145 keV photons at a scattering angle of 110° are shown in column 3 of table 1.

Relativistic theories which are expected to give better agreement with experimental results are a few and no such calculations are available for 145 keV Most of the theoretical investigations on incoherent scattering of photons by atomic electrons use non-relativistic treatment based on either atomic form factor approximations or incoherent function approach Approximating ψ_i by a non-relativistic wave function of a K-shell electron in a hydrogen like atom and ψ_f by a plane wave, Shimizu *et al* (1965) have calculated the value $\frac{d\sigma_k}{d\sigma_f}$ which is given by

$$\frac{d\sigma_k}{d\sigma_f} = \frac{32\sqrt{2}\ (137)^3(E_{max}{}^{3/2}-E_{min}{}^{3/2})}{3\pi^2 Z^3(m_0c^2)^{3/2}\left(1+\frac{p_0{}^2}{b^2}\right)^4} \tag{1}$$

where Z is the atomic number of the target, m_0 the electron mass, c the velocity of light, $p_0 = \sqrt{2m_0}B$ is the initial momentum of the electron, $b = \frac{Z\hbar}{a_0}$, B is the binding energy of the electron, a_0 is the first Bohr radius.

$$E_{max} = T+B+2\sqrt{TB}, \quad E_{min} = T+B-2\sqrt{TB},$$

$$T = [h\nu_0\gamma(1-\cos\theta)]/[1+\gamma(1-\cos\theta)],$$

θ is the scattering angle, $\gamma = \frac{h\nu_0}{m_0c^2}$ and $h\nu_0$ is the incident photon energy. Theoretical values calculated by using equation (1) are shown in column 4 of table 1.

Lenz (1952) derived a relation between the incoherent scattering function $S(v)$ and diamagnetic susceptibility of the scattering atom by taking into account the electronic charge distribution based on the Wentzel model of atom. This expression is given as

$$S(v) = 1-\frac{1}{\left[1+9\cdot04Z^{4/3}v^2\left(-1\cdot25\times10^6\psi_{dia}\frac{A}{\rho}\frac{1}{6Z}\right)\right]^2} \tag{2}$$

where ρ is the density of the scattering material, A is the atomic weight, $v = qa_0/[3\hbar Z^{2/3}]$ and ψ_{dia} is the diamagnetic susceptibility of the atom. Using equation 2, the values calculated for the present energy are shown in column 5 of table 1.

The errors shown in the experimental values are standard deviations. These include counting statistics, error in the measurement of solid angle and target thickness and the errors associated with the absorption coefficients, detector efficiency and fluorescent yield etc. For molybdenum the measured cross-section ratio $d\sigma_k/d\sigma_F$ is in agreement with the theoretical value obtained from equation (1); for tin and silver the experimental results are higher.

Table 1. Differential cross-section ratio $d\sigma_k/d\sigma_F$ for 145 keV photons at scattering angle of 110°.

Element		Experimental	Theoretical Results based on eq.(1)	Theoretical Results based on eq.(2)
Tin	50	0·506±0·070	0·369	1·00
Silver	47	0·560±0·078	0·414	1·00
Molybdenum	42	0·521±0·070	0·511	1·00

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