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Polar and azimuthal angular dependence of coherent to incoherent scattering differential cross-section ratios of Au at 59.54 keV

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HIGHLIGHTS

- The coherent to Compton cross-section ratios are measured for 59.54 keV photons.
- The measured ratios for polar angles are agreed with the theoretical predictions.
- No data is available in literature at azimuthal angle of 30°, 20°, 10°, −10°, −20°.

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ABSTRACT

Coherent to incoherent differential cross-section ratios of Au have been measured for several polar scattering angles (90°, 100°, 110°, 120° and 130°) and azimuthal angles (30°, 20°, 10°, 0°, −10°, and −20°) at 59.54 keV photon energy by using high purity germanium (HPGe) detector, which has a resolution of 199.6 eV at the 5.9 keV. The samples were excited with 59.54 keV gamma rays emitted from 3.7×10^9 Bq (100 mCi) Am^{241} point source. The intensity ratios were corrected due to the photopeak efficiency of gamma detector and absorption of photons in the target and air. The experimental values obtained in this study were compared with those estimated on the basis of the non-relativistic form factors and relativistic form factors.

1. Introduction

The gamma or x-rays having energies less than 1.022 MeV can interact with the matter by three principal mechanisms: photoelectric absorption, elastic (coherent) scattering and inelastic (incoherent) scattering. In the first process, the photon interacts with an atom of the absorbing material, and the photon completely disappears; its energy is transferred to one of the orbital electrons of the atom. In the second process photon is deviated from its trajectory without any change in energy; and in the last process, inelastic scattering results in degradation of gamma photon energy. The amount of the energy decreasing depends on the scattering angle and the incoming photon energy.

Coherent scattering of x-rays provide useful information about the ground state structure of the atoms. The scattering mechanism can be formally described as absorption of the incident photon by a bound electron and then the electron emitting a new photon with the same energy that of incoming photon. The total result of the process is the atom is neither ionized nor excited. The probability of the process is relatively high at low energies and for high Z elements. Incoherent scattering is an important mode of photon interaction with atoms in the energy range below 5 MeV and is predominant for medium Z elements.

Differential cross section is used in the calculation of radiation attenuation, reactor shielding, industrial radiography, transport and energy deposition in medical physics and in a variety of other fields (Kurucu et al., 1998). The coherent to incoherent differential cross-section ratio has been investigated experimentally before: Ertugrul (2001) investigated dependencies of the coherent to incoherent intensity ratio on mean atomic number of the compounds. Icelli and Erzeneoglu (2002) experimentally investigated coherent to incoherent scattering differential cross section ratios of some elements at scattering angles of 55° and 115° at 59.54 keV. Simsek and Ertugrul (2004) measured the ratio of differential cross sections for coherent to Compton scattering of 59.54 keV at scattering angles of 40° and 135° for Zr, Nb and Mo targets. Singh et al. (2007) have measured effective atomic number of composite materials using coherent to Compton scattering of 279 keV gamma rays. Singh et al. (2012) have measured coherent to incoherent

Abbreviations: Comp, Compton; coh, coherent; obs, observed

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cross section ratio of elements in the range $6 \leq Z \leq 82$ for 59.54 keV gamma photons. Singh et al. (2013) have measured the ratio of differential cross sections for coherent to incoherent scattering at 145 keV at scattering angles of 50°, 70° and 90° for C, Al, Fe, Mo, Sn, W, Au and Pb. However, to the best of our knowledge there are no theoretical calculations for the azimuthal angle dependence except 0° of the photon scattering in the literature. This prompted us to carry out this work. In the present work, coherent to incoherent differential cross-section ratios of Au have been measured at several polar scattering angles (90°, 100°, 110°, 120° and 130°) and azimuthal angles (30°, 20°, 10°, 0°, −10°, −20°) at 59.54 keV photon energy by using high purity germanium (HPGe) detector.

2. Theory

Theoretically, the coherent scattering differential cross-sections can be calculated using scattering amplitudes. The most commonly used approach to obtain the cross-sections are those based on the form factor formalism. The coherent scattering differential cross-section based on the form factor formalism is represented as a product of the differential Thomson scattering cross-section per free electron, $d\sigma_T/d\Omega$, and the square of the form factor $F(q, Z)$ as follows:

$$\frac{d\sigma_{coh}}{d\Omega} = \frac{r_0^2}{2}\left(1 + \cos^2\theta\right)|F(q, Z)|^2 \tag{1}$$

where $F(q, Z)$ is the atomic form factor, r_0 (2.8179×10^{-15} m) is the classical electron radius, Z is the atomic number and q is the momentum transfer parameter measured in units of 1/ Å and defined as

$$q = (\sin\theta/2)\cdot(1/\lambda) \tag{2}$$

where λ is the incident photon's wavelength and θ is the angle of scattering.

Inelastic cross-sections can be calculated using the well-known Klein–Nishina formula. The Klein–Nishina cross-section represents the probability that photon suffers deflection through some angle and transfer an amount of momentum to the electron commensurate with that predicted for a free electron.

The differential cross-section for Compton scattering gamma rays per electron assumed free and at rest is given by the Klein–Nishina equation (Klein and Nishina, 1929)

$$\frac{d\sigma_{KN}(\theta)}{d\Omega} = \frac{r_0^2}{2}\left[\frac{1}{1+\alpha(1-\cos\theta)}\right]^{-2}\left[1 + \cos^2\theta + \frac{\left[\alpha(1-\cos\theta^2\right]}{1+\alpha(1-\cos\theta)}\right] \tag{3}$$

For scattering from bound electrons one has

$$\frac{d\sigma_{Comp}}{d\Omega} = \frac{d\sigma_{KN}}{d\Omega}S(q, Z) \tag{4}$$

where $S(q, Z)$ is the incoherent scattering function and represents the probability that an atom will be raised to the excited state or ionized state when a photon imparts a recoil momentum (q) to any one of the atomic electrons.

The coherent to Compton scattering cross section ratio becomes

$$\frac{d\sigma_{coh}}{d\sigma_{Comp}} \propto \frac{|F(q, Z)|^2}{S(q, Z)} \tag{5}$$

The theoretical values of $S(q, Z)$ and $F(q, Z)$ are tabulated (Hubbell et al., 1975) on the basis of non-relativistic Hartree–Fock calculations.

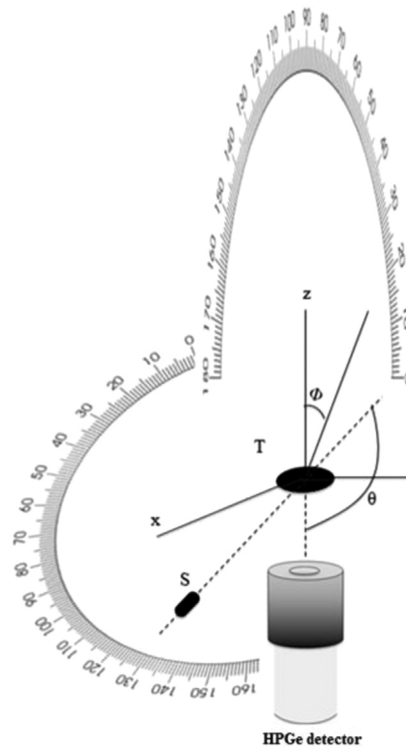

Fig. 1. Schematic representation of the experimental set up. T: target, S: Am^{241} source, Φ: azimuthal angle, θ: polar angle.

3. Experimental

The experimental arrangement is schematically shown in Fig.1. The polar angle and azimuthal angle scatterings are measured in the range $90° \leq \theta \leq 130°$ and $+30° \leq \Phi \leq -20°$, respectively, with 10° steps. While the detector was kept in a fixed position, both the radioactive source and the sample were rotated around the z axis to obtain the spectral distribution (for each azimuthal angle mentioned above) and sample is rotated to obtain the azimuthal angle distribution at each fixed scattering polar angle mentioned above.

The foil Au sample of mass thickness 1.06 g/cm^2 was used. The sample was excited with 59.54 keV gamma rays emitted from 3.7×10^9 Bq (100 mCi) Am^{241} point source. The Compton and coherent peaks were acquired by a PGT HPGe detector has a resolution of 199.6 eV at the 5.9 keV, with active area 200 mm^2 and beryllium window of 12.5 µm thickness (Princeton Gamma-Tech Europa GmbH (1982)).

A lead collimator shielded the detector so that only photons from a very small solid angle around the scattering foils could arrive at the detector. The source and target were rotated around z axis for polar angular measurement while the detector was held fixed. The distances from source to target and target to the detector were chosen 4.25 cm and 4.50 cm, respectively. Background spectrum was measured for each angle and subtracted from total pulse-height raw spectrum. Operating parameters of the system are governed and controlled by the computer program Genie 2000. The data were collected into 4096 channels of the MCA. Data were analyzed by Origion 7.5 software program. A typical spectrum of Au target is shown in Fig. 2.

As can be seen from Fig. 2, coherent peak height is more dominant than Compton peak height in observed spectra. The intensities of coherent and Compton scattered peaks are corrected for photo peak efficiency, absorption in air between target and the