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Investigation of coherent to incoherent scattering cross section ratios of some foil metals depending on the temperature

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Abstract. In this study, it was aimed at examining the cross section ratios of coherent and incoherent scattering depending on the temperature for the elements Cd, In, Sn and Pb by 59.5 keV γ-rays from a 100 mCi ²⁴¹Am radioisotope point source. The coherent and incoherent cross section of Cd, In, Sn and Pb have been measured by using a Si(Li) solid-state detector at temperature between 30-300 ºC. Coherent to incoherent cross section ratios and FWHM (Full width at half maximum) of the elements have been calculated. Temperature-dependent changes of the parameters have been given in the graphical forms. Based on the results obtained, coherent to incoherent cross section ratios of the elements are dependent on the temperature. It is observed that coherent to incoherent cross section ratios of Cd, In, and Pb decrease with increasing temperature. For Sn, first of all coherent and incoherent intensity ratios decrease, then increase and decrease again respectively. To sum up, coherent to incoherent cross section ratios tend to decrease with increasing temperature.

1. Introduction
Coherent and incoherent scattering is a type of interaction of γ-rays and x-rays with matter. Coherent and Compton scattering are major processes for obtaining information about the structural properties of matter. The bound electrons of an atom, which dominate coherent scattering for most of the X-ray and low-energy γ-ray regimes, make the contribution to coherent scattering. In condensed matter physics as well, coherent and Compton scattering have played a central role in the understanding of the excited states of many important systems. (Içelli and Erzenoğlu, 2002) The coherent scattering of photons by atoms includes Rayleigh scattering, nuclear Thomson scattering, Delbruck scattering and nuclear resonance scattering. Incoherent scattering is one of the major processes by which γ-rays interact with matter in the energy range from 0.1 to 5 MeV (Shivaramu et al., 1980; Kürçü et al., 1998). Coherent and incoherent scattering cross-sections are used in such diverse applications as medical X-ray technology, power reactor shielding, industrial radiation processing and analysis of nuclear physics experiments (Hubbell et al., 1975).

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 (Kürçü et al., 1998). Ertugrul (2001) investigated dependencies of the coherent to incoherent intensity ratio on mean atomic number of the compounds. Içelli and Erzenoğlu (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. Sogut et al (2003) investigated atomic number of coherent to incoherent scattering intensity ratios in compounds depending on average atomic number. 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 incoherent scattering of 279 keV gamma rays. Singh et al. (2012) have measured coherent to incoherent cross section ratio of elements in the range 6 ≤ Z ≤ 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. Akkus et al (2015) have measured coherent to incoherent scattering differential cross-section ratios of Au at 59.54 keV depending on polar and azimuthal angular. As far as we know there is no study depending on the temperature even though several studies about coherent and incoherent scattering cross section ratios exist in the related literature. In the present work, coherent to incoherent differential cross-section ratios of Cd, In, Sn and Pb have been measured at temperature between 30°-300°C) at 59.54 keV photon energy by using Si (Li) solid-state detector.

2. Theory
The theory of scattering of X-rays from free electrons was studied by J.J. Thomson, and it is called as the Thomson scattering. The unpolarized Thomson scattering cross section contains Rayleigh’s result (Strutt, 1871a,b). Differential Thomson scattering cross section per electron, is given as:

$$\frac{d\sigma^T}{d\Omega} = \frac{r_e^2}{2} \left(1 + \cos^2 \theta\right)$$  \hspace{1cm} (1)

and the total, angle-integrated Thomson scattering cross section is:

$$\sigma^T = \frac{8\pi}{3} r_e^2$$  \hspace{1cm} (2)

where the classical electron radius is $$r_e = e^2/m_e c^2$$

The differential Rayleigh scattering cross section for elastic scattering of unpolarized photons through an angle y, and averaged over scattered-photon polarizations in form-factor approximation may be written

$$\frac{d\sigma^R}{d\Omega} = \frac{r_e^2}{2} \left(1 + \cos^2 \theta\right)[F(x, Z)]^2$$  \hspace{1cm} (3)

where $F(q, Z)$ is the atomic form factor, $r_e (2.8179 \times 10^{-15} m)$ 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

$$q = (\sin \theta/2) \left(1/\lambda\right)$$

where $\lambda$ is the incident photon’s wavelength and $\theta$ is the angle of scattering.

The incoherent scattering from free electrons is accurately described by Klein and Nishina (1929) theory. Klein and Nishina (1929) derived an expression applying relativistic quantum theory to the scattering from a free electron for the cross section singly differential in scattered photon angle. Theoretically, the differential incoherent scattering cross section per unit solid angle for elements is expressed in terms of the Klein–Nishina cross section as:

$$\frac{d\sigma_{(KN)}(\theta)}{d\Omega} = \frac{r_e^2}{2} \left[1 + k (1 - \cos \theta)^{-2} \times \left[1 + k \left(1 + \cos \theta + \frac{k^2 (1 - \cos \theta)}{1 + k (1 - \cos \theta)} \right)^2 \right] \right]$$ \hspace{1cm} (4)

where $d\sigma_{(KN)}(\theta)/d\Omega$ is the differential cross section per electron for the number of photons scattered into the solid angle in the direction $\theta$, $r_e = e^2/m_e c^2$ is the classical electron radius and $k = E(keV)/511.0034$ is the photon energy in units of the electron restmass energy. The Klein and Nishina (1929) theory is valid for the scattering of high-energy photons where the atomic electrons are relatively free. Departures from the Klein and Nishina (1929) theory occur in situations where the photon energies are comparable with the binding energies of the inner-shell electrons of the target. When the incident energy is comparable to the binding energy, the binding effects have to be taken into account. The electron binding effect is incorporated by incoherent scattering function $S(x,Z)$. Many effects of the interaction of radiation with atoms depend on the incoherent scattering function $S(x,Z)$. To obtain the bound electron differential incoherent scattering cross section, the free electron
The differential incoherent scattering cross section is then multiplied by the incoherent scattering function $S(x, Z)$ as:

$$\frac{d\sigma_{\text{inc}}}{d\Omega} = S(x, Z) \frac{d\sigma_{\text{KN}}(\theta)}{d\Omega}$$  \hspace{1cm} (5)

The coherent to Compton scattering cross section ratio becomes:

$$\frac{d\sigma_{\text{coh}}}{d\sigma_{\text{inc}}} \propto \frac{|F(q, Z)|^2}{S(q, Z)}$$ \hspace{1cm} (6)

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.

3. **Experimental procedure and calculations**

[Diagram of experimental setup]

Pure elements which commercially obtained Cd (% 99.99), In (% 99.999), Sn % 99.9), and Pb (% 99,99) were taken from Alfa Aesar. The foil samples diameter were cut into 13 mm. High purity, thin uniform samples were excited using a radioactive annular source of Am-241 of strength 100 mCi and $\gamma$-photon energy 59.54 keV. A Si(Li) detector (FWHM=160 eV at 5.96 keV, active area 20 mm2, sensitive depth 5 mm and Be window thickness 0.008 mm) with a multichannel analyzer was used to detect X-rays in the measurements.
Fig. 2. A typical observed spectrum from In target at scattering of temperature 30 °C

The experimental setup consist of a Si (Li) detector, Am-241 radioactive annular source, ceramic and aluminum container, thermocouple and temperature controller as shown in Fig.1. During the study, the temperature was changed by 50 °C increments between 30-300 °C degrees. Coherent and Compton X-ray spectrums of the elements were measured at the given temperatures as in-situ. A typical Compton and coherent X-ray spectrum of In is shown in Fig. 2 as an example. All the X-ray spectra were carefully analyzed by means of the Origin 9.0 software program using a multi-Gaussian least-square fit method in order to determine the net peak. The coherent and incoherent scattering cross section ratios were determined from peak areas fitted to Gaussian function after applying necessary corrections to the data.

The intensities of coherent and Compton scattered peaks are corrected for photo peak efficiency, absorption in air between target and the detector and self-absorption in the target using the following equation:

\[ N_{\text{actual}} = \frac{N_{\text{obs}}}{\epsilon_{\gamma} \beta_{\gamma a} \beta_{\gamma t}} \]  

(7)

where \( N_{\text{obs}} \) is observed intensity under coherent or Compton peak, \( \epsilon_{\gamma} \) is photo peak efficiency of gamma detector for coherent or Compton scattered photons, \( \beta_{\gamma a} \) is correction factor for absorption of photons in air between target and detector and \( \beta_{\gamma t} \) is self absorption correction factor for scattered photons in the target.

The ratio of coherent to Compton scattering cross-section based on the equation given above is given as follows:

\[ \frac{d\sigma_{\text{coh}}}{d\sigma_{\text{inc}}} = \frac{N_{\text{coh}} \beta_{\gamma t \text{ inc}} \beta_{\gamma a \text{ inc}} \epsilon_{\gamma \text{ inc}}}{N_{\text{inc}} \beta_{\gamma t \text{ coh}} \beta_{\gamma a \text{ coh}} \epsilon_{\gamma \text{ coh}}} \]  

(8)
where $N_{coh}/N_{inc}$ is the ratio of the number of counts under coherent and Compton scattered peaks, $\beta_{yt}(inc)/\beta_{yt}(coh)$ is the ratio of self-absorption correction factors in the target for coherent and Compton scattered photons, $\beta_{ya}(inc)/\beta_{ya}(coh)$ is the ratio of the air absorptions for Compton scattered and coherent scattered gamma rays in air and $\varepsilon_{\gamma}(inc)/\varepsilon_{\gamma}(coh)$ is the ratio of photo-peak efficiencies of the SiLi detector for Compton and coherent scattered photons.

The self-absorption correction factor $\beta$ is given by:

$$\beta_{yt} = \frac{1 - \exp\left( (-1) \left( \frac{\mu_i}{\cos \theta_1} + \frac{\mu_s}{\cos \theta_2} \right) t_t \right)}{\left( \frac{\mu_i}{\cos \theta_1} + \frac{\mu_s}{\cos \theta_2} \right) t_t}$$

(9)

The air absorption correction is given by:

$$\beta_{ya} = \frac{1 - \exp\left( (-1) \left( \frac{\mu_i}{\cos \theta_1} + \frac{\mu_s}{\cos \theta_2} \right) t_a \right)}{\left( \frac{\mu_i}{\cos \theta_1} + \frac{\mu_s}{\cos \theta_2} \right) t_t}$$

(10)

where $\mu_i$ and $\mu_s$ are the mass attenuation coefficients (cm$^2$/g) of incident photons and emitted characteristic X-rays respectively. $\theta_1$ and $\theta_2$ are the angles of incident photons and emitted X-rays with respect to the normal at the surface of the sample in the present setup and $t$ is the mass thickness of the sample in g/cm$^2$. To estimate the self-absorption correction in the sample and the absorption correction in the air path we used the mass attenuation coefficients obtained by means of a computer program named WinXCom (Gerward et al., 2001, 2004) [initially developed as XCOM (Berger and Hubbell, 1995)]. This program provides total cross-sections and attenuation coefficients of elements, compounds or mixtures as well as partial cross-sections for incoherent and coherent scattering, photoelectric absorption and pair production both in the field of nucleus and electrons at energies from 1 keV to 100 GeV.

The photopeak efficiency curve for the SiLi detector was obtained experimentally in the range 26.345–661.657 keV photon energy by using $^{24}$Am, $^{133}$Ba, $^{152}$Eu and $^{337}$Cs radioactive calibration sources. Each of these radioactive sources of known activity was placed at position of the target and the energy spectra were recorded by the SiLi detector. The equation used for the efficiency calculations is as follows (Demir and Tursucu, 2013)

The equation was calculated as:

$$\varepsilon_{\gamma} = -30,9037 + 15,51926E^1 - 2,95852E^2 + 0,16207E^3$$

The excitation energy can be supplied by raising the sample to a high temperature, by irradiating it with electromagnetic radiation, or by exposing it to an electrical arc or spark. If the sample is excited by radioactive sources as well as is exposed to different temperatures, how the compton and coherent scattering spectrum of the sample is affected? Compton and coherent scattering will be severely affected by fluctuations in temperature since signal is dependent on the number of atoms in the excited state. Temperatures can have a dramatic effect on the ratio of excited atomic particles and unexcited atomic particles. Compton and coherent scattering spectra where quantitative values are being measured would be temperature sensitive.
4. Result and discussion

Table 1. Experimental values of differential cross section ratios of Cd, In, Sn and Pb at different temperatures.

| Temperature (°C) | Cd       | In       | Sn       | Pb       |
|----------------|----------|----------|----------|----------|
|                | Compton  | Coherent | Compton  | Coherent | Compton  | Coherent | Compton  | Coherent | Compton  | Coherent |
| 30             | 15.6782  | 12.4088  | 16.845242| 11.5405  | 15.40829 | 12.38435 | 17.45528 | 12.063242|
| 100            | 17.1217  | 12.6414  | 17.139605| 12.53922 | 15.49665 | 12.34261 | 18.23458 | 12.27721 |
| 150            | 18.4878  | 13.0887  | 18.818334| 13.20909 | 18.27693 | 12.65987 | 20.25369 | 12.32614 |
| 200            | 20.2213  | 13.1546  | -        | -        | 19.17815 | 12.68604 | 20.40269 | 12.45229 |
| 250            | 20.1007  | 12.8393  | -        | -        | -        | -        | 20.72563 | 12.59632 |
| 300            | 21.9292  | 12.8116  | -        | -        | -        | -        | 20.80632 | 12.78905 |

Table 2. Experimental values of FWHM for Cd, In, Sn and Pb at different temperatures

| Temperature(°C) | Cd       | In       | Sn       | Pb       |
|----------------|----------|----------|----------|----------|
|                | Compton  | Coherent | Compton  | Coherent | Compton  | Coherent | Compton  | Coherent |
| 30             | 0.061694 | 0.050196 | 0.056002 | 0.759613 |
| 100            | 0.061611 | 0.048336 | 0.057275 | 0.742554 |
| 150            | 0.061137 | 0.046309 | 0.055654 | 0.729155 |
| 200            | 0.061091 | -        | 0.053169 | 0.727328 |
| 250            | 0.060084 | -        | -        | 0.721082 |
| 300            | 0.058675 | -        | -        | 0.715505 |

Therefore in this study, effect of the temperature changes on the Compton and coherent scattering spectra of the some foil metals (Cd, In, Sn, Pb) have been investigated. Compton and coherent scattering spectrums of Mo, Nb, Zr and Y pure metals was determined using Si (Li) solid-state detector at between 30-300 °C degrees. The measured values of coherent to incoherent differential cross-section ratio of Cd, In, Sn and Pb for the different temperetures (30 °C-300 °C) are given in Table 1, and full width at half maximum (FWHM) values of Cd, In, Sn and Pb for the different temperetures (30 °C-300 °C) are given in Table 2. Figs. 3, 4, 5 and 6 show these changes at graphical form. There are no available data in literature for comparison with the present results.
Fig. 3. Coherent to incoherent cross section ratio as a function of temperature for Cd

Fig. 4. Coherent to incoherent cross section ratio as a function of temperature for In
Fig. 5. Coherent to incoherent cross section ratio as a function of temperature for Sn

Fig. 6. Coherent to incoherent cross section ratio as a function of temperature for Sn

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