Determination of the X-ray Scattering Cross Section and the imaginary part of the form factor of Nickel

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Abstract: In this paper x-ray mass attenuation coefficients of nickel were measured with precision between 0.2% and 0.5% for four characteristic wavelengths: copper and molybdenum K lines. The mass photoelectric absorption coefficients were determined by subtracting the calculated coherent and incoherent scattering from the total scattering and the values of measured attenuation coefficients. The values of the imaginary component of atomic scattering factor for x-ray in nickel were determined from the difference between the values of measured attenuation coefficients and theoretical calculations, it is shown that In the low energy at $\omega \ll \omega_e$, and the high energy at $\omega \gg \omega_e$, the imaginary component approximately is zero, and the electrons are so tightly bound to the atom. In the region $\omega \sim \omega_e$ where the imaginary component of the scattering is dominate and the electron become highly absorbing. There was good agreement between the values of the imaginary component of atomic scattering factor has been found and the theoretical FFAST (Chantler, 1995) tabulated values..

Key Words: atomic scattering factor, the imaginary component of atomic scattering factor, coherent scattering.

1. Introduction:
Measurements of the attenuation of x-rays by materials provide a wide variety of other information about the fundamental properties of matter. In particular, relative and absolute measurements of mass attenuation coefficients are used to investigate the dynamics of atomic processes, including shake-up, shake-off, and Auger transitions [1, 2, 3, 4], and to provide information on the density of electronic states [5], molecular bonding, and other solid-state properties [6]. The diversity of these studies is evidence of the wide variety of processes that influence the attenuation of x-rays.

The accurate attenuation coefficient values of materials are a very essential parameter in nuclear and radiation physics, radiation dosimetry, radiography, spectrometry, crystallography, biological, medical, agricultural, environmental and industrial [7]. The imaginary component of the atomic form-factor $f_2$ determines the photoabsorption of x-rays by atoms. In the x-ray energy region (from about 1 to 100 keV) photoabsorption dominates the atomic cross section for medium and high-Z atoms, typically representing over 90% of the total attenuation. Other significant components are Compton and Rayleigh scattering, and for crystalline materials, Laue-Bragg and thermal-diffuse scattering. Where photoabsorption is dominant, $f_2$ can be determined accurately from measurements of the mass attenuation coefficient ($\mu/\rho$), and used to test theoretical predictions of photoelectric absorption using bound-state electron wave functions [8, 9].
2. X-ray interactions with matter:
The probability $P$ that a single photon of energy $E$ will be transmitted through the material is described by the Beer-Lambert absorption law [8]:
\[
P = \frac{I}{I_0} = e^{-\left(\frac{\rho \mu}{\rho x}\right)}
\]
where $I$ is the intensity of the attenuated beam, $I_0$ is the initial intensity of the beam, $\rho$ and $x$ are the density (8.87 g/cm$^3$) and the thickness of the attenuating material, and $\rho x$ is the mass per unit area in g/cm$^2$, and $\left(\frac{\mu_m}{\rho}\right)$ is the mass attenuation coefficient of attenuating material.

where the ratio of the transmitted $I$ and incident $I_0$ intensities expresses the transmission probability when many photons are incident upon the material. The mass attenuation coefficient $\left(\frac{\mu_m}{\rho}\right)$ describes all processes whereby a photon is absorbed or scattered.

The mass attenuation coefficient is related to the scattering cross section of the form [9]:
\[
\sigma_{\text{Total}} = \left(\frac{\mu}{\rho}\right) \times \frac{M}{N_a}
\]
where $N_a$ Avogadro's number (atoms/mol), $M$ the atomic weight (58.7 g/mol).
The mass attenuation coefficient can be written as a sum of absorbing and attenuating processes. In the 1–100 keV photon energy range, the significant atomic cross sections are represented by photoelectric absorption $\left(\frac{\mu}{\rho}\right)_{pe}$, Compton scattering $\left(\frac{\mu}{\rho}\right)_{c}$, and Rayleigh scattering $\left(\frac{\mu}{\rho}\right)_{r}$, and so we write the mass attenuation coefficient as
\[
\left(\frac{\mu}{\rho}\right) = \left(\frac{\mu}{\rho}\right)_{pe} + \left(\frac{\mu}{\rho}\right)_{c} + \left(\frac{\mu}{\rho}\right)_{r}
\]
The photoelectric absorption coefficient $\left(\frac{\mu}{\rho}\right)_{pe}$ is related to the imaginary component of the atomic form-factor $f_2$ [10].
\[
f_2 = \frac{2\pi a}{\hbar c r_e} \times \left(\frac{\mu}{\rho}\right)_{pe}
\]
where $E$ is the photon energy in eV, $\upsilon$ the atomic mass unit, $A$ the relative atomic mass of the absorbing atom, $h$ the Planck constant, $c$ the speed of light, and $r_e$ the classical electron radius.

3. Experimental Setup and measurements
In this experiment, the Copper and molybdenum targets were used as x-ray sources at the energies of their $K_\alpha$ and $K_\beta$ lines. For Copper, these lines are at 8.048 keV and 8.906 keV respectively. For molybdenum, these lines are at 17.480 keV and 19.609 keV respectively.
The steps listed below were followed to measure and calculate the values of mass attenuation coefficients ($\mu_m$) of X-ray samples and steps are:
1- X-ray sources of the experiment shown in Figure (1).
2- feed the device information and data measurements (Input), which are:
- Determination of the energy to be measured by determining the diffraction angle of the radiation using lithium fluoride crystal (LiF) and applying the Bragg’s Law.
3- Recording the output measurements which are:
- $(I_0)$ Radiation intensity without a sample at the beginning and end of each attempt to reduce the percentage of experimental errors.
- $(I)$ the intensity of the x-rays in the presence of the sample and repeat readings more than once to reduce the proportion of experimental errors and to increase accuracy.
Repeat steps (2 and 3) for all energies under study and Table (1) shows the measurements obtained.
Figure (1): X-ray device of the experimental

Table (1):- The Values of the intensity of the x-rays in the presence of the sample at all energies under study.

| X (g/cm²) | 8.048(keV)  | 8.906(keV)  | 17.48(keV)  | 19.609(keV)  |
|-----------|-------------|-------------|-------------|-------------|
| I (c/s)   | I (c/s)     | I (c/s)     | I (c/s)     |
| 0.005     | 7746        | 2657        | 7785        | 8225        |
| 0.010     | 6155        | 724         | 6216        | 6939        |
| 0.015     | 4890        | 197         | 4964        | 5854        |
| 0.020     | 3885        | 53          | 3964        | 4939        |
| 0.025     | 3087        | 15          | 3165        | 4167        |

The mass attenuation coefficients measured were obtained from the inclination of the line through a linear adjustment of the plot of the absorption logarithm in function of the thickness (g/cm²) of Nickel by using Eq. (2), the average of these measurements and their standard deviations were used for ($\mu$) calculations. Figures (2-5) depict the graphs of absorption in function of thickness. In these figures, a good agreement between the values measured and the values calculated by FFAST (Chantler, 1995) can be observed.
Figure (2) relationship between absorption logarithm of x-ray with thickness (g/cm²) at 8.048 KeV and standard deviation.

\[ \text{Ni at } E = 8.048 \text{ KeV} \]
\[ y = 46 \times X + 0.8e-7 \]

Figure (3) relationship between absorption logarithm of x-ray with thickness (g/cm²) at 8.906 KeV and standard deviation.

\[ \text{Ni at } E = 8.906 \text{ KeV} \]
\[ y = 260 \times X + 0.5e-5 \]
Figure (4) relationship between absorption logarithm of x-ray with thickness (g/cm²) at 17.48 keV and standard deviation.

Figure (5) relationship between absorption logarithm of x-ray with thickness (g/cm²) at 19.609 keV and standard deviation.
The total photon interaction cross-section was calculated with Eq. (3) using the measured attenuation coefficients. The photoelectric absorption cross-sections were obtained from the total photon interaction cross-section by subtraction the contribution of Compton and Rayleigh scattering cross-section. Finally, the imaginary part of the atomic scattering factor...
was calculated with Eq. (5) using the determined values of the photoelectric absorption cross-section.

Table (2):- Measured mass attenuation coefficient, values of Compton and Rayleigh form FFAST (Chantler, 1995), determined photoelectric absorption scattering cross-section and imaginary part of the atomic scattering factor for Nickel obtained in this work.

| X-ray lines | $\rho$ (cm$^2$/g) | $\sigma_{\text{Total}}$ (barn/atom) | $\sigma_C + \sigma_R$ (cm$^2$/g) | $\sigma_{\text{Pe}}$ (cm$^2$/g) | $f_2$ (barn/atom) | $f_2^*$ (barn/atom) |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| CuK$\alpha$ | 46              | 4482            | 1.94            | 44.06           | 0.49            | 0.51            |
| CuK$\beta$ | 260             | 25337           | 1.74            | 258.26          | 3.2             | 3.4             |
| MoK$\alpha$| 45              | 4385            | 0.85            | 44.15           | 1.07            | 1.09            |
| MoK$\beta$ | 34              | 3313            | 0.75            | 33.25           | 0.9             | 0.91            |

* (Chantler, 1995) [11]

4. Results and Discussion
The mass attenuation coefficients of Nickel metal foils were determined and presented in Table 2. Five Nickel foils with different thicknesses were used in the energy range between 8.048 keV and 19.609 keV. To obtain the final attenuation coefficient at a given energy, the measurements of the mass attenuation coefficient of Nickel taken with different thickness can provide information about the effect that fluorescence and scattering have on such measurements. Theoretically tabulated (FFAST) scattering cross sections were derived coherent and incoherent scattering for the measured experimental energies at which X-ray mass attenuation coefficients were determined. The photoelectric mass absorption coefficient was then determined by subtracting the theoretically tabulated scattering cross sections from the measured total mass attenuation coefficients. The imaginary component of the atomic form factor $f_2$ is directly related to the photoelectric absorption. In particular, show that when using mass attenuation coefficients in the vicinity of an absorption edge the effects are not only observable but also are in excellent accord with theoretical calculations, agreeing with them both in trend and absolute value.

5. Conclusion
The X-ray mass attenuation coefficients of Nickel were determined with an accuracy of 0.01–0.2%. This analysis provides the most accurate measured X-ray mass attenuation coefficients of Nickel in the 8.048–19.609 keV energy range. The mass attenuation coefficients depend on the photon energy. The mass attenuation coefficients of materials are decrease with increasing photon energy. As shown in Table 2, Also, the present results illustrate the importance of specific energy values, which can be observed from the figure (7) it is shown that In the low energy at $\omega \ll \omega_e$, and the high energy at $\omega \gg \omega_e$, the imaginary component approximately is zero, and the electrons are so tightly bound to the atom. In the region $\omega \sim \omega_e$ where the imaginary component of the scattering is dominate and the electron become highly absorbing. Therefore, measuring the imaginary component of the atomic scattering factor is more useful for accurate measurements that will improve our understanding of these processes known as resonant scattering and are more appropriate to describe resonant behavior near absorption edges.
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