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The Dependence of X-Ray Attenuation Parameters of (Al, Cu, And Zr) Metals on their Atomic Number

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Abstract

This paper studied X-ray attenuation in metals (Al-13, Cu-29, Zr-40). X-ray energy of 17 keV of kα line of molybdenum was directed to metal bars with 0.05 cm thickness. These three metals have differences in their atomic numbers and electronic distributions in the electronic shells; aluminum (Al-13) was chosen as the low atomic number, copper (Cu-29), and zirconium (Zr-40) as the high atomic number. The linear and mass attenuation coefficients, atomic and electronic cross-sections, and electron density for X-ray attenuation through each element were determined experimentally. The results explained a new idea to describe X-ray scattering: the effect of valance and bound electron (electron distribution) of the metals. The metal with more bound electrons in its outermost shell scattered more radiation for a specific range of energy, even though the metal has a less atomic number.

1. Introduction

A lot of medical and industrial applications employ X-ray attenuation measurements. The photon mass attenuation coefficient, effective atomic number, and electron density are crucial in determining the penetration of X-rays and gamma-rays in matter. The mass attenuation coefficient can be used to calculate the probability of incident photons interacting with matter. [1]. When an X-ray beam strikes an atomic target, two processes may occur; the beam may be absorbed with an ejection of electrons from the atoms, or the beam may be scattered [2]. The intensity loss of incident X-rays passing through a substance is known as attenuation. Numerous experimental and theoretical investigations have investigated the relationship between the attenuation coefficient and the atomic number of polymers, liquids, crystals, and some metals. The WinXCom software has estimated the mass attenuation coefficients for the materials provided. This program, which is based on the DOS-based compilation XCom [3], provides the total mass attenuation coefficient and the total attenuation cross-section data for about 100 elements as well as partial cross-sections for incoherent and coherent scattering, photoelectric absorption, and pair production at energies ranging from 1 keV to 100GeV [4]. Manohara & Hanagodimath measured the effective atomic number for some amino acids [5], and Midgley in [6] estimated X-ray linear attenuation coefficients for low atomic number plastics, liquids, crystals, and aluminum. Some applied science needs to quantify absorption and scattering parameters for matters such as nuclear medicine, nuclear diagnostics, nuclear engineering, security, industrial inspections, and agriculture [7]. The researchers in [8–10] took soil samples and [11,12] tested some biomedical elements for measuring the attenuation coefficient parameters. Researchers have presented and discussed various experimental measurements to determine the attenuation coefficients for solid materials [13,14]. Considerable efforts have been devoted to describing the attenuation coefficient values concerning the photon energy range [15–17]. Akca and Erzeneoglu [18] measured the mass attenuation coefficient for Na, Mg, Al, Ca, and Fe using the collimated-beam transmission method at 59.5 keV. Almost the previous studies were worked with the support of the software WinXcom and Phy-X/PSD [4,19]. The NIST tabulation [20] incorporates coherent scattering cross-sections [21] based upon the independent atomic model, which predicts an angular distribution of coherently scattered photons that is confined to a narrow cone in the forward direction [6].

In the present work, linear and mass attenuation coefficients will be determined for three metallic elements with different atomic numbers (Al-13, Cu-29, and Zr-40) at the same X-ray energy value and compare the attenuation coefficients of the elements according to their atomic numbers. This work's importance is that specifying the metals according to their atomic number is crucial to use as a radiation protector.

2. Theory

Beer–Lambert's law states that the intensity (or counting rate, which is directly proportional to intensity) of an incident monochromatic beam, I_o, decreases exponentially with the distance it has traveled inside a material [22, 23], which is expected as:

$$\mathrm{I} = \mathrm{I_o} \mathrm{e}^{-\mu x} \tag{1}$$

Where the linear attenuation coefficient, μ (cm^(-1)) Is the probability of photon interaction with matter per unit of length x (cm) [24].

This formula yields the experimental mass-attenuation coefficient (μ/ρ):

$$\frac{\mu}{\rho} = \frac{1}{\rho x} \ln\left(\frac{I_o}{I}\right) \tag{2}$$

The mass-attenuation coefficient can be used to determine the atomic cross-section σ_a, from the following formula [11, 25]:

$$\sigma_a = \frac{A}{N_A}\frac{\mu}{\rho} \tag{3}$$

Where N_A is Avogadro's number, and A is atomic weight. The electronic cross-section σ_e for the individual element is expressed by the following formula [12]:

$$\sigma_e = \frac{\sigma_a}{Z} \tag{4}$$

The effective electron number or electron density, N_e (number of electrons per units mass), can be found from this formula [5, 12, 18]:

$$N_e = \frac{(\mu/\rho)}{\sigma_e} \tag{5}$$

3. Material and Methods

The setup configuration of the experiment is shown in Fig. 1 [26]. The high voltage (U) of 30 kV and the electrical current (I) of 1 mA were applied to the X-ray tube with the X-ray source of molybdenum (Mo). Due to the impact of electrons on the molybdenum target, those electrons may deviate from their path. During this process, electromagnetic radiation (photon) emit; according to Duane-Hunt's relation [27], the endpoint energy of those photons (X-ray) is equal to the maximum energy of electrons that hit the molybdenum target. Here, the emitted X-ray photons have a continuous energy spectrum and are not monoenergetic, the K_α line of molybdenum energy is about 17 keV. This amount of energy was directed through a collimator of 0.1 cm to metal absorbers of different atomic numbers (Al-13, Cu-29, and Zr-40) with the same thicknesses of ($x = 0.05$ cm) and dimensions (0.2, 1) cm. The transmitted X-ray energy was detected by the end-window counter, which is known as the Geiger Muller counter.

4. Experimental Data

The X-ray counting rate (I_o) directed to the target (f) for about ($t = 300s$), and the counting rate (I) of the X-ray transmitted from the target was counted. The transmittance (T) was determined for each element (attenuator) Al-13, Cu-29, and Zr-40, from Eq. 1, ($T = I/I_0$). The greater the transmittance of an absorber material (attenuator), the lower the attenuation coefficient. The transmittance is affected by the thickness of the absorber. The thickness (x) of all attenuators was (0.05 cm), and the incident energy of the K_α of molybdenum X-ray was also (17 keV). The transmittance was then written as Lambert's law [28];

$$\ln T = -\mu . x \tag{6}$$

Where μ is the linear attenuation coefficient. For X-ray energy of 17 KeV, the incident counting rate (I_o) was equal to (10376 /s). The counting rate was reduced when passed through the absorbers (Al-13, Cu-29, and Zr-40); the results are shown in Table 1. Then Eq. 6 &2 were used to determine each element's linear and mass attenuation coefficients, and the results tabulated in Table 2.

5. Result and Discussion

The attenuation coefficient as a function of the atomic number in the middle range of the atomic numbers was studied and compared using three metallic elements (Al-13, Cu-29, and Zr-40). Previous studies and experiments have reported that the attenuation coefficient is directly related to materials' atomic and electronic cross-section values [12, 25, 29, 30], and the atomic cross-section is proportional to the atomic number Eq. 4 [11].

As a result, the attenuation coefficient can be considered proportional to the atomic number of the elements (materials) at all energy ranges. However, looking at the results presented in Table 2, for a specific energy of K_α line of a molybdenum anode source, it is clear that this was true when comparing the data of Al-13 and Cu-29 but incorrect when comparing Cu-29 and Zr-40. The attenuation coefficient for Cu-29 is more significant than that for Al-13, while the atomic number of Cu-29 is greater than the atomic number of Al-13. Nevertheless, for Zr-40, which has a more significant atomic number than Cu-29, the attenuation coefficient is less than that for Cu-29. The questions will appear here, why has this happened? Is this happening for other complex atoms (atoms with a large atomic number?)?

The answer to the second question is not because there are experimental data for some other elements [12,17,29,31–33], which show that the more significant atomic number has a greater attenuation coefficient. In contrast, the values produced (for different elements with different atomic numbers) at a specific energy (for example, 17 keV and 30 keV) by WinXCom [4] and [34] correspond with the present findings.

Finding the values of the mass attenuation coefficient of X-ray for the specific elements (Al-13, Cu-29, and Zr-40) with the incident energy of 17 keV (of kα line of molybdenum) between the present experimental results and theoretical data is attributed to the configurations of outer shell electrons in the atoms (elements). The valance electron takes a role in making this difference because of X-ray scattering when it interacts with the atom. From eq. (3, 4, & 5) the atomic cross-section, electron cross-section, and effective electron number can be determined, respectively. The results are shown in Table 3.

From Table 3, one can investigate the electron configuration of the elements to describe the differences in X-ray attenuation between the elements. Al-13 has valance electrons at 3s23p1, Cu-29 at 3d104s1, and Zr-40 valance electrons at 4d25s2. Comparing the number of valance electrons in these configurations, one can be seen that aluminum has three valance electrons in the third shell with a filled 3s orbital, an unfilled 3p orbital, and an empty orbital 3d. Copper has filled all orbitals in the third level. Still, only one electron in the 4s orbital of the fourth electronic level, and zirconium has four valance electrons, two in the 4d, which is unfilled with empty 4f, and two electrons in 5s at their outer shells. Here, we can say that copper has more bounded electrons in its outer shell and less valance; therefore, copper can scatter X-ray radiation more strongly than aluminum and zirconium. Due to the scattering process between X-ray and electrons, the transmitted radiation in copper is smaller than that of zirconium (at an energy range of 17 keV); however, Zr-40 has a higher atomic number than Cu-29.

6. Conclusion

The X-ray transmission, the linear attenuation coefficient, mass attenuation coefficient, atomic and electronic cross sections, and the electron density for three crucial elements (Al-13, Cu-29, and Zr-40) were determined experimentally. As known, the attenuation coefficient is proportional to the atomic number, but for specific energy (17 keV of kα line of molybdenum), an abrupt change was seen for Zr-40. While the atomic number of Zr is larger than the atomic number of Cu and Al, and the attenuation coefficient for Zr is less than that for Cu and Al. As discussed before, this occurred according to the scattering of the X-ray while interacting with the electrons on the outer shell of the atoms. An atom with more bounded electrons in the outer shell can scatter more radiations than those with more valance electrons. From this result, we can conclude that all higher atomic number elements are not suitable protectors for X-rays at all energy ranges. Therefore if someone wants to choose a metal to protect from X-rays, it is essential to look at the energy of the X-ray and the electron distributions of the metallic atom. To unravel some of the practical implications of our theoretical idea about the atomic structure and electronic distribution of atoms, we need to do more work in collaboration with theoretical physicists.

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