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Study of the Efficiency of some Quaternary Alloys (Al-Cu-Pb-Zn) in Attenuating Gamma Radiation

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ABSTRACT

The fields of use of aluminum and its alloys have diversified, making it essential in our daily lives, due to the various properties of aluminum, including light weight, durability, formability, remanufacturability, and resistance to corrosion. It has been used in the aviation industry, high-speed trains, and most advanced engineering industries. Despite the low melting point of aluminum alloys, it is used in the manufacture of missiles and in the construction of internal combustion chambers. Here, aluminum alloys were employed in the fields of protection from electromagnetic radiation, especially gamma rays, by manufacturing gamma ray shields. Three alloys of (AlCuZnxPb10-x) were manufactured, differing in the proportions of zinc and lead elements. The main attenuation parameters were studied, including the linear and mass attenuation coefficient, the value-describing layer, the tenth value layer, and the free path rate, through a theoretical study using the X-COM program. It was noted that with an increase in the zinc concentration, the value of the linear and mass attenuation coefficient increased.

Keywords: Aluminum alloys, mass attenuation coefficient µm, half-layer thickness, XCOM.

INTRODUCTION

Radiation refers to the energy emitted as small particles of matter, which can manifest in different forms, including X-rays, gamma rays, and radiation from nuclear reactors. Humans are exposed to radiation daily, as it has always been a natural part of life on earth (Al-Buriahi *et al*., 2021; Ahmed *et al*., 2024). However, radiation pollution can have significant effects on both the environment and human health. It originates from natural sources like cosmic rays and radioactive substances in nature, as well as human activities such as nuclear testing and industrial processes, which introduce additional radiation into the ecosystem. Understanding these sources and their impacts is crucial for effective radiation management strategies (Benhadjira *et al*., 2024). Gamma rays, as high-energy electromagnetic waves, possess the ability to ionize matter, leading to significant biological effects. While they are utilized beneficially in medical applications such as cancer treatment and diagnostics, excessive exposure can result in severe health issues, including oxidative damage to cells, hair loss, skin burns, and increased cancer risk. The following sections elaborate on the dual nature of gamma rays. (Kaur *et al*., 2016; Mheemeed *et al*., 2012), radiation protection is an essential field that has gained increasing global attention, especially in medicine, nuclear technology, and scientific research. As technology advances, the need for effective radiation safety measures becomes more critical. This field plays a vital role in safeguarding human health and the environment, driving continuous research and innovation to develop better protective solutions (Sayyed *et al*., 2025). To reduce radiation hazards, materials with high density, such as cement, lead, and other elements with high atomic numbers, are commonly used to build protective barriers these materials effectively absorb and weaken radiation, thus lowering the risks of exposure (Taqi *et al*., 2021). Protective shields made from materials like concrete, stone, lead, and iron are essential for blocking harmful gamma rays. These materials function through attenuation, where radiation is absorbed or scattered, thus reducing exposure. Effective shielding design considers factors such as material density, thickness, and composition. Additionally, minimizing exposure time and increasing distance from radiation sources are critical strategies for reducing radiation risk. The following sections elaborate on these aspects (Kim, 2018; Şahin *et al*., 2021). Lead is commonly used for gamma-ray shielding because of its high density, atomic mass, resistance to corrosion, and ease of fabrication. Its shielding ability increases with thickness, making it a reliable material for radiation protection (Aldawood *et al*., 2024; Elmzainy *et al*., 2022). Alloys have distinct characteristics, including higher rigidity and lower ductility, which can improve their ability to provide radiation shielding. Understanding how radiation interacts with materials is crucial for designing suitable materials for high-radiation environments. These advancements have important uses in fields such as medicine, engineering, and scientific research (Sufian and Hamood, 2023; Turner, 2005). For example, (Singh *et al*., 2016) investigated the linear and mass attenuation coefficients, effective atomic number, and electron density of copper-lead alloys across a wide energy range (1keV-100GeV). Their study analyzed variations in mass attenuation coefficients, atomic number, and electron density by examining interactions such as Compton scattering, the photoelectric effect, and pair production. Similarly, researchers (Najam *et al*., 2016) compared different types of commonly used granite with lead and measured the linear and mass attenuation coefficients, and found that these coefficients decrease with increasing incident photon energy and found that the linear attenuation coefficients are linearly proportional to the density while the mass attenuation coefficient is not affected.

Materials used and method of operation

The experience of producing quaternary alloys of aluminum, copper, zinc and lead (Al-Cu-Pb-Zn) highlights the importance of alloy composition and technological processing techniques in determining the microstructure and properties of common materials. By melting the coating and copper, zinc and lead (Al-Cu-Pb-Zn). Then, the melting machine was made in a mold made of wrought iron in a shape with dimensions that fit using pen and measuring devices. The results of the attenuation results were theoretically tested using the XCOM program.

Table 1: Show the physical properties of the prepared alloys.

Sample	Compounds	Thickness (cm)	Volume (cm^3)	Density ($g\ cm^{-3}$)
A1	Al67Cu23Pb1Zn9	1	7.3004	2.372
A2	Al67Cu23Pb2Zn8	1	7.603	2.465
A3	Al67Cu23Pb3Zn7	1	8.461	2,623

Scientists have studied how metal alloys block gamma radiation, using data from mass, linear, and half-value attenuation coefficients to identify effective radiation shielding materials. The attenuation coefficient is crucial and is often used to determine shielding parameters. μm can be calculated using Beer-Lambert's law, which defines a constant that describes how a material's properties lead to photon radiation attenuation and is measured in cm^{-1}. The linear attenuation coefficient increases as the material's density and atomic number increase. These coefficients are calculated using the exponential attenuation law (Kadri and Bouchendouka, 2024; Al Aziz, 2022):

$$I_x = I_0 \exp(-\mu_l x) \text{ ……… (1)}$$

I_o: The initial intensity, I_X: Is the transmitted intensity, X: Depth of penetration and μ_L: Represents the linear attenuation coefficient for a given photon energy. The mass attenuation coefficient is a key parameter and is determined using the following relationship (Majeed *et al*., 2025):

$$\mu_m = \frac{\mu_l}{\rho} \quad \text{……… (2)}$$

The half-value layer is the material thickness needed to reduce the incident radiation intensity by half.

It was calculated using the following equation (Aygun *et al*., 2023):

$$HVL = \frac{Ln2}{\mu_L} \quad \text{……… (3)}$$

The tenth-value layer (TVL) was also calculated using the following equation:

$$TVL = \frac{Ln10}{\mu_l} \quad \text{……… (4)}$$

In this study, the mean free path was determined:

$$MFP = \frac{1}{\mu_L} \quad \text{………… (5)}$$

The attenuation of gamma rays depends on the energy of the incident rays, the density and atomic number of the shielding material, and its thickness (Ali *et al*., 2024).

XCOM program

A web program called XCOM was developed by Berger and Hubbell between 1987 and 1999. It calculates photon mass attenuation coefficients (ρ/μ) or cross sections (σ) for elements, compounds, and mixtures with atomic numbers Z≤100 and energies ranging from 1keV to 100GeV. The program displays data as attenuation coefficients (μ) and total attenuation cross-sections, as well as partial cross-sections for processes like incoherent and coherent scattering, photoelectric absorption, and pair formation in atomic nuclei and electrons (Nulk, 2014). XCOM program lets users enter material compositions and calculate their interaction with electromagnetic radiation. It provides results that help in designing radiation shielding materials and assessing their effectiveness in reducing exposure.

These results are used in fields like nuclear medicine, materials science, and environmental protection (Medhat *et al*., 2014).

RESULTS AND DISCUSSION

Mass attenuation coefficient μ_m

The data indicate that as the energy of the gamma-ray photons increases, the mass attenuation coefficient values decrease. The highest value of the mass attenuation coefficient was found in alloy A3 at 60 keV, with a measurement of 0.8262 cm²/g, which contains the highest amount of zinc. On the other hand, the lowest value occurred for alloy A1 at 1332 keV, with a value of 0.05254 cm²/g. This shows an inverse relationship between the two variables.

Table (2): displays the mass attenuation coefficient (µm) of the quaternary alloys across different energies, from 60 to 1332 keV.

Samples		E(Kev)								
		60	186	242	295	352	609	662	1173	1332
		Am^{241}	Ra^{226}					Cs^{137}	Co^{60}	
		μ_m(cm^2/gm)								
A1	XCOM	0.7611	0.1508	0.1247	0.1109	0.1010	0.07743	0.07441	0.05607	0.05254
A2	XCOM	0.7936	0.1609	0.1298	0.1139	0.1029	0.07789	0.07478	0.05612	0.05259
A3	XCOM	0.8262	0.1711	0.1348	0.1169	0.1048	0.07835	0.07515	0.05621	0.05264

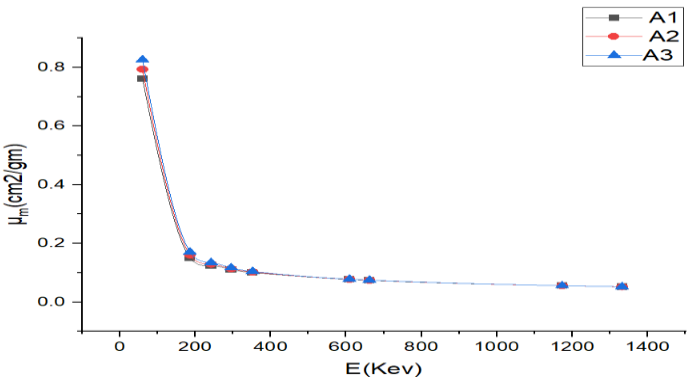

Fig. 1: Illustrates the relationship between the mass attenuation coefficient and energy for the quaternary alloys.

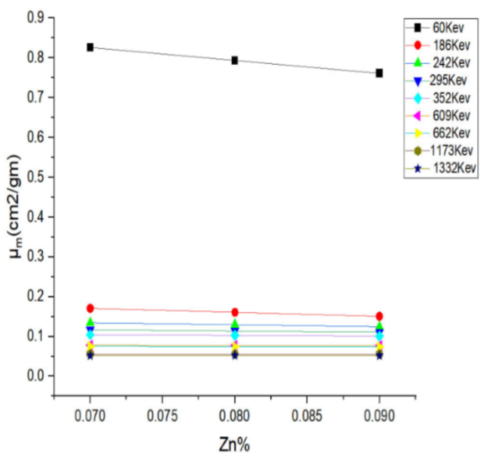

Fig. 2: Illustrates the relationship between Zinc concentration and the mass attenuation coefficient.

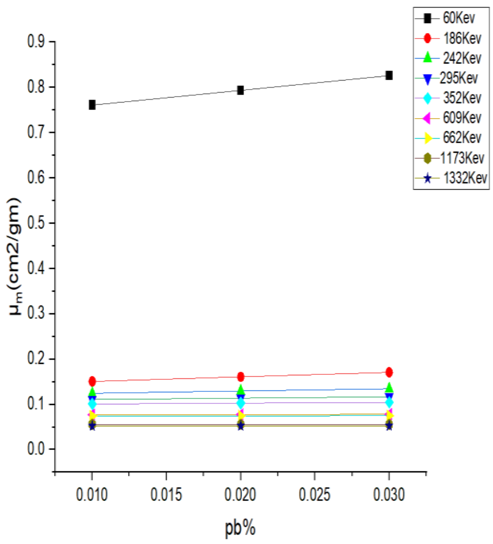

Fig. 3: Shows the relationship between lead concentration and mass attenuation coefficient.

Halve value layer (HVL)

The HVL was calculated theoretically using the linear attenuation coefficient (μ). The results shown in (Table 3) reveal that a maximum thickness of 5.78628325cm is required in the quaternary A3 alloy to reduce the intensity of gamma rays with an energy of 1332keV to half its original value. This is attributed to the higher energy of the gamma rays in this case. In contrast, a thickness of 0.383864cm is needed in alloy A1 to reduce the intensity of 60keV gamma rays to half its value. The significant difference between these two values is evident, as HVL is directly proportional to the energy of the gamma rays.

Table 3: Show halve value layer (HVL) of the quaternary alloy for different range of gamma ray energy.

Samples		E(Kev)								
		60	186	242	295	352	609	662	1173	1332
		Am-241	**Ra-226**					**Cs-137**	**Co-60**	
		HVL(CM)								
A1	XCOM	0.383864	1.937389	2.342894	2.63443	2.892659	3.773195	3.926323	5.089862	6.408419
A2	XCOM	0.354234	1.747269	2.165916	2.468265	2.732122	3.609394	3.7595	5.120854	6.162575
A3	XCOM	0.3197788	1.54413485	1.95995249	2.2600602	2.5210084	3.37206586	3.51566067	4.589221562	5.78628325

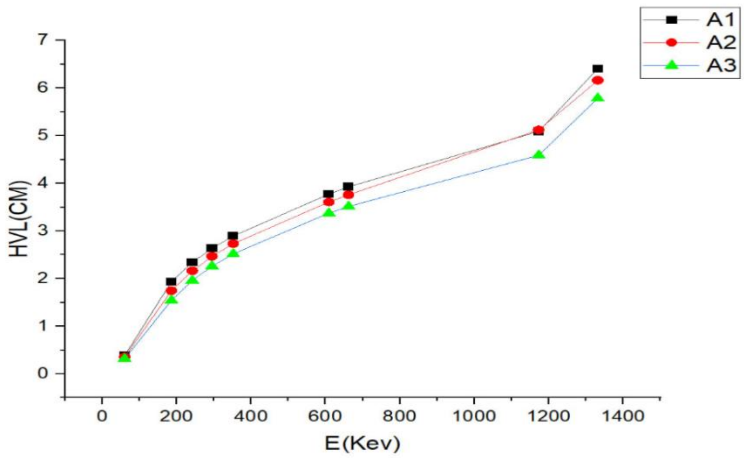

Fig. 4: Shows the correlation between the half-value layer and energy of gamma ray for the quaternary alloys at different energies.

Mean free path (MFP)

It can be seen from the table that the MFP values are directly proportional to the gamma ray energy values, where the highest MFP value was 8.34961508cm at 1332Kev while the lowest MFP value was 0.55391566cm at 60Kev for the quadrilateral alloys.

Table 4: Show the mean free path (MFP) of the quadrilateral alloys.

Samples		E(Kev)								
		60	186	242	295	352	609	662	1173	1332
		Am-241	**Ra-226**					**Cs-137**	**Co-60**	
		MFP (cm)								
A1	XCOM	0.55391566	2.7956443	3.38079976	3.80148638	4.1741105	5.44472515	5.66569028	7.34467841	9.24735757
A2	XCOM	0.5111889	2.52131138	3.12541998	3.56171019	3.94245591	5.20836046	5.4249646	7.38939917	8.89260402
A3	XCOM	0.46144127	2.22818882	2.82821427	3.26127013	3.6378187	4.86589591	5.07310342	6.62225342	8.34961508

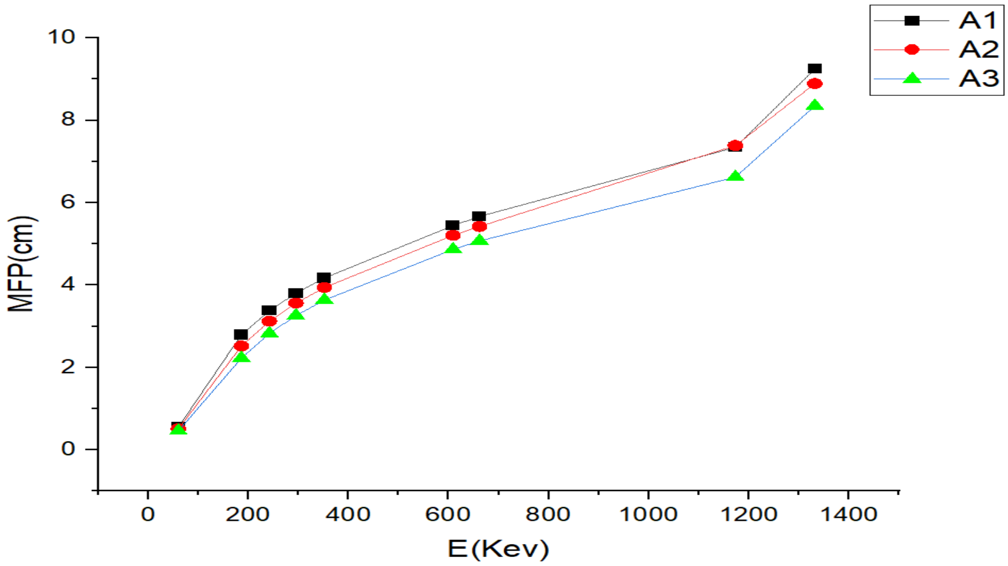

Fig. 5: Shows the relationship between the MFP of the quadrilateral alloy and the gamma ray energy, which shows that there is a direct correlation between them.

CONCLUSIONS

In this study, some shielding parameters for gamma rays of various energies were analyzed theoretically using XCOM software, and the shielding parameters of quaternary alloy samples containing the elements aluminum (Al), copper (Cu), lead (Pb), and zinc (Zn) were studied. Which were synthesized in the laboratory at various concentrations. The theoretical results showed that as the energy increases, the mass attenuation coefficient decreases and the MFP, TVL, HVL increases, the mass attenuation coefficient reaches its highest value in alloy A3 at 60 keV, measuring 0.8262 cm^2/g and the lowest value in alloy A1 equal to 0.05254 cm^2/g at energy 1332Kev.

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دراسة كفاءة بعض السبائك الرباعية (Al -Cu-Pb-Zn) في توهين اشعة كاما

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الملخص

تعددت استخدامات الألومنيوم وسبائكه في العديد من المجالات، مما جعله جزءًا أساسيًا في حياتنا اليومية، بفضل خصائصه المتنوعة مثل خفة الوزن، المتانة، قابلية التشكيل، القابلية لإعادة التصنيع، ومقاومته للتآكل. وقد تم استخدامه في صناعات الطيران، القطارات السريعة، ومعظم الصناعات الهندسية المتقدمة. ورغم انخفاض درجة انصهار سبائك الألومنيوم، إلا أنه يُستخدم في صناعة الصواريخ وبناء غرف الاحتراق الداخلي. في هذا السياق، تم توظيف سبائك الألومنيوم في مجالات الحماية من الأشعة الكهرومغناطيسية، خاصة أشعة كاما، من خلال تصنيع دروع واقية. حيث تم تصنيع ثلاثة سبائك من (AlCuZnxPb10-x) تتفاوت في نسب عناصر الزنك والرصاص، وتمت دراسة المعلمات الأساسية للتوهين مثل معامل التوهين الخطي والكتلي، طبقة القيمة، طبقة القيمة العاشرة، ومعدل المسار الحر من خلال الدراسة النظرية باستخدام برنامج "إكس كوم". وقد لوحظ أنه مع زيادة تركيز الزنك، زادت قيم معامل التوهين الخطي والكتلي.

الكلمات الدالة: سبائك الألمنيوم، معامل التوهين الكتلي μ_m، سمك الطبقة النصفية، معدل المسار الحر ، XCOM.