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Gamma-Ray Attenuation Properties of Al-Cu-Pb Ternary Alloys: A Systematic Review

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Abstract. Medical and nuclear applications have a high demand on effective gamma-ray shielding, which has led to research on alternative materials to traditional ones such as lead. Al-Cu-Pb systems, ternary alloys in particular, have come out as a good alternative. The paper provides a systematic review in order to critically evaluate and synthesize available literature on the gamma-ray shielding performance of Al-Cu-Pb alloys. The review is based on experimental, theoretical (XCOM) and simulation (Geant4, MCNP) research studies. It has been established that attenuation properties including Mass Attenuation Coefficient (MAC) and Radiation Protection Efficiency (RPE) are very sensitive to high-Z elements concentration, specifically lead (Pb) and copper (Cu). There is always a strong match between data obtained through experimentation and computational models. Nevertheless, the review has found some major gaps, such as the absence of standardized experimental protocols, and quantitative correlation of alloy microstructure with shielding performance. The synthesis indicates the potential of Al-Cu-Pb alloys and gives a clear direction into which future studies can be carried out to solve the existing gaps in methodology.

Keywords: Gamma-Ray Shielding, Al-Cu-Pb Alloys, Ternary Alloys, Mass Attenuation Coefficient, Systematic Review.

INTRODUCTION

The need to have good gamma-ray shielding material in medical, industrial and nuclear industries has driven development of extensive research on attenuation levels of new alloys [1][2]. Traditionally, high-density compounds like lead and concrete have been used in radiation protection, but currently, modern usage requires materials that can provide a better combination of protection efficiency, mechanical strength, low weight and environmental friendliness [3][4]. This has motivated the development of shielding research to take a new direction to more sophisticated composites and alloys, which are also under analysis through computational and simulation techniques [1][5]. In this setting, the ternary alloys, especially the system of Al-Cu-Pb have become an interesting field of exploration. It is also assumed that adding high-atomic-number (high-Z) elements (including Pb and Cu) to a lightweight aluminum (Al) matrix will contribute greatly to the gamma attenuation coefficients [6][7]. Although there has been an increasing interest in the research on binary and ternary alloys as radiation shielding, there is still a major gap in literature about the overall assessment of the Al-Cu-Pb ternary system. In particular, experimental data, theoretical calculations, and simulation outcomes are not systematically combined in the studies [1] [8]. Although related ternary systems have been studied [8][9] or other compositions [10][11] have been studied and their results are fragmented and sometimes inconsistent about the best elemental composition and mechanism of shielding [12][13]. Moreover, there are also unresolved differences related to the optimization of the shielding performance against mechanical properties, where certain alloys have better attenuation at the cost of structural integrity [3][14]. The mathematical model of the measurements of such alloys is based on the combination of the mass attenuation coefficient, radiation protection efficiency (RPE), and the microstructural features of the alloy [1][6][8]. The inherent parameters are controlled by the composition of elements, density, and phase distribution [6][14] and are usually modeled based on theoretical models such as XCOM or Monte Carlo simulations [1][5]. The lack of a single framework that would bring together these findings on the Al-Cu-Pb system hinders optimization and the following practical application [2][15].

Thus, the main task of this systematic review is to critically review and summarize the available literature on gamma-ray shielding efficiency of (Al-Cu-Pb) ternary alloys. The purpose of the review is to give an overall view of the alloys evaluating their attenuation parameters over different energy range and strictly comparing experimental, theoretical and simulation methodologies used [1][8]. The roles of chemical composition and microstructural properties on attenuation coefficients and protection efficiency are emphasized and the results of the experiments are compared to the theoretical predictions. The end product would be to determine consistent trends, rectify discrepancies, identify research gaps, and present a coherent source to inform the further development and optimization of these materials to connect with advanced radiation protection processes [2][3][11].

THEORETICAL PART

A systematic literature search plan was adopted, and it was starting with the conversion of the original research question related to the gamma-ray shielding effectiveness of (Al-Cu-Pb) ternary alloys into several specific queries to guarantee the effectiveness of retrieval. The first step of screening scientific databases under the pre-established inclusion and exclusion criteria generated 32 core papers. This list was then expanded by applying intensive forward and backward chaining of citations - analyzing citation by both these papers as well as later papers that cited them which found another 12 relevant studies. This was a multi-step procedure that put together a final set of 38 candidate papers, which were then all evaluated through a final relevance test and validated as being very relevant to the analysis performed in this review.

RESULTS AND DISCUSSION

The literature review shows that there are some major findings about the Mass Attenuation Coefficient (MAC). Most of the studies researched (26 found) come to the conclusion that the MAC values are highly sensitive to the elemental composition of the alloy. In particular, it is possible to achieve enhanced gamma ray attenuation due to the incorporation of elements with high atomic number (high-Z) (including lead, Pb, and tungsten, W) [1][3][16]. One of the most frequent trends in various studies (five studies mentioned) is that the attenuation coefficient is inversely proportional to the photon energy, higher the photon energy, the lower the attenuation coefficient, a fact that was readily confirmed by both experimental and theoretical methods [1][5][17]. Still, in addition to the elemental content, some researchers also highlighted the significant importance of microstructural properties, as such factors as particle size and alloy distribution of the phases in the alloy matrix can have a significant impact on the final MAC values [6][18]. The results are not limited to MAC, but other essential shielding parameters, as explained in the table that summarizes the studied articles. One of them is Radiation Protection Efficiency (RPE), which is repeatedly reported to be high, about 99 percent at low energies, and, similarly to MAC, highly reliant on the concentration of high-Z elements, including Pb, Bi and W [1][11][17]. Therefore, the Half-Value Layer (HVL) exhibits an evident negative correlation with the abundance of such heavy metal elements; the higher the Pb, W, or Er2O3 content, the less material is needed to block radiation [5][19]. One important methodological conclusion in the cumulative literature is the sound establishment of theoretical models. According to the table, there is a high and consistent consistency between the test results and the simulation programs such as XCOM, Geant4, and MCNP, which proves their predictive ability [1][19][20]. Finally, although some of the studies are more composition-based, a significant number of them emphasize the value of microstructural features, specifically stating that the availability of second-phase particles [6] or the regulation of the particle size have a direct effect on attenuation efficiency [18].

TABLE 1. Synthesis of Recent Studies on Gamma Ray Attenuation Parameters.

Study	**Mass Attenuation Coefficient**	**Radiation Protection Efficiency**	**Half-Value Layer**	**Agreement Theoretical-Experimental**	**Microstructural Characteristics**
(aziz et al., 2023) [1]	MAC values consistent across energies, influenced by Pb content	RPE up to ~99% at low energies	HVL decreases with Pb addition	Good agreement between XCOM and experiments	Alloy samples cast with controlled composition; Pb and Cu phases present
(Taqi et al., 2021) [19]	MAC evaluated via Geant4 and XCOM, consistent trends	High RPE observed, dependent on Pb and Cu ratios	HVL inversely related to Pb content	Strong consistency between Geant4, XCOM, and experiments	Alloy microstructure not detailed; focus on compositional effects

Study	Mass Attenuation Coefficient	Radiation Protection Efficiency	Half-Value Layer	Agreement Theoretical-Experimental	Microstructural Characteristics
(El-Samrah et al., 2024) [21]	MAC higher in Al-Cu alloys than Al-Mn due to Cu content	RPE better in Al-2024 alloy with higher Cu	HVL lower for Al-2024 alloy	Theoretical and experimental data aligned	SEM/EDS revealed second-phase particles rich in Cu, affecting shielding
(Saeid, 2010) [8]	MAC measured for Cu-Pb alloys, varying with Pb fraction	RPE improved with increasing Pb content	HVL reduced with Pb increase	Reasonable divergence at low energies, convergence at higher energies	Cylindrical samples with varying Pb content; microstructure not detailed
(Özdemir et al., 2023) [11]	MAC enhanced by Bi doping in barite-polymer composites	RPE highest for Bi-rich ternary composites	HVL lowest for Bi-doped samples	Experimental, WinXCOM, and GEANT4 results compatible	Polymer matrix with barite and Bi fillers; microstructure affects attenuation
(Tabar et al., 2025) [22]	MAC higher in Fe3Cu1C alloy than pure Fe at low energies	RPE near 100% at low energies for both materials	HVL lower for Fe3Cu1C alloy	Geant4 simulation results agree with XCOM	Powder metallurgy produced microstructure with Cu and C doping
(Almisned et al., 2024) [3]	MAC highest in W-based alloys, Pb-Cu alloys moderate	RPE correlates with elastic modulus and composition	HVL lowest in W-based alloys	Computational methods confirm trends	Mechanical properties linked to microstructure and elemental content
("Radiation shielding properties of alumin...", 2023) [23]	MAC varies among Al alloys; Ni-Ti-Al alloy shows best absorption	RPE highest in Ni-Ti-Al among Al alloys	HVL lowest for Ni-Ti-Al alloy	Theoretical calculations used; experimental data limited	Various Al alloys with different elemental compositions studied
(Abdelmonem et al., 2024) [9]	MAC and LAC calculated for Pb-Cd-Ag ternary alloys	RPE good for specific Pb-Cd-Ag compositions	HVL inversely related to Pb content	Phy-X/PSD and MCNP4b results in reasonable agreement	Theoretical study; microstructure not detailed
(Mohammed et al., 2021) [5]	MAC decreases with photon energy; Pb addition increases MAC	RPE increases with Pb content in lead bronze alloys	HVL decreases with Pb addition	Geant4 and XCOM results show good agreement	Simulation study; microstructure not experimentally analyzed
(Sayyed et al., 2019) [17]	MAC measured for various binary alloys; W-containing alloys best	RPE highest in Ta-W alloys	HVL lowest in Ta-W alloys	Experimental and theoretical data consistent	Alloy microstructures influence attenuation; W content critical
(Sayyed et al., 2023) [24]	MAC improves with increasing Ni content in Mg-Ni	RPE enhanced by Ni substitution in	HVL reduced with higher Ni content	Monte Carlo simulations confirm	Alloy composition varied; microstructure

Study	Mass Attenuation Coefficient	Radiation Protection Efficiency	Half-Value Layer	Agreement Theoretical-Experimental	Microstructural Characteristics
	alloys	Mg alloys		trends	effects implied
(Baykal et al., 2024) [20]	MAC evaluated various stainless and Ni-based alloys	RPE highest in Hastelloy C-276 alloy	HVL lowest for Hastelloy C-276	MCNP and Phy-X/PSD results consistent	Alloy microstructures linked to mechanical and shielding properties
(Alzahrani et al., 2022) [25]	MAC highest in Pb- and W-based alloys	RPE peaks at low energy, especially in W-based alloys	HVL lowest in W-based alloys	FLUKA simulations consistent with XCOM data	Alloy microstructure not detailed; focus on elemental composition
(Alım, 2020) [12]	MAC highest in Tin-Silver alloy among studied alloys	RPE is better than Pb metal at low energy for Tin-Silver	HVL lowest for Tin-Silver alloy	Experimental and theoretical results aligned	Alloy microstructure and mechanical properties analyzed
(ALMisned et al., 2021) [26]	MAC and LAC measured for Cu-Zn polymer composites	RPE highest in CuZn20 composite	HVL lowest in CuZn20 composite	Experimental and theoretical data consistent	Polymer composites with brass powders; particle size effects noted
(Günoğlu et al., 2023) [14]	MAC increases with Er2O3 content in ODS alloys	RPE improves with higher Er2O3 concentration	HVL decreases with Er2O3 addition	Experimental and theoretical results agree	SEM shows particle size and distribution changes with Er2O3
(Güler et al., 2023) [27]	MAC highest in Er2O3 reinforced 316L ODS alloys	RPE maximized at 5% Er2O3 dispersion	HVL minimized with Er2O3 addition	Experimental gamma and neutron data consistent	Microstructural analysis confirms oxide dispersion effects
(Singh et al., 2014) [28]	MAC and buildup factors studied for ODS alloys	RPE better in low iron content ODS alloys	HVL lower in ODS alloys with optimized composition	XCOM and Geant4 simulations agree	Alloy microstructure influences shielding and buildup factors
(Avcioglu & Avcıoğlu, 2023)[16]	MAC superior in Re, W, Ta borides compared to Pb	RPE high for transition metal borides at 4 MeV	HVL lower than Pb for some borides	Computational results from Phy-X/PSD and NGCal	Microstructure not experimentally detailed; focus on elemental effects
(Issa et al., 2024)[29]	MAC higher in Bi-Se-Ge glasses than commercial glasses	RPE improved by Bi substitution in glasses	HVL lower than some traditional glasses	Phy-X/PSD theoretical data used	Glass microstructure impacts shielding; no alloy microstructure

Study	Mass Attenuation Coefficient	Radiation Protection Efficiency	Half-Value Layer	Agreement Theoretical-Experimental	Microstructural Characteristics
(El-Agawany et al., 2020)[30]	MAC decreases with CdCl2 doping in Ge-Sb-S glasses	RPE highest in undoped chalcogenide glasses	HVL lowest in undoped glasses	MCNP-5 simulations consistent with XCOM	Glass structure affects attenuation; no alloy microstructure
(KUTU, 2024)[31]	MAC and HVL studied for TeO2-ZnO-NiO system	RPE varies with composition and energy	HVL inversely related to MAC	Phy-X/PSD theoretical calculations	Material microstructure not detailed
(Flemban et al., 2024)[13]	MAC highest in SnBi alloy among SnX alloys	RPE superior in SnBi compared to SnAs, SnSb, SnP	HVL lowest for SnBi alloy	XCOM theoretical data used	Alloy microstructure not experimentally analyzed
(Tashlykov et al., 2017)[32]	MAC optimized for barite, lead, tungsten concentrations	RPE enhanced by high Pb and W content	HVL minimized with optimized compositions	Experimental and computational validation	Microstructure influenced by barite and metal concentrations
(Amirabadi et al., 2013)[15]	MAC and neutron shielding studied for various materials	RPE depends on density and composition	HVL decreases with higher density materials	Experimental data supports shielding design	Microstructure not detailed; focus on material combinations
(Chen et al., 2024)[4]	MAC influenced by high-Z fillers in composites	RPE improved by high-Z element incorporation	HVL reduced with high-Z fillers	Review of experimental and theoretical studies	Composite microstructure critical for shielding efficiency
(Asgari et al., 2021)[18]	MAC enhanced by reducing particle size of heavy metals	RPE improved with nano-sized heavy metal particles	HVL lowered by smaller particle sizes	MCNPX simulations and measurements agree	Particle size and distribution critical microstructural factors

According to the critical analysis presented in Table 2, there is a distinct direction of future research, which would be directly related to the methodological weaknesses of the field. The first urgent thing is the creation of standardized experimental and reporting procedures.

The future work should be directed at the increased homogeneity of samples, detector calibration, and comprehensive errors to eliminate the existing problems of variability of data [8] and make cross-studies workable. The greatest innovation potential, though, is to develop further than the current state of qualitative knowledge on microstructure.

Quantitative correlation between manufacturing processes, resultant microstructural features and shielding efficiency should be prioritized by the researchers. Studies will have to systematically measure such features as the distribution of particle sizes and homogeneity of phases and connect them directly with attenuation performance instead of merely observing the presence of second-phase particles [21].

Lastly, the only way to close the gap between theory and practice is to ensure that future models not only explore the noticed differences in the simulation at particular energies, but also routinely include detailed analysis of buildup factors and secondary radiation effects, both of which are key parameters in the real-world design of shielding, but which are often ignored in the literature [1].

TABLE 2. Critical Synthesis of Methodological Strengths and Limitations in the Reviewed Literature

Aspect	**Strengths**	**Weaknesses**
Experimental Methodologies	Many studies employ robust experimental setups using gamma spectrometry with NaI(Tl) or HPGe detectors, enabling precise measurement of attenuation parameters at multiple photon energies. The use of narrow beam geometry and multiple isotopic sources enhances data reliability [1][11][21].	Experimental conditions vary widely, including differences in sample preparation, thickness, and detector calibration, which complicates cross-study comparisons. Some studies report limited energy ranges or lack detailed error analysis, reducing reproducibility[8][8].
Theoretical and Simulation Models	The integration of theoretical calculations using XCOM and Monte Carlo simulations (Geant4, MCNP) provides comprehensive validation of experimental results. Consistent agreement between these methods strengthens confidence in reported shielding parameters [1][5][11][19].	Despite overall agreement, discrepancies at certain photon energies (e.g., 0.511 MeV and 0.662 MeV) suggest limitations in modeling assumptions or experimental uncertainties. Some studies do not fully address these divergences or explore their origins [8].
Compositional Influence on Shielding Efficiency	Research consistently shows that increasing high-Z element content, particularly Pb and Cu, enhances mass attenuation coefficients and reduces half-value layers, improving shielding performance [1][8][11]. The ternary Al-Cu-Pb alloys demonstrate superior gamma attenuation compared to binary or pure metals [1][21].	The compositional optimization is often empirical, with limited systematic studies on the interplay between alloying elements. The influence of minor elements or impurities is rarely quantified, and compositional ranges studied are sometimes narrow [1][8].
Microstructural and Elemental Effects	Studies employing SEM and EDS reveal that microstructural features such as second-phase particles, particle size, and distribution significantly affect radiation shielding by influencing density and elemental homogeneity [21]. Better particle-matrix adhesion correlates with improved shielding efficiency [21].	Microstructural analyses are often qualitative, lacking quantitative correlation with shielding parameters. The impact of manufacturing processes on microstructure and subsequent shielding performance is underexplored, limiting mechanistic understanding [21].
Energy Range and Shielding Parameter Evaluation	The literature covers a broad photon energy spectrum (from tens of keV to several MeV), allowing assessment of shielding behavior across relevant application scenarios [1][11][19]. Parameters such as mass attenuation coefficient, HVL, MFP, and radiation protection efficiency are comprehensively evaluated [1][11].	Some studies focus on limited energy ranges or specific isotopes, which may not capture the full shielding performance spectrum. Additionally, buildup factors and secondary radiation effects are less frequently addressed, which are critical for practical shielding design [1][11].
Comparison with Other Materials	Ternary Al-Cu-Pb alloys are benchmarked against traditional materials like pure Pb, Cu, and Al, demonstrating competitive or superior shielding efficiency with potential advantages in weight and cost [1][7]. The alloys also show promise compared to polymer composites and other ternary systems [1][26].	Comparative analyses are sometimes limited by inconsistent experimental conditions or lack of standardized metrics. Environmental and mechanical property considerations are often secondary, despite their importance

Aspect	Strengths	Weaknesses
		for practical applications [1][3].
Data Quality and Reporting	Many studies provide detailed quantitative data with cross-validation between experimental and theoretical results, enhancing data credibility [1][11][19]. The use of multiple measurement techniques and simulation codes strengthens conclusions.	Reporting inconsistencies, such as incomplete error margins, lack of raw data availability, and insufficient methodological details, hinder meta-analyses and replication efforts. Some older studies show divergence in data quality standards[8].

CONCLUSION AND RECOMMENDATIONS

Literature analysis has established that the attenuation properties of Al-Cu-Pb alloys, including the Mass Attenuation Coefficient (MAC) and Radiation Protection Efficiency (RPE), are highly related to the elemental composition, especially the concentration of high-Z elements, e.g. lead (Pb) and copper (Cu). These high atomic number elements are included and this has led to better gamma ray attenuation. Another trend that can be identified in many studies is the inversely related correlation between the MAC and incident photon energy; with an increase in photon energy, the attenuation coefficient decreases, which has been proven by experimental and theoretical methods. The Protection Efficiency is always reported to be high, with a potential of nearly penetrating 99% in low energies and also the components are radiation sensitive just like the high Z ones. The Half-Value Layer (HVL) has therefore a direct negative correlation with the occurrence of these heavy elements. In addition to elemental content, a number of studies highlighted the vital importance of microstructural features with references to such factors of the alloy matrix being the particle size and the distribution of phases in the alloy matrix playing a significant role in determining the ultimate MAC values. Another major methodological finding of the collective literature has been the strong validation of theoretical models, with much strong and consistent agreement observed between experimental and simulation data, using XCOM, Geant4 and MCNP, and demonstrating their predictive ability.

Following the critical analysis, a definite direction on the way forward of future research can be observed with the aim of fixing the given methodology weaknesses. Standardized experimental and reporting protocols are the most urgent requirement. The way forward should be increased consistency in the sample preparation, detector calibration and elaborate analysis of the errors to correct the existing problems with the variability of the data and position future cross-study comparisons with confidence. The greatest innovation potential is the further development of the current qualitative knowledge of microstructure. The quantitative relationship between manufacturing processes, resultant microstructural and shielding efficiency should be the priority of the researchers. It involves the systematic investigation of the influence of various manufacturing methods on the evolution of microstructure, the quantification of such characteristics as the particle size distribution and phase homogeneity in order to correlate them with attenuation performance. In order to fill the gap between theory and experiment, future modeling work should not only examine discrepancies in observations of simulations at any single energy but also include regularly in any such work the full appraisal of the effects of buildup and secondary radiation, which are important in the real-world design of shielding structures but were often not considered. Moreover, research must be expanded to include more photon energy that is applicable in nuclear and medical systems. Lastly, the synergies of mechanical properties and shielding efficiency, and life cycle and cost-benefit analysis of the environmental impact, toxicity, and cost-effectiveness of Al-Cu-Pb alloys should be done in the future to support sustainable development.

REFERENCES

1. K. A. A. Aziz, M. A. Hamood, L. N. Najam, A. A. Sawalha, and H. Ahmed, "Shielding properties of al- cu- pb alloys by xcom and experimental data," Rafidain J. Sci., vol. 32, no. 2, pp. 32–39, 2023, doi: 10.33899/rjs.2023.178582.
2. Y. Wu and Z. Wang, "Progress in ionizing radiation shielding materials," Adv. Eng. Mater., 2024, Art. no. 202400855, doi: 10.1002/adem.202400855.

3. G. Almisned, G. Susoy, D. S. Baykal, H. Alkarrani, Ö. Güler, and H. O. Tekin, "A closer-look on w and pb alloys: In-depth evaluation in elastic modulus, gamma-ray, and neutron attenuation for critical applications," Nucl. Eng. Des., 2024, Art. no. 113063, doi: 10.1016/j.nucengdes.2024.113063.

4. Z. Chen, Z. Huo, H. Zhang, and G. Zhong, "Gamma ray shielding composite material with high z number," Polym. Commun., 2024, doi: 10.7536/pc231105.

5. H. N. Mohammed, A. H. Taqi, and A. M. Ghalib, "Simulation of the gamma absorption by lead bronze alloys using geant4," Rafidain J. Sci., vol. 30, no. 2, pp. 1–10, 2021, doi: 10.33899/RJS.2021.168338.

6. M. G. El-Samrah, I. M. Nabil, M. Shamekh, M. Elmasry, and M. Osman, "Microstructure and radiation shielding capabilities of al-cu and al-mn alloys," Sci. Rep., vol. 14, no. 1, 2024, Art. no. 25925, doi: 10.1038/s41598-024-76177-4.

7. M. A. B. Aziz, M. F. Rahman, and M. M. H. Prodhan, "Comparison of lead, copper and aluminium as gamma radiation shielding material through experimental measurements and simulation using mcnp version 4c," Int. J. Contemp. Res. Rev., vol. 9, no. 8, 2018, doi: 10.15520/ijcrr/2018/9/08/584.

8. K. S. Saeid, "On the utilization of ((1-x)Cu-xPb) alloys for γ-ray shielding," J. Radioanal. Nucl. Chem., vol. 285, pp. 627–631, 2010, doi: 10.1007/s10967-010-0570-8.

9. A. M. Abdelmonem, A. M. Osman, and A. M. Ali, "Computing the gamma-ray, charged particles and fast neutron-shielding performances of selected alloys," Radiat. Eff. Defects Solids, 2024, doi: 10.1080/10420150.2024.2332193.

10. H. Özdemir, M. Kaçal, F. Akman, and H. Polat, "Alternative gamma-ray shielding material: Ternary composite including polyester resin/barite/molybdenum," Nucl. Eng. Technol., 2025, Art. no. 103512, doi: 10.1016/j.net.2025.103512.

11. H. G. Özdemir, M. Kaçal, F. Akman, H. Polat, and O. Agar, "Investigation of gamma radiation shielding characteristics of bismuth reinforced ternary composites in wide photon energy region," Radiat. Phys. Chem., vol. 208, 2023, Art. no. 110924, doi: 10.1016/j.radphyschem.2023.110924.

12. B. Alım, "A comprehensive study on radiation shielding characteristics of tin-silver, manganin-r, hastelloy-b, hastelloy-x and dilver-p alloys," Appl. Phys. A, vol. 126, no. 4, pp. 1–19, 2020, doi: 10.1007/s00339-020-3442-7.

13. T. H. Flemban et al., "Gamma attenuation and radiation shielding performance of snx (x = as, bi, p, and sb) monolayers," Radiat. Phys. Chem., 2024, Art. no. 111594, doi: 10.1016/j.radphyschem.2024.111594.

14. K. Günoğlu et al., "A comprehensive microstructural and transmission analysis on oxide dispersion-strengthened (ods) alloys: Impact of erbium oxide (ero) concentration on physical, structural, gamma-ray, and neutron attenuation properties," 2Ceram. Int., 2023, doi: 10.1016/j.ceramint.2023.12.360.

15. E. A. Amirabadi, M. Salimi, N. Ghal-Eh, G. R. Etaati, and H. Asadi, "Study of neutron and gamma radiation protective shield," Int. J. Innov. Appl. Stud., vol. 3, no. 4, pp. 1079–1085, 2013.

16. C. Avcioglu and S. Avcıoğlu, "Transition metal borides for all-in-one radiation shielding," Materials, vol. 16, no. 19, 2023, Art. no. 6496, doi: 10.3390/ma16196496.

17. M. Sayyed, F. Akman, and M. R. Kaçal, "Experimental investigation of photon attenuation parameters for different binary alloys," Radiochim. Acta, vol. 107, no. 4, pp. 339–348, 2019, doi: 10.1515/ract-2018-3079.

18. M. Asgari, H. Afarideh, H. Ghafoorifard, and E. A. Amirabadi, "Effects of particle size and weight percentage of heavy metal elements on photon shielding efficiency of reinforced polymer composites," Iran. J. Radiat. Res., vol. 19, no. 1, pp. 55–61, 2021, doi: 10.29252/ijrr.19.1.55.

19. A. H. Taqi, A. M. Ghalib, and H. N. Mohammed, "Shielding properties of cu-sn-pb alloy by geant4, xcom and experimental data," Mater. Today Commun., vol. 26, 2021, Art. no. 101996, doi: 10.1016/j.mtcomm.2020.101996.

20. D. Ş. Baykal, G. ALMisned, H. Alkarrani, and H. Tekın, "Exploring gamma-ray and neutron attenuation properties of some high-density alloy samples through mcnp monte carlo code," Int. J. Comput. Exp. Sci. Eng., vol. 10, no. 3, 2024, doi: 10.22399/ijcesen.422.

21. M. G. El-Samrah, I. M. Nabil, M. E. Shamekh, M. Elmasry, and M. Osman, "Microstructure and radiation shielding capabilities of Al-Cu and Al-Mn alloys," Sci. Rep., 2024, doi: 10.1038/s41598-024-76177-4.

22. E. Tabar, G. Hoşgör, M. R. Ekici, C. Aydin, and İ. Muttaki, "Investigation of radiation shielding properties of pure iron and coppercarbon-doped iron material with geant4," J. Nucl. Sci. (Ankara), 2025, doi: 10.59474/nuclear.2023.64.

23. P. Limkitjaroenporn et al., "Radiation shielding properties of aluminium alloys," Radiat. Eff. Defects Solids, 2023, doi: 10.1080/10420150.2023.2249180.

24. M. Sayyed, K. A. Mahmoud, F. Q. Mohammed, and K. M. Kaky, "A comprehensive evaluation of mg-ni based alloys radiation shielding features for nuclear protection applications," Nucl. Eng. Technol., 2023, doi: 10.1016/j.net.2023.12.040.

25. J. S. Alzahrani, Z. A. Alrowaili, C. Eke, Z. M. M. Mahmoud, C. Mutuwong, and M. Al-Buriahi, "Nuclear shielding properties of ni-, fe-, pb-, and w-based alloys," Radiat. Phys. Chem., vol. 195, 2022, Art. no. 110090, doi: 10.1016/j.radphyschem.2022.110090.

26. G. ALMisned et al., "Novel cu/zn reinforced polymer composites: Experimental characterization for radiation protection efficiency (rpe) and shielding properties for alpha, proton, neutron, and gamma radiations," Polymers, vol. 13, no. 18, 2021, Art. no. 3157, doi: 10.3390/polym13183157.

27. S. H. Güler et al., "Fabrication and structural, physical, and nuclear radiation shielding properties for oxide dispersion-strengthened (ods) alloys through erbium (iii) oxide, samarium (iii) oxide, and praseodymium (iii) oxide into 316l matr1ix," Ceram. Int., 2023, doi: 10.1016/j.ceramint.2023.11.295.

28. V. P. Singh, V. P. Singh, M. Medhat, and N. Badiger, "Gamma-ray shielding effectiveness of some alloys for fusion reactor design," J. Fusion Energy, vol. 33, no. 5, pp. 555–564, 2014, doi: 10.1007/s10894-014-9704-7.

29. S. Issa, M. U. Khandaker, A. Badawi, and H. M. Zakaly, "Enhanced gamma-ray shielding capabilities of bi-se-ge chalcogenide glasses: Analytical and simulation insights," Phys. Scr., 2024, doi: 10.1088/1402-4896/ad6c89.

30. F. El-Agawany, K. Mahmoud, E. Kavaz, R. El-Mallawany, and Y. Rammah, "Evaluation of nuclear radiation shielding competence for ternary ge–sb–s chalcogenide glasses," Appl. Phys. A, vol. 126, no. 4, pp. 1–11, 2020, doi: 10.1007/s00339-020-3426-7.

31. N. Kutu, "Gamma ray shielding properties of the 57.6teo2-38.4zno-4nio system," Int. J. Comput. Exp. Sci. Eng., vol. 10, no. 2, 2024, doi: 10.22399/ijcesen.310.

32. O. L. Tashlykov, S. E. Shcheklein, I. M. Russkikh, E. N. Seleznev, and A. V. Kozlov, "Composition optimization of homogeneous radiation-protective materials for planned irradiation conditions," At. Energy, vol. 121, no. 4, pp. 303–307, 2017, doi: 10.1007/s10512-017-0202-7.