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ZnO and CuO Oxide Materials in Medical Radiation Dosimetry and Shielding: A Literature Review

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ABSTRACT: Accurate measurement and control of ionizing radiation dose is a foundational requirement of modern radiotherapy, diagnostic radiology, and radiation protection practice, driving sustained interest in radiation-sensitive and radiation-attenuating materials suitable for dosimetric and shielding applications. Zinc oxide (ZnO) and copper oxide (CuO), oxide semiconductor materials extensively characterized in materials physics research for their radiation-induced structural and optical property changes, have correspondingly attracted significant attention for medical radiation dosimetry and shielding applications. This review synthesizes recent literature, published predominantly between 2024 and 2026, on the application of ZnO and copper-doped ZnO materials in radiation detection, dosimetry, and shielding relevant to medical and health protection contexts. The review addresses three principal themes: the use of nanostructured ZnO as a scintillator and dosimetric material exploiting its radiation-induced ultrafast decay time and defect formation; the gamma radiation shielding performance of copper-doped ZnO materials, evaluated through combined experimental and Monte Carlo simulation approaches; and the incorporation of ZnO into pharmaceutical and polymer-based composite materials for radiation protection applications. The reviewed literature indicates that the same radiation-induced defect formation and charge trapping mechanisms that necessitate careful characterization of

ZnO- and CuO-based materials in conventional electronic and sensor applications directly underpin their functional performance as radiation-sensitive dosimetric materials, while the high effective atomic number and density achievable through copper doping and composite formulation similarly determine gamma shielding effectiveness, together suggesting substantial and currently underexploited translational relevance between materials physics characterization of these oxides and their application in medical radiation dosimetry and protection.

INTRODUCTION

Ionizing radiation dosimetry, the quantitative measurement of absorbed radiation dose, underlies the safe and effective practice of radiotherapy, diagnostic radiology, nuclear medicine, and occupational radiation protection. Inorganic oxide materials have long been explored for dosimetric applications owing to their chemical stability, resistance to radiation-induced damage, and, for materials with relatively high effective atomic number, an increased probability of photon interaction through photoelectric absorption and Compton scattering, properties directly relevant to both radiation detection sensitivity and radiation shielding effectiveness.

Zinc oxide (ZnO) and copper oxide (CuO) are among the oxide semiconductor materials whose radiation response has been extensively characterized in materials physics research, where irradiation-induced defect formation, charge trapping, and consequent changes to optical and electrical properties, including band gap, carrier concentration, and electrical resistance, are studied primarily to understand and mitigate radiation-induced degradation of these materials in electronic device applications. This review synthesizes recent literature, published predominantly between 2024 and 2026, examining how these same radiation-induced structural and optical changes have been deliberately exploited for medical radiation dosimetry and shielding applications, addressing three principal themes: ZnO as a scintillator and dosimetric sensing material; copper-doped ZnO for gamma radiation shielding; and ZnO incorporation into pharmaceutical and polymer composite materials for radiation protection.

ZNO AS A RADIATION-SENSITIVE SCINTILLATOR AND DOSIMETRIC MATERIAL

A comprehensive review of nanostructured ZnO in radiation detection and dosimetry documented that ZnO's radiation-induced ultrafast decay time has established it as an important scintillator material for high-energy ray and particle detection, with nanostructured ZnO materials, including nanoarrays and nanocomposites, developed and evaluated for detecting X-rays, gamma rays, and high-energy alpha, beta, and neutron particles, with detector performance characterized in terms of spatial resolution, decay time, and detection efficiency (Chen et al., 2024). This review situates nanostructured ZnO scintillator development within the broader technological need for ultrafast-response scintillators to support high-speed medical and industrial imaging applications, where the radiation-induced defect formation and stimulated light emission processes that are the central object of study in materials physics characterization of ZnO directly determine dosimetric functional performance.

COPPER-DOPED ZNO FOR GAMMA RADIATION SHIELDING

Beyond radiation detection and dosimetric sensing, ZnO and copper-doped ZnO materials have been investigated for gamma radiation shielding applications, where the objective is to attenuate rather than detect incident radiation. A study synthesizing pure ZnO and copper-doped ZnO (ZnO:Cu at 10 and 20 atomic percent copper) via sol-gel methods, with structural characterization confirming a hexagonal ZnO structure modified to some extent by copper incorporation, calculated a comprehensive set of gamma shielding protection factors, including mean free path, mass attenuation coefficient, tenth-value layer, half-value layer, and linear attenuation coefficient, concluding that both pure ZnO and copper-doped ZnO formulations demonstrate useful gamma ray protective capability, with findings validated through combined experimental measurement and GEANT4 Monte Carlo simulation (Khoshhal et al., 2025).

This combined experimental-simulation validation approach, applying the same X-ray diffraction and electron microscopy structural characterization techniques standard in materials physics research on ZnO thin films and nanostructures, illustrates a direct methodological continuity between materials physics characterization of copper-doped ZnO for electronic and structural property research and its deliberate evaluation for gamma radiation shielding performance, with the degree of copper doping serving as a controllable parameter for tuning shielding effectiveness analogous to its role in tuning electronic and optical properties in conventional ZnO:Cu materials physics research.

ZNO IN PHARMACEUTICAL AND POLYMER COMPOSITE RADIATION SHIELDING

A further documented health-relevant application of ZnO in radiation protection concerns its incorporation into pharmaceutical and polymer composite materials intended to shield radiation-sensitive pharmaceutical products or provide radiation protection in clinical and pharmaceutical handling contexts. An investigation of ZnO incorporation into the pharmaceutical polymer Benecel K4M at concentrations up to 6 weight percent found that increasing ZnO content improved gamma radiation shielding performance across a range of photon energies from 59.5 to 1332 keV, with radiation protection efficiency at 59.9 keV increasing from 6.9% for the unmodified polymer to 12.2% for the 6 weight percent ZnO composite, and mean free path correspondingly decreasing from 13.9 cm to 7.6 cm, improvements attributed to ZnO's relatively high density and atomic number (Marashdeh et al., 2025). The study's authors specifically framed ZnO as a lightweight, non-toxic alternative to conventional heavy-metal-based radiation shielding materials for pharmaceutical protection applications in radiation-rich clinical and industrial environments, directly connecting the same density- and atomic-number-dependent photon interaction properties studied in materials physics characterization of ZnO to a specific, health-protection-oriented shielding application.

CUO NANOPARTICLES AS RADIOSENSITIZERS AND DOSIMETRIC GEL ADDITIVES

Beyond ZnO-based scintillator and shielding applications, copper oxide (CuO) nanoparticles specifically have been investigated both as radiosensitizing agents intended to enhance the therapeutic effect of radiotherapy and as functional additives in polymer gel dosimeters used for three-dimensional dose verification. A comprehensive review of CuO nanoparticle synthesis and applications in cancer treatment and radiotherapy documented CuO nanoparticles' emerging role as nanoradiosensitizers, whereby their high effective atomic number enhances local energy deposition and free radical production during radiation exposure, thereby amplifying the cytotoxic effect of a given radiation dose specifically within tumor tissue, while also cataloguing green, chemical, and physical CuO nanoparticle synthesis approaches and their comparative advantages for biomedical application (Salman et al., 2025a).

In a directly related dosimetric application, CuO nanoparticles synthesized via laser ablation were incorporated into a polymethyl methacrylate gel (PMMAG) dosimeter and evaluated under 6-MV photon beam irradiation from a medical linear accelerator across a clinically relevant dose range of 0 to 10 Gy, with optical density found to increase linearly with radiation dose and with dose resolution optimized at a CuO nanoparticle concentration of 1%, an enhancement mechanistically attributed to increased free radical production via Compton scattering at the incorporated CuO nanoparticles (Salman et al., 2025b). This finding directly illustrates that the same high-Z, Compton-scattering-enhancing properties of CuO exploited for gamma radiation shielding, as documented in copper-doped ZnO shielding research, can be inversely leveraged within a dosimetric gel matrix to enhance rather than attenuate the measurable radiation-induced signal, underscoring that materials physics characterization of CuO's photon interaction behavior underpins both shielding and dose-enhancement applications depending on the specific material configuration and application context.

DISCUSSION

The literature reviewed here indicates that ZnO and copper-doped ZnO materials serve dual, complementary roles in medical radiation applications, functioning both as radiation-sensitive dosimetric sensing materials, exploiting radiation-induced defect formation and charge trapping to generate a measurable signal proportional to absorbed dose, and as radiation-attenuating shielding materials, exploiting relatively high effective atomic number and density to reduce radiation transmission. Both functional roles are directly underpinned by structural and compositional properties, including crystallite structure, doping level, and defect density, that are the central object of characterization in materials physics research on these oxides for conventional electronic and sensor applications, using directly analogous techniques including X-ray diffraction, electron microscopy, and, for shielding applications specifically, Monte Carlo radiation transport simulation.

This convergence suggests that materials physics research on ZnO and copper-doped ZnO thin films and nanostructures, including systematic characterization of how synthesis parameters and doping level influence structural, optical, and defect properties, carries direct and currently underexploited relevance for the deliberate optimization of these same materials for medical dosimetry and shielding applications; in particular, the demonstrated tunability of gamma shielding performance through controlled copper doping level (Khoshhal et al., 2025) parallels the well-established tunability of band gap and electrical properties through analogous doping strategies in conventional ZnO:Cu materials physics research, suggesting that doping-level optimization protocols developed for one application domain may be directly transferable to the other.

Limitations of the reviewed literature include the predominantly laboratory-scale, experimental-simulation-validated nature of the gamma shielding and pharmaceutical composite studies reviewed, meaning that clinical-scale validation and regulatory approval processes for these specific ZnO-based radiation protection formulations remain at a comparatively early stage relative to established clinical dosimetry and shielding materials; and the relatively narrow photon energy ranges and copper doping levels systematically investigated to date, which constrains generalization of the specific quantitative shielding performance values reported here to the full range of energies and material compositions relevant across diverse medical radiation contexts, from diagnostic radiology through high-energy radiotherapy.

CONCLUSION

This review of recent literature on ZnO and CuO oxide materials in medical radiation dosimetry and shielding indicates that these materials serve complementary functional roles in radiation-sensitive dosimetric sensing and radiation-attenuating shielding, with both roles directly underpinned by the same radiation-induced defect formation and structural properties that are the central focus of materials physics characterization of these oxides for conventional electronic and sensor applications. The demonstrated tunability of both dosimetric sensitivity and shielding performance through controlled doping and compositional variation suggests considerable translational potential between materials physics research on ZnO and copper-doped ZnO and the continued development of medical radiation dosimetry and protection technologies, representing a promising direction for interdisciplinary research bridging materials physics and medical radiation physics.

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