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Advances in Zero-Dimensional Hybrid Antimony Halides: Structural Property Relationships for High-Performance X-ray Detection

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Abstract

Zero-dimensional (0D) hybrid antimony halides have recently emerged as a promising class of lead-free materials for next-generation X-ray detection. Their unique structural motif comprising isolated Sb - halide clusters confined within an organic or inorganic matrix creates highly localized electronic states that enable strong radiative recombination, suppressed ion migration, and excellent environmental stability. These structures collectively address the long-standing limitations of conventional perovskite - based detectors, such as toxicity, instability, and signal noise under prolonged irradiation. This review highlights recent advances in understanding the structure property relationships that govern the X-ray response of 0D antimony halides. Main factors include the role of the Sb^{3+} $5s^2$ lone-pair electrons in dictating optical absorption and exciton behavior, the influence of cluster geometry on charge-carrier trapping, and the impact of organic spacers on thermal and mechanical robustness. We further discuss how compositional engineering, ligand modification, and dimensional confinement strategies enhance X-ray attenuation, light yield, carrier mobility, and response linearity. Emerging device demonstrations show that 0D hybrid antimony halides can achieve high sensitivity, low detection limits, and stable operation under low - dose irradiation, making them strong contenders for medical imaging, nondestructive testing, and security technologies. By connecting atomic-scale structure with macroscopic performance metrics, this review provides a comprehensive foundation for designing optimized 0D antimony halide materials and accelerating their translation into practical, high-performance X-ray detection platforms.

Keywords: X-ray detection, antimony halides, Zero - dimensional material, structural properties.

1. Introduction

X-ray detection technologies are indispensable across a wide range of fields, including medical imaging, nondestructive industrial testing, environmental monitoring, security screening, and scientific instrumentation. Traditional X-ray detectors rely heavily on crystalline inorganic scintillators, amorphous semiconductors, or bulky photoconductive materials that often require high operating voltages, involve complex fabrication steps, or depend on toxic heavy metals. As demand grows for lightweight, low-dose, flexible, and environmentally benign X-ray detection platforms, the development of new functional materials capable of surpassing the limitations of conventional systems has become a critical research priority. In recent years, metal halide semiconductors have emerged as leading candidates for next-generation optoelectronic devices. Among them, lead-halide perovskites initially received tremendous attention due to their excellent photophysical properties, high mobility–lifetime products, strong absorptivity, and tunable bandgaps. However, their practical deployment in X-ray detection is hindered by two major challenges: intrinsic instability, especially under ionizing radiation, heat, and moisture; and lead toxicity, which raises serious environmental and biomedical concerns [1]. These limitations have stimulated significant interest in exploring lead-free alternatives that can maintain, or even improve upon, the functional advantages of perovskites without compromising safety and reliability. Within this context, zero-dimensional (0D) hybrid antimony halides have emerged as one of the most promising material families. Their distinctive structural configuration, composed of

isolated antimony - halide clusters encapsulated within organic or inorganic frameworks, creates a unique combination of electronic localization, exciton confinement, and structural rigidity. A defining feature of these materials is the complete spatial isolation of the Sb-halide polyhedra, which fundamentally suppresses long-range charge migration and minimizes defect-driven non-radiative losses [2]. This 0D architecture also mitigates ion migration, a common degradation mechanism in 3D perovskites, thereby ensuring superior operational stability under continuous X-ray exposure.

Antimony itself plays a central role in shaping the photo physics of these materials. The ns^2 ($5s^2$) electronic configuration of Sb^{3+} gives rise to strong spin–orbit coupling, tunable band structures, and characteristic self-trapped exciton (STE) emissions. These properties contribute to efficient radioluminescence and enhanced scintillation behavior, both of which are crucial for accurate X-ray detection. Furthermore, antimony-based materials offer an environmentally safer and more sustainable alternative to lead-containing compositions, aligning with global efforts toward greener electronic technologies [3]. Beyond compositional safety, structure property relationships in 0D hybrid antimony halides have become a major focus of current research. Several key structural factors influence their X-ray response, including the size and geometry of the Sb - halide clusters, the chemical nature of the surrounding organic spacers, and the extent of electronic confinement within the 0D environment. The interplay of these elements determines essential properties such as exciton binding energy, charge-carrier recombination pathways, and luminescence efficiency. Understanding these relationships is essential for rational material design and targeted improvements in detector performance [4].

A number of material engineering strategies have recently been explored to enhance the performance of 0D antimony halides. Compositional engineering including halide mixing, metal-site substitution and cluster-modulating chemical reactions has enabled fine control over bandgap tuning, X-ray attenuation coefficients, and scintillation intensity. Meanwhile, ligand engineering has proven effective in improving material robustness, reducing defect densities, and modulating exciton behavior. Advanced synthetic routes such as solvent engineering, hot-injection crystallization, and template-assisted assembly have further supported the formation of high-quality crystals with superior optical and mechanical properties. Together, these developments have significantly expanded the functional utility of 0D antimony halides for X-ray detection. Recent device studies highlight the remarkable capabilities of these materials. 0D antimony-halide-based detectors have demonstrated high sensitivity, ultralow detection limits, improved signal-to-noise ratios, and outstanding stability under low-dose irradiation. Their strong X-ray attenuation, driven by the relatively high atomic number of antimonies, enables efficient photon-to-electron conversion even in thin-film or low-density formats [5]. Moreover, the suppressed ion migration and reduced dark current noise inherent to the 0D structure contribute to superior long-term operational stability an essential requirement for practical deployment in clinical or industrial environments.

The rapid progress in this field reflects a growing recognition of the unique advantages offered by 0D hybrid antimony halides. Unlike their higher-dimensional perovskite counterparts, these materials combine wide structural tunability, low toxicity, inherent robustness, and exceptional photophysical characteristics in a single, design-flexible platform. Their ability to convert X-ray photons into strong luminescent or electrical signals with high fidelity makes them particularly attractive for next-generation radiation-sensing technologies [6]. Despite these advances, several challenges remain. The mechanisms governing self-trapped exciton formation, carrier dynamics under ionizing radiation, and long-term stability pathways require further investigation. Additionally, consistent upscaling of material synthesis, device integration, and encapsulation strategies will be essential for transitioning these materials from laboratory demonstrations to commercial applications. Understanding how subtle structural variations influence performance metrics will also guide the development of standardized design rules for optimized detector designs [7]. Taken together, the rapid evolution of zero-dimensional hybrid antimony halides underscores their significant potential as high-performance, eco-safe, and technologically versatile materials for X-ray detection. By bridging atomic-level chemistry with macroscopic device engineering, current research efforts are laying the foundation for practical, durable, and high-sensitivity X-ray detectors suited for diverse real-world applications. This introduction therefore aims to provide a comprehensive overview of the fundamental structural characteristics, photophysical mechanisms, material engineering strategies, and emerging device applications that define the current state of the art in 0D hybrid antimony-halide-based X-ray detection.

2. X-ray Detection Principle

The luminescence mechanism of scintillators can be broadly divided into three fundamental stages energy conversion, carrier transport, and radiative recombination (Figure 1). In the initial energy conversion stage, high-energy X-ray photons interact with the host lattice primarily through the photoelectric effect and Compton scattering, generating cascades of hot electrons and deep core holes. These energetic primary carriers rapidly induce secondary electron multiplication via Coulomb interactions, continuing until their kinetic energies fall below the lattice

ionization threshold. Once this avalanche process subsides, the system enters the carrier transport stage. Here, energetic carriers lose momentum through electron - phonon coupling as they migrate across the lattice. During migration, a fraction of carriers becomes trapped by intrinsic or extrinsic defect sites such as halide vacancies, dislocations, grain boundaries, or impurity centers leading to nonradiative recombination and quenching losses [8, 9]. The remaining free carriers that successfully avoid these traps eventually recombine radiatively at designated luminescence centers. In the final radiative recombination stage, these carriers emit photons spanning the ultraviolet, visible, or near-infrared range. These emitted photons are subsequently collected and converted into electrical signals by a photodetector, enabling high-resolution detection and imaging. It is important to note that this relatively straightforward picture is characteristic of inorganic scintillators. In contrast, organic and amorphous scintillators often exhibit more intricate photophysical behavior, involving exciton dynamics, molecular orbital transitions, and π-π interactions* rather than purely lattice-based carrier processes.

Different metal-centered luminescence systems such as those incorporating Mn^{2+}, Sb^{3+}, Sn^{2+}, or Eu^{3+} ions display diverse emission mechanisms. For instance, Mn^{2+} typically emits through spin and parity-allowed d–d transitions, while Sb^{3+}-based complexes frequently exhibit self-trapped exciton (STE) emission driven by their characteristic $5s^2$ lone-pair electrons. In low-dimensional metal halides, Sb^{3+} demonstrates particularly intriguing optical properties originating from the stereochemically active $5s^2$ lone pair, which strongly interacts with the surrounding halide coordination field. This lone-pair activity places Sb^{3+} in a delicate position between dynamically distorted (as in $6s^2$ cations) and statically distorted (as in $4s^2$ cations) electronic configurations. Such behavior significantly enhances lattice deformation and exciton self-trapping, especially in zero-dimensional (0D) metal-halide frameworks, where isolated $[SbX_6]$ units (X - halogen) promote highly localized excitons. Consequently, 0D Sb-based materials exhibit intense, broadband STE emission, strong structural rigidity, suppressed nonradiative pathways, and high stability attributes that make them highly promising candidates for next-generation scintillation and X-ray detection applications.

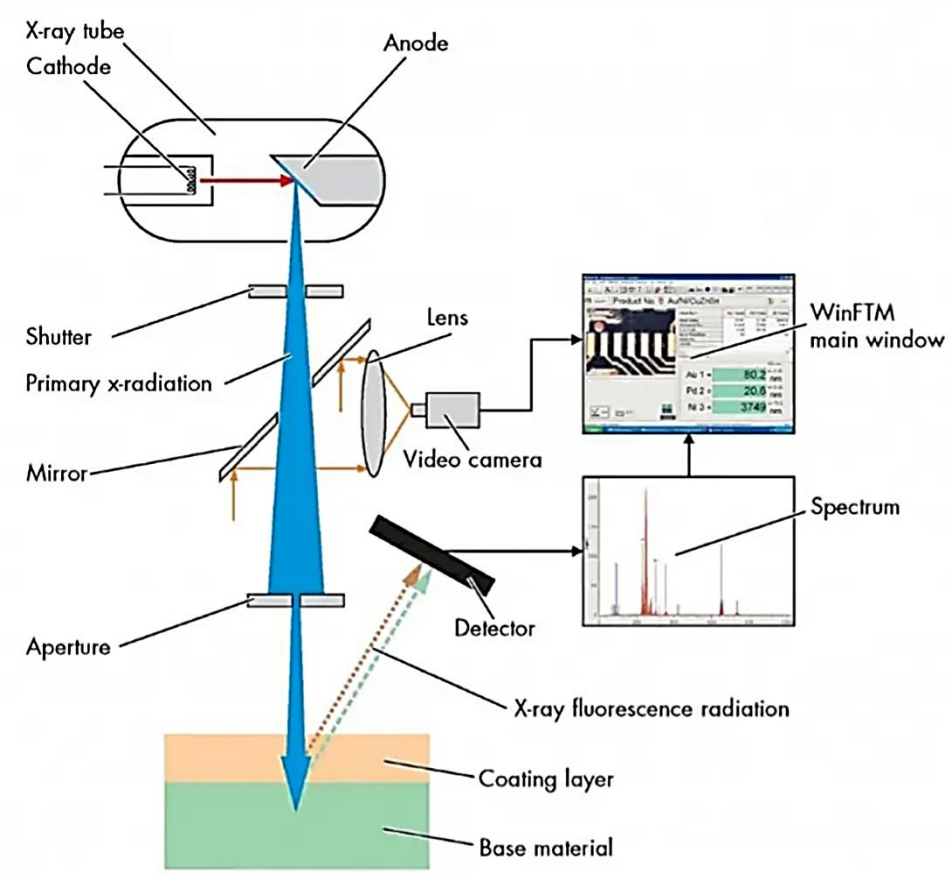

Figure 1. Mechanism of operation of an indirect X-ray detector and the principle of luminescence of a hybridized antimony-based scintillator

3. Design Strategy for Zero-Dimensional Hybrid Antimony-Based Scintillators

The operational principle of an indirect X-ray detector can be understood through two interconnected aspects: (a) the fundamental scintillation mechanism and (b) the luminescence behavior of antimony-based hybrid scintillators. Zero-dimensional (0D) antimony halides represent a rapidly emerging class of scintillation materials whose performance arises from their unique structural and photophysical attributes. Their isolated inorganic units, coupled with strongly localized excitons, offer an advantageous platform for high-efficiency X-ray detection. A key component of designing high-performance Sb^{3+}-based hybrid scintillators lies in precise structural regulation, particularly through solvent engineering. Studies such as those by Xing et al. demonstrate that selecting appropriate solvents including DMF and CAN can significantly influence crystal growth pathways [10]. Because antimony halides possess a large lattice volume, strong electron - phonon coupling, and inherently robust optical stability, tailoring the crystallization environment is essential. Optimized solvent environments can stabilize desirable crystal structures and thereby enhance scintillation properties.

3.1. Exciton Dynamics and STE Formation

When Sb^{3+}-based 0D halides are excited by X-rays or UV light, the ground-state exciton ($^1S_0$) initially transitions to higher excited states ($^1P_1$ or $^3P_1$). This is followed by rapid lattice relaxation driven by pronounced electron phonon coupling. The resulting transient lattice distortion induces self-trapped exciton (STE) formation a defining feature of Sb^{3+} luminescence. The strong localization of excitons in these materials leads to exceptional luminescence efficiency. In contrast, analogous s^2 cation systems such as $4s^2$ or $6s^2$ typically fail to achieve strong emission due to insufficient localization, resulting in weak or nonradiative decay pathways [11]. During the relaxation cascade, part of the exciton energy is lost through multiphoton processes, and some charge carriers may be captured by defect states. However, excitons that avoid quenching recombine radiatively at luminescent centers such as $[SbX_5]^{2-}$ or $[SbX_6]^{3-}$ polyhedral, producing broadband emissions with large Stokes shifts. These characteristics contribute to strong light output an essential criterion for scintillator performance [12].

3.2. Inherent Stability and Structural Flexibility

A key advantage of 0D hybrid antimony scintillators is their excellent intrinsic stability. Owing to the strongly localized electron phonon coupling associated with STEs, their luminescence properties exhibit minimal sensitivity to grain size, surface defects, or morphological irregularities [13]. This robustness allows high-quality materials to be prepared even under mild or solution-based synthesis conditions.

Moreover, these materials offer substantial structural tunability. By varying organic cations, researchers can systematically manipulate lattice packing, inorganic organic interactions, and coordination geometries. Such tunability enables fine optimization of emission behavior and scintillation performance [14].

3.3. Strategies for Enhancing PLQY and Structural Optimization

Despite rapid advances in hybrid antimony halides, achieving high photoluminescence quantum yield (PLQY) still remains a central challenge. Much of the current progress relies on intuitive or empirical screening of organic components, while systematic structural optimization is comparatively rare. A notable example is the work by Lin et al. [15], who enhanced the PLQY by 57% through controlled water-molecule incorporation in the $(C_6N_2H_{16})$ $SbCl_5$ lattice. Hydrogen bonding between water molecules and organic cations expanded the spacing between inorganic polyhedra, reduced their mutual interactions, and strengthened electron localization-effectively suppressing nonradiative decay. Another promising strategy involves dimensionality reduction. Lei et al. [16] achieved a transformation from a one-dimensional (1D) chain structure ($[DMPZ]SbCl_5 \cdot H_2O$) to a fully zero-dimensional (0D) structure ($[DMPZ]_2SbCl_6 \cdot Cl \cdot (H_2O)$). This transition from extended $[SbCl_5]^{2-}$ chains to isolated $[SbCl_6]^{3-}$ octahedra significantly enhanced exciton confinement and PLQY, demonstrating the importance of dimensional engineering.

3.4. Role of Organic Cations and Crystal Growth Methods

Tuning the structure of organic cations offers another effective route for designing 0D antimony-based scintillators. Xie et al. [17] prepared high-purity single crystals of $(TTA)_2SbCl_5$ and $(TE\text{-}BA)_2SbCl_5$ using anti-solvent vapor diffusion. Although these crystals exhibited promising luminescent properties, their small sizes limited further device integration. To overcome this constraint, Yang et al. [18] used EPT cations and implemented a melt-growth approach to synthesize large-scale $(EPT)_2SbCl_5$ amorphous crystals. The resulting materials enabled large-area, high-resolution X-ray imaging, demonstrating the scalability and application potential of this structural design. Additional solvent-mediated structural tuning was demonstrated in the growth of $(TMS)_nSbCl_n$ crystals using three different solvents. Each crystal structure displayed distinct photoluminescence characteristics, with the cubic phase showing markedly different emission behavior due to its high symmetry.

3.5. Dimensional Control and Enhanced Photophysical Properties

Transitioning from higher-dimensional (1D or 2D) frameworks to fully zero-dimensional architectures enhance photoelectron localization, promotes STE formation, and modifies the band structure through quantum confinement. These effects collectively boost photoluminescence efficiency [19]. Therefore, careful control over molecular components, solvent environments, and structural dimensionality offers powerful tools for designing next-generation Sb^{3+}-based scintillators.

4. Applications of Zero-Dimensional Hybrid Antimony-Based Scintillators in X-Ray Detection and Imaging

Zero-dimensional (0D) hybrid antimony-based scintillators have emerged as highly promising candidates for next-generation X-ray detection due to their exceptional ability to convert high-energy photons into visible emission with high efficiency. Compared with traditional scintillator materials, these hybrid systems typically exhibit higher photoluminescence quantum yields (PLQY), lower detection limits, and robust luminescence stability, giving them a clear competitive advantage. Recent breakthroughs further underscore their potential to push the boundaries of radiation imaging technology. The following sections summarize key research progress and highlight their innovative contributions to the field of X-ray detection.

4.1 X-ray Detection

The application of 0D hybrid antimony halides in X-ray detection was first demonstrated by Ma et al. [20], who successfully synthesized a zero-dimensional $(PPN)_2$ $SbCl_5$ single crystal with intense orange-red emission. This material delivers a light yield of 49,000 photons·MeV^{-1}, approaching that of commercial CsI (Tl) (54,000 photons·MeV^{-1}). Remarkably, the scintillator maintains an almost perfectly linear response across a broad dose-rate range down to 90 $nGy_{air}·s^{-1}$, and continues to exhibit high linearity even under ultra-low dose conditions. The resulting detection limit of 191.4 $nGy_{air}·s^{-1}$ is 28.7 times lower than the clinical diagnostic dose benchmark of 5.5 $\mu Gy_{air}·s^{-1}$, representing a major advancement for high-sensitivity radiation detection. Another important contribution came from the development of TEBA-2 $SbCl_3Br_2$, which achieved one of the highest reported light yields among hybrid Sb-based scintillators. Its detection limit of 50.1 $nGy_{air}·s^{-1}$ corresponds to just 1/110 of the medical diagnostic standard, demonstrating outstanding sensitivity. After 16 repeated X-ray on/off cycles, the luminescence intensity remained stable, confirming the material's excellent radiation durability and highlighting its promise for real-world X-ray imaging applications. Because X-ray absorption efficiency strongly depends on the atomic number of constituent elements, compositional engineering plays a crucial role in optimizing detector performance. To enhance absorption and emission, Zhao et al. [21] synthesized a series of (TEBA) $2SbCl_{5-x}Br_x$ (x = 0-5) compounds by tuning the Cl/Br halogen ratio. The light yield increases significantly with higher Br^- content, benefiting from the enhanced X-ray attenuation capability of heavier halide ions.

Further structural innovation was demonstrated by Shen et al. [22], who synthesized $C_{38}H_{36}P_2Sb_2Cl_8$ single crystals containing a highly luminescent $[Sb_2Cl_8]^{2-}$ dimer structure via an anti-solvent diffusion method. This material exhibited an exceptional PLQY of 99.8% and a light yield of 41,300 photons·MeV^{-1}, along with a detection limit as low as 45.6 $nGy_{air}·s^{-1}$. These metrics place the material among the most sensitive hybrid scintillators reported to date. More importantly, the dimeric structure offers enhanced radiative pathways and strong exciton localization, which collectively strengthen its scintillation performance.

4.2 X-ray Imaging

X-ray imaging technology enables visualization of the internal structure of objects by utilizing the penetrating ability of X-rays, generating high-resolution images that reveal hidden features and material composition [23]. This powerful technique has been widely applied across diverse fields including medical diagnostics, industrial non-destructive evaluation, security screening, and scientific research due to its ability to provide fast, accurate, and highly detailed internal imaging [24]. In recent years, zero-dimensional (0D) hybrid antimony-based scintillators have gained considerable interest as emerging imaging materials owing to their simple synthesis, exceptionally high PLQY, and large Stokes shift, all of which contribute to bright and high-fidelity scintillation signals. These properties collectively enhance image clarity and contrast, underscoring the strong potential of 0D antimony halides for next-generation radiation imaging technologies. Although 0D hybrid antimony scintillator single crystals exhibit remarkable sensitivity and light yield in X-ray detection, their inherently small size places significant constraints on practical imaging applications. To overcome this limitation, developed a strategy to uniformly disperse $C_{50}H_{44}P_2SbCl_5$ crystal powders into a polymethyl methacrylate (PMMA) polymer matrix, producing a large-area, flexible scintillator screen [25]. Under X-ray excitation, the composite screen emits bright and spatially uniform yellow luminescence. Notably, the resulting thin film achieves an impressive spatial resolution of 8.2 $lp·mm^{-1}$, positioning it as a promising candidate for X-ray photography, security inspection, and portable imaging systems. The scintillator screen also enables clear visualization of printed circuit boards, further validating its practical utility. However, the traditional direct-blending

approach where metal halide powders are physically mixed into a polymer often introduces substantial light scattering due to refractive index mismatches, residual grains, and uneven particle distribution. This leads to decreased transparency, reduced light yield, and compromised spatial resolution. To address these limitations, a crystallization strategy was proposed, growing $C_{38}H_{36}P_2SbCl_5$ crystals directly within a polyvinylidene fluoride (PVDF) matrix [26]. The resulting films exhibit significantly lower light scattering and markedly improved imaging performance. Compared with opaque blending-derived films, which achieve only 4.5 $lp \cdot mm^{-1}$, the in-situ film delivers a high spatial resolution of 10.2 $lp \cdot mm^{-1}$. When imaging integrated circuits, the in-situ film allows clear visualization of intricate internal details, demonstrating its superior applicability to high-precision X-ray imaging.

Achieving high optical transparency is essential for maximizing scintillation efficiency and spatial resolution in imaging screens. A transparent scintillator minimizes light absorption and scattering, allowing more scintillation photons to reach the detector with minimal loss. In this context, successfully fabricated a large-area, transparent 0D antimony-based perovskite medium, $(C_{20}H_{20}P)_2SbCl_5$, using a facile solvent-free melt-quenching method. The steric hindrance introduced by $C_{20}H_{20}P^+$ effectively suppresses crystal nucleation during cooling, yielding a glassy, low refractive index material with >80% transmittance in the 450–800 nm range and a large 245 nm Stokes shift. These features greatly reduce reabsorption and scattering losses. Polycrystalline scintillators exhibit rapidly decreasing resolution with increased thickness, the transparent quenched screen maintains an outstanding 30 $lp \cdot mm^{-1}$ resolution. When imaging printed circuit boards, the transparent screen provides significantly clearer and more detailed images than conventional opaque polycrystalline screens highlighting its superior performance in high-resolution X-ray imaging. Flexible scintillation screens offer several advantages, including ease of fabrication, low cost, compatibility with large-scale production, and adaptability to curved surfaces making them ideal for wearable or portable X-ray devices. However, their transparency and spatial resolution are often affected by scattering centers and polymer - crystal interfaces. While in-situ deposition techniques can mitigate these issues, flexible screens generally exhibit lower thermal stability and long-term durability compared with rigid screens. In contrast, rigid scintillator screens typically provide higher spatial resolution and improved stability, making them more suitable for precision medical imaging and high-definition industrial inspection. Nevertheless, their brittleness and inability to conform to irregular geometries limit their use in portable or flexible devices. Therefore, the choice between rigid and flexible scintillation screens must be made based on application-specific requirements: rigid screens excel in high-resolution, stable imaging environments, whereas flexible screens are preferred for adaptable, lightweight, and shape-conforming detection systems [27 - 33].

5. Conclusions

Zero-dimensional (0D) hybrid antimony halide scintillators, characterized by the stereochemically active $5s^2$ lone-pair electron configuration of Sb^{3+}, have rapidly emerged as promising candidates for next-generation, low-dose, high-resolution X-ray detection and imaging. Their intrinsic photophysical advantages including high photoluminescence quantum yields (PLQY), large Stokes shifts, and excellent environmental and structural stability make them particularly well-suited for sensitive radiation detection applications. In addition, the vast compositional and structural tunability of lead-free hybrid antimony halides offers extensive opportunities for rational material design, enabling continued optimization of scintillation efficiency, exciton dynamics, and device performance. Despite their strong potential, the technological readiness of 0D hybrid antimony-based scintillators remains at an early research stage, and several key barriers must be addressed before commercialization can be realized. One of the major intrinsic limitations arises from their self-trapped exciton (STE)-dominated emission mechanism, which typically leads to relatively long radiative decay lifetimes on the order of microseconds. While beneficial for achieving strong broadband emission, these long decay times hinder their applicability in real-time or high-frame-rate X-ray imaging, where rapid temporal response is essential. Moreover, the development of large-area scintillation screens suitable for practical detectors remains a substantial challenge. Current fabrication approaches must be further refined to achieve uniform large-area films, high optical transparency, mechanical flexibility, and long-term operational stability under continuous X-ray exposure. Addressing these difficulties will be critical for integrating 0D hybrid antimony scintillators into next-generation medical, industrial, and security imaging systems.

- Tuning STE kinetics through compositional engineering, molecular design, and lattice modulation to shorten decay lifetimes without compromising PLQY.
- Developing low-cost and scalable synthesis routes, enabling the production of bulk crystals, single-phase powders, and large-area scintillation films suitable for industrial deployment.
- Exploring device-level engineering, including photodetector coupling, screen fabrication techniques, and encapsulation strategies to enhance durability and imaging performance.

- Establishing structure - property - performance correlations to guide the rational design of next-generation scintillation materials.

Advances in structural engineering, synthesis technology, and device integration, zero-dimensional hybrid antimony-based scintillators hold strong promise for enabling ultra-sensitive, low-dose, and high-resolution X-ray imaging, contributing to transformative improvements in medical diagnostics, industrial inspection, and radiation monitoring.

References

1. Wang, Y. Y., Wang, Y., Du, X. W., Zhang, X. H., Zhao, L., Yan, B. R., & Lin, G. (2025). A zero-dimensional hybrid halide with superior water resistance for high-efficiency X-ray scintillation and solid-state lighting. Journal of Materials Chemistry C, 13(16), 8320-8327.

2. Wang, Y. Y., Kang, Q., She, M. Q., Qi, S. Y., Zhao, X. T., Hu, Y. J., & Lin, G. (2025). Water-Resistant Zero-Dimensional Hybrid Copper Halide for High-Efficiency X-ray Scintillation and Sensitive Fluorescent Probing. Inorganic Chemistry, 64(20), 10087-10096.

3. Xu, T., Li, Y., Nikl, M., Kucerkova, R., Zhou, Z., Chen, J.,& Wu, Y. (2022). Lead-free zero-dimensional organic-copper (I) halides as stable and sensitive X-ray scintillators. ACS Applied Materials & Interfaces, 14(12), 14157-14164.

4. Lv, J. N., Lin, N., Zhang, J. Y., Liu, Y. M., Niu, L. C., Shi, J., & Chen, Z. W. (2024). Zero-dimensional cuprous halide scintillator with ultra-high anti-water stability for X-ray imaging. Inorganic Chemistry Frontiers, 11(23), 8555-8563.

5. Liu, Y. H., Wang, N. N., Ren, M. P., Yan, X., Wu, Y. F., Yue, C. Y., & Lei, X. W. (2023). Zero-dimensional hybrid cuprous halide of [BAPMA] Cu_2Br_5 as a highly efficient light emitter and an X-ray scintillator. ACS Applied Materials & Interfaces, 15(16), 20219-20227.

6. Lin, N., Wang, R. C., Zhang, S. Y., Lin, Z. H., Chen, X. Y., Li, Z. N., & Yue, C. Y. (2023). 0D hybrid cuprous halide as an efficient light emitter and X-ray scintillator. Laser & Photonics Reviews, 17(12), 2300427.

7. Zhan, Y., Cai, P., Pu, X., Ai, Q., Si, J., Yao, X., & Liu, Z. (2024). Exceptional optical performance of the zero-dimensional hybrid cuprous halide ETPA 2 Cu 2 I 4 as an X-ray scintillator. Inorganic Chemistry Frontiers, 11(2), 579-588.

8. Zhou, C., Zhou, Y., Xu, O., Kong, L., Tian, W., Kan, X., & Zou, B. (2025). Record-High Photoluminescence Efficiency and Excellent Scintillation in Two-Dimensional Diamine Hybrid Copper (I) Halides. ACS Applied Materials & Interfaces, 17(38), 53503-53511.

9. Wang, Y. Y., Feng, Y., Liu, X. T., Cao, L. Y., Xu, Q. Y., Qu, H., & Lin, G. (2024). Organic–inorganic hybrid halide X-ray scintillator with high antiwater stability. Inorganic Chemistry, 63(35), 16224-16232.

10. Wang, X., Lian, L., Zhang, P., Zhu, J., Zhang, X., Gao, J.,& Zhang, J. (2021). Highly luminescent zero-dimensional organic copper halides for X-ray scintillation. The Journal of Physical Chemistry Letters, 12(29), 6919-6926.

11. Meng, H., Chen, B., Zhu, W., Zhou, Z., Jiang, T., Xu, X., & Zhao, Q. (2023). Stable Organic Antimony Halides with Near-Unity Photoluminescence Quantum Yield for X-Ray Imaging. Laser & Photonics Reviews, 17(7), 2201007.

12. Cao, S., Lai, J. A., Wang, Y., An, K., Jiang, T., Wu, M.,& Tang, X. (2024). Organic-Inorganic Cuprous Halides With Reversible Photoluminescence for Multiple Optical Applications. Laser & Photonics Reviews, 18(12), 2400799.

13. Lian, L., Xiong, D., Zhang, J., Jia, M., Liu, Y., Ma, Z., & Shi, Z. (2025). Highly efficient and blue-light-excitable zero-dimensional hybrid copper iodides toward solid-state lighting and x-ray imaging applications. Applied Physics Reviews, 12(3).

14. Gao, W., Niu, G., Yin, L., Yang, B., Yuan, J. H., Zhang, D., & Tang, J. (2020). One-dimensional all-inorganic K_2CuBr_3 with violet emission as efficient X-ray scintillators. ACS Applied Electronic Materials, 2(7), 2242-2249.

15. Lin, H., Zhou, C., Wang, L., Chen, Z., Zhang, Q., & Wang, G. (2020). **Water-molecule-assisted structural modulation and enhanced photoluminescence in hybrid antimony chloride ($C_6N_2H_{16}$)$SbCl_5$.** *Journal of Materials Chemistry C*, 8, 13510–13518