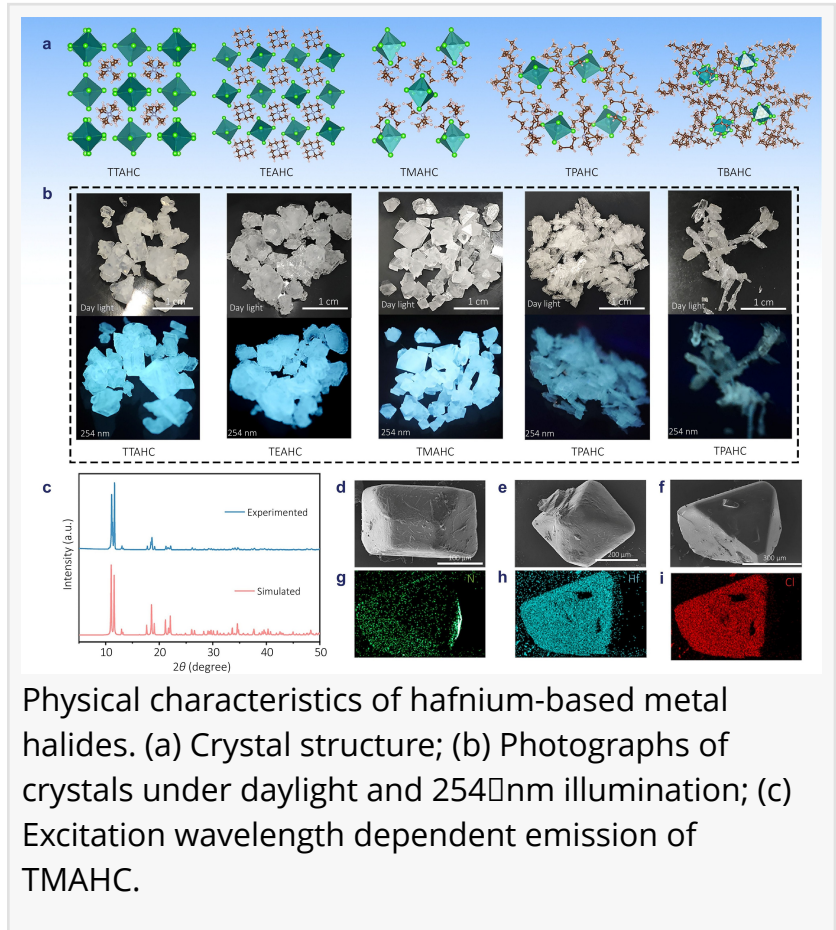


Hafnium-Based Scintillator for Ultrahigh-Resolution X-ray Imaging

Triplet exciton harvesting in a silicon micropore array scintillator improves light output, suppresses crosstalk, and delivers ultrahigh resolution

CHINA, July 2, 2026 /EINPresswire.com/ -- Since Wilhelm Röntgen discovered X-rays in 1895, X-ray imaging has become an indispensable tool in modern medical diagnosis, industrial non-destructive testing, security screening, and even cultural heritage preservation. In X-ray imaging systems, detection methods fall into two main categories: direct and indirect. Direct detection uses semiconductor materials to convert X-ray photons directly into electrical signals, offering fast response and high spatial resolution, but it is often expensive and complex to manufacture. Indirect detection employs a "scintillator + photodetector" structure: X-rays are first absorbed by a scintillator material and converted into visible or ultraviolet light, which is then captured by a photodiode or CCD/CMOS sensor and transformed into electrical signals. Indirect detection dominates the current X-ray imaging market because of its mature technology, controllable cost, and excellent compatibility with existing sensors.

However, the choice and design of scintillator materials have always faced a fundamental trade-off: thickness versus resolution. From the perspective of X-ray absorption, a thicker scintillation screen absorbs more X-ray photons, thereby improving signal strength and detection sensitivity. Yet from the optical imaging perspective, a thicker screen means that during propagation from the conversion point to the sensor surface, photons undergo multiple scattering and refraction, leading to spot spreading—the so-called "optical crosstalk." Conventional commercial scintillator



Physical characteristics of hafnium-based metal halides. (a) Crystal structure; (b) Photographs of crystals under daylight and 254 nm illumination; (c) Excitation wavelength dependent emission of TMAHC.

materials struggle with this trade-off.

Against this background, a research team from China set out to resolve the “mystery of high light yield” in hafnium (Hf)-based scintillators by combining in-depth investigation of the luminescence mechanism with dual modulation of material structure and optical management, ultimately achieving a breakthrough in imaging resolution. It was led by Dr. Jun'an Lai and Professor Dong Zhang from Department of Radiology, Xinqiao Hospital, Army Medical University, in collaboration with Associate Professor Peng He and Professor Xiaosheng Tang from the College of Optoelectronic Engineering, Chongqing University. The findings were made available Online on April 15, 2026, and published in Volume 9, Issue 6 of Opto-Electronic Advances on June 07, 2026.

The team designed and synthesized a series of Hf-based organic-inorganic hybrid metal halides with systematically varied organic cation chain lengths: TTA-HfCl₄, TEA-HfCl₄, TMA-HfCl₄, TPA-HfCl₄, and TBA-HfCl₄. Under 254 nm excitation, TMA-HfCl₄ (TMAHC) exhibited the strongest emission, and inductively coupled plasma mass spectrometry confirmed that the Zr content in TMAHC is only 0.01%, essentially ruling out any influence from zirconium impurities.

Temperature-dependent photoluminescence spectra of TMAHC revealed key features. Under 200 nm excitation, the 388 nm emission intensity increased with rising temperature, a hallmark of thermally activated delayed fluorescence (TADF). To further verify the TADF mechanism, the team measured temperature-dependent photoluminescence decay lifetimes, excitation-power-dependent photoluminescence (PL) spectra, temperature-dependent Raman spectra, and three-dimensional thermoluminescence measurements.

Having established the TADF mechanism, the team systematically evaluated the scintillation performance of TMAHC. TMAHC exhibited a light yield of $56,563.31 \pm 1250$ photons/MeV. More importantly, the detection limit of TMAHC is as low as 23.86 nGyair/s, and the encapsulated scintillation screen showed minimal light-output degradation and excellent radiation stability.

Despite the excellent light yield and detection limit of TMAHC, conventional planar scintillation screens still suffer from optical crosstalk, preventing the full utilization of the material's high light yield. To address this, the team developed a silicon-based micropore array scintillation screen. Zemax optical simulations confirmed the effectiveness of crosstalk suppression, and for the screen with 25 μm pores and a filling factor of 95%, the spatial resolution at a modulation transfer function of 0.2 reached 31.41 lp/mm, far exceeding that of gadolinium oxysulfide and thallium-doped cesium iodide screens.

Dr. Lai said, “The ambiguity surrounding the luminescence mechanism severely hindered further performance enhancement and rational material design.” The demonstration of TADF in this Hf-based hybrid system elucidates the physical process by which triplet excitons are converted to singlet excitons via reverse intersystem crossing to contribute delayed fluorescence, offering a unified framework for understanding the luminescence behavior of this material class.

Prof. Tang said, "The extremely low defect density in TMAHC is a critical structural basis for its ultra-high light yield." The study also reveals that the organic cation chain length influences the ΔE_{ST} and charge-transfer efficiency by modulating the distortion of the $[HfCl_4]^{2+}$ octahedra, pointing to design strategies for further performance optimization.

Prof. Zhang said, "The development of silicon-based micropore array scintillation screens provides a low-cost, scalable solution for high-resolution X-ray imaging." The excellent imaging performance demonstrated on an industrial chip and a biological model foreshadows broad applications in high-precision non-destructive testing, microelectronics inspection, orthopedics, dentistry, and beyond.

Opportunities for further improvement remain. First, the PL quantum yield of TMAHC can still be enhanced by optimizing crystal growth conditions and reducing surface defects. Second, the filling factor of the array structure, especially for small pore sizes, requires further optimization. Third, the optical properties of the pore walls significantly affect crosstalk; depositing highly reflective metal or dielectric layers could further suppress crosstalk and improve resolution. As understanding of the underlying mechanisms deepens and structural designs continue to improve, Hf-based TADF scintillators and their array platforms are poised to become a core technology for next-generation high-resolution X-ray imaging.

Reference

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About The Army Medical University, China

Founded in 1954 and located in Chongqing, China, the Army Medical University is a prestigious public military institution affiliated with the People's Liberation Army Ground Force. Rich in history, it evolved from the merger of the Sixth and Seventh Medical Universities and was famously known as the Third Military Medical University until its restructuring in 2017. Today, the university is a vital hub for advanced medical education, research, and military healthcare. It operates three renowned affiliated hospitals essential to its clinical training and public medical service: Southwest Hospital, Xinqiao Hospital, and Daping Hospital.

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About Dr. Jun'an Lai from Army Medical University, China

Dr. Jun'an Lai received his Ph.D. from the College of Optoelectronic Engineering, Chongqing University, under the supervision of Professor Xiaosheng Tang and Associate Professor Peng He. His research focuses on novel optoelectronic materials and devices for high-energy particle detection and imaging, as well as image signal processing. Dr. Lai is currently a postdoctoral fellow in the Department of Radiology, Xinqiao Hospital, Army Medical University, where he is working on the medical applications of novel scintillators under the supervision of Professor Dong Zhang. The research group has established a state-of-the-art laboratory for advanced nanomaterials and molecular imaging. It has been supported by 10 NSFC grants and 12 projects

from the Chongqing Science and Technology Commission. Its research spans the development of novel MRI probes, photoacoustic imaging probes, NIR-II fluorescence probes, as well as therapeutic strategies including chemoradiotherapy, chemodynamic therapy, photodynamic therapy, and immunotherapy. The group has published a series of high-impact papers in journals such as Advanced Materials, ACS Nano, Advanced Functional Materials, and Biomaterials.

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