

Preparation of Organic Scintillators and Applications in Neutron-Gamma Discrimination

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Abstract

Neutron detection holds significant strategic importance in fields such as nuclear safety, medicine, and high-energy physics. However, it is often compromised by gamma-ray interference, making efficient discrimination technology a critical challenge. Organic scintillators, with their advantages of high neutron detection efficiency, rapid response time, and morphological adaptability, have emerged as core materials in neutron-gamma discrimination research. This paper systematically reviews the luminescence mechanisms of organic scintillators and the principles of pulse shape discrimination (PSD). It analyzes the preparation methods, performance characteristics, and research progress of crystalline, liquid, plastic, and loaded scintillators. Case studies highlight the effective enhancement of neutron signal-to-noise ratios and imaging resolution in nuclear power plant monitoring, PET imaging, and high-energy physics experiments using organic scintillators. Future developments in organic-inorganic composite systems and novel perovskite materials are anticipated to expand the broader application of organic scintillators in neutron detection. Among these materials, perovskite-based organic scintillators exhibit the most promising application prospects in future high-precision neutron detection scenarios due to their unique combination of high crystallinity, tunable optical bandgap, and excellent radiation resistance.

Keywords

Neutron detection; Organic scintillators; Neutron-gamma discrimination.

Introduction

Neutrons play a crucial role in high-energy physics, nuclear physics, nuclear energy, nuclear medicine, nuclear safety, space radiation, and materials science. However, in neutron measurement applications, γ -rays often accompany neutrons due to their interactions with the surrounding environment. Detectors sensitive to neutrons are typically also responsive to γ -rays, making the

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discrimination between neutrons and γ -rays a key challenge in neutron detection. Organic scintillators show great potential in neutron-gamma discrimination due to their unique physicochemical properties, and an in-depth discussion of their research progress is of significant importance (Hajagos et al., 2018).

Neutron detection is irreplaceable in nuclear safety (e.g., radiation monitoring in nuclear power plants), national defense (nuclear weapon monitoring), medicine (cancer treatment), and fundamental physics research (neutron scattering experiments) (Zmeškal, 2023). However, mixed radiation fields of neutrons and gamma rays (such as the ^{252}Cf source) lead to confused detection signals, requiring efficient discrimination techniques to improve the signal-to-noise ratio.

As the core materials for neutron-gamma discrimination, organic scintillators present both advantages and challenges. The core advantages are reflected in three aspects: First, their fast response characteristics enable nanosecond-scale decay times (<10 ns), meeting the real-time detection needs of high-count-rate scenarios (Liu, 2019). Second, the low atomic number ($Z \approx 6$) of hydrocarbon-based materials preferentially responds to neutron signals through the proton recoil effect, effectively reducing gamma-ray interference (Qin, 2021). Third, their strong morphological plasticity allows them to be formed into liquid, plastic, or gaseous states, providing flexible detection solutions for nuclear medical imaging, high-energy physics experiments, and other scenarios (Particle Data Group, 2012).

Currently, two major technical challenges are faced: First, the Compton scattering effect causes gamma-ray interference, especially in the low-energy region below 100 keV, where electron recoil signals overlap with neutron signals in energy, requiring pulse shape discrimination techniques to improve the signal-to-noise ratio (Febbraro, 2014). Second, the light yield is significantly lower than that of inorganic scintillators (e.g., NaI (Tl) with 38,000 photons/MeV). Due to energy transfer losses between molecules, the typical light yield of organic materials is only 8,000-10,000 photons/MeV. Studies have shown that doping quantum dots or constructing nanostructures can increase light extraction efficiency by 30%, but chemical stability and radiation damage still restrict their engineering applications (Maddalena et al., 2019; Sabot et al., 2024).

The development trend points to molecular engineering and microstructure regulation, such as developing deuterated plastic scintillators to reduce background noise or designing dual-fluorophore systems to achieve self-discrimination functions (Porter et al., 1966). With the emergence of new perovskite materials (theoretical light yield up to 300,000 photons/MeV), organic-inorganic hybrid systems may break through existing performance bottlenecks (Garcia et al., 2017).

Currently, organic scintillators have made significant progress in the field of neutron-gamma discrimination. Their unique advantages enable them to exhibit great potential in various application scenarios, while technical challenges should not be overlooked. Future research will focus on molecular engineering and microstructure regulation to enhance the performance of organic scintillators and overcome existing bottlenecks. Through continuous innovation and in-depth research, organic scintillators are expected to become key materials in the field of neutron detection, providing strong support for the development of related disciplines.

Scintillation Mechanism of Organic Scintillators

Organic scintillators are primarily composed of organic molecules containing carbon and hydrogen atoms, whose symmetry forms a π -electron structure. When organic molecules with π -electron structures are excited by ionizing radiation, they transition to higher singlet states. Excited-state molecules dissipate part of the energy through vibration, and after reaching the minimum energy of the excited state, they de-excite back to the ground state, producing scintillation light. During the energy level transition, instantaneous fluorescence, phosphorescence, and delayed fluorescence are generated simultaneously. Instantaneous fluorescence is produced by the de-excitation of the singlet state S_1 back to the vibrational state of the ground state S_0 ; phosphorescence is generated when π -electrons in the singlet state undergo "intersystem crossing" into the triplet state T_1 and then de-excite back to S_0 ; delayed fluorescence occurs when π -electrons in the triplet state T_1 are thermally excited back to S_1 , followed by normal de-excitation to S_0 (Zhang et al., 2022), as shown in Figure1.

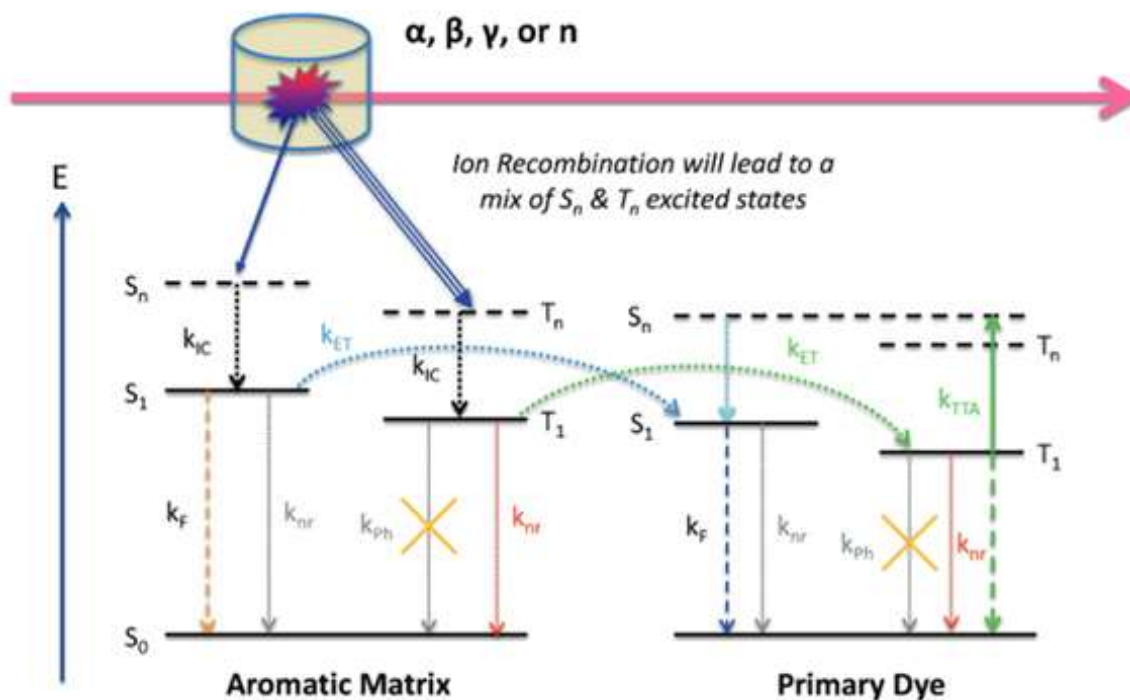


Figure 1. Schematic diagram of excited-state interactions and energy transfer between aromatic matrix and primary dye in organic scintillators

Neutrons and gamma rays form recoil protons and electrons in organic scintillators, respectively. Due to the quenching effect, protons produce reduced fluorescence and excite denser π -electron triplet states, leading to less instantaneous fluorescence and more delayed fluorescence from neutrons compared to gamma rays, resulting in differences in n/γ pulse signals. The Pulse Shape Discrimination (PSD) technique utilizes this principle to achieve n/γ discrimination by comparing characteristics such as the decay time of pulse signals (Watanabe et al., 2015).

Research Progress of Organic Scintillators

Organic Crystals

Organic crystals such as anthracene and stilbene crystals exhibit good basic properties and PSD performance. Anthracene crystals have high luminous efficiency, short light decay time, stable performance, and complete structure (Zaitseva et al., 2015), and their luminous efficiency is often used as a reference standard for other organic scintillators. As shown in Figure 2, anthracene has the best PSD capability compared to stilbene and p-terphenyl. Stilbene crystals have a smaller light output but a short luminescence decay time, are relatively easy to prepare and purify, and have good crystal transparency. However, organic crystals suffer from the disadvantage of anisotropic response to incident particles, and the preparation of large-size organic crystals remains challenging. Currently, solution growth technology has been used to prepare large-size trans-stilbene single crystals exceeding 10 cm, with improved Figure of Merit (FOM) values, showing promise for large-scale neutron detection (Arulchakkaravarthi et al., 2003). Additionally, large-volume composite stilbene scintillators prepared using styrene single crystals and the Bridgeman-Stockbarger growth method have successfully achieved separation of neutron signals from γ background radiation signals (Ji, 2014). The performance of organic crystals is highly dependent on purity, as impurities cause fluorescence quenching, prompting researchers to continuously strive to improve crystal purity.

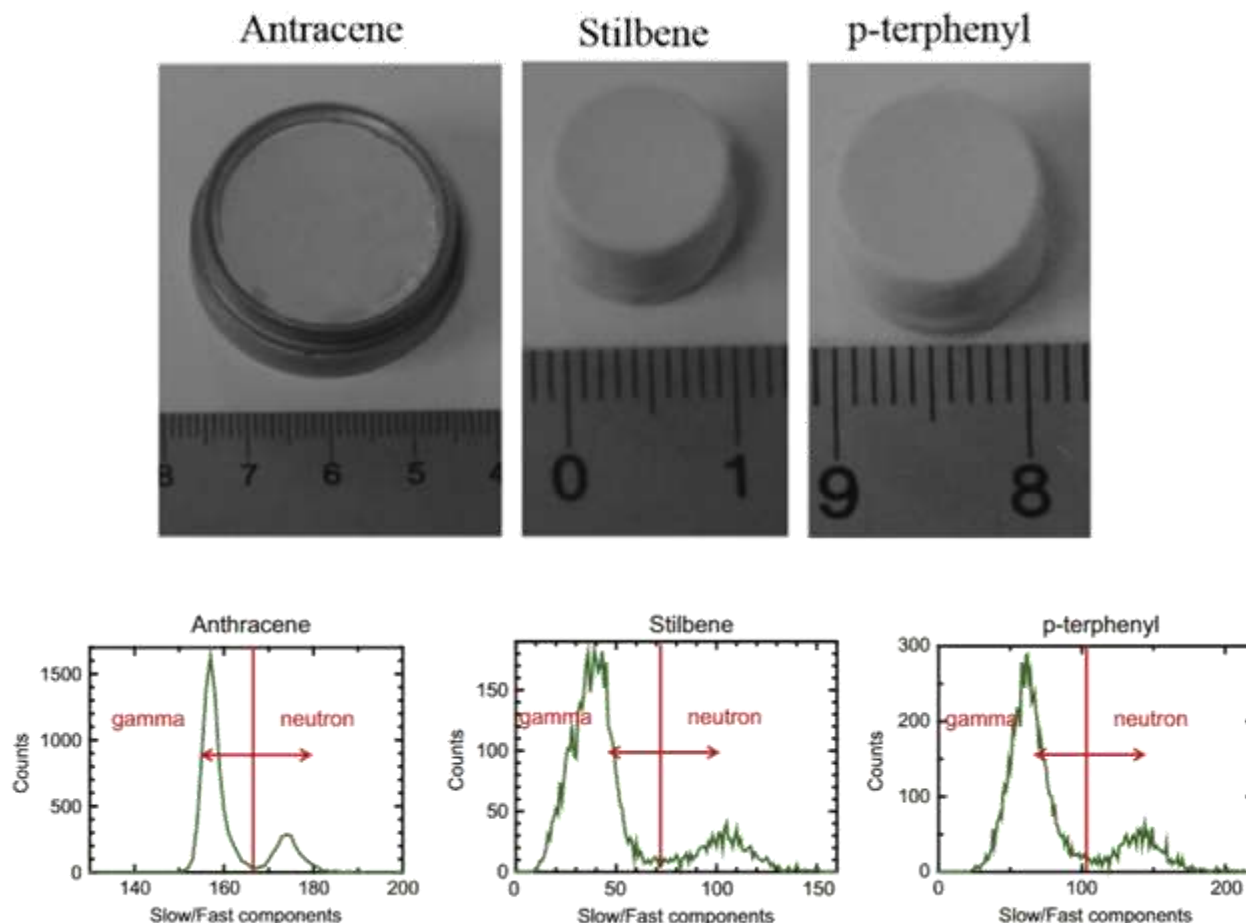


Figure 2. Research Progress of Organic Crystal Scintillators: Physical Samples of Anthracene, Stilbene, and p - terphenyl and Their Pulse Shape Discrimination (PSD) Capability Comparison

Liquid Scintillators

Liquid scintillators consist of a solute and a solvent, where the solute produces scintillation light and the solvent dissolves the solute and absorbs radiation energy (Bertrand et al., 2014). Typical solutes include PPO, PBD, p-Terphenyl, etc., and solvents include benzene, toluene, xylene, etc. As shown in Figure 3, NE-213 is an early liquid scintillator widely used in neutron detection, and subsequent liquid scintillators such as EJ-301 and EJ-309 also exhibit excellent performance. For example, the optical output response and neutron detection efficiency of EJ-309 are consistent with Monte Carlo simulation results, and its PSD performance is dependent on the angle (Glenn et al., 2018). Liquid scintillators have high light output, short decay time, and good PSD performance, but they suffer from problems such as high toxicity, easy foaming, complex packaging, low flash point, difficult long-term storage, and low detection density, limiting their application in special experimental environments and on-site detection.



Figure 3 Liquid scintillators: NE-213, EJ-301, EJ-309 liquid scintillator

Plastic Scintillators

Plastic scintillators are essentially solid-polymerized liquid scintillators, which are easy to process into various shapes and larger sizes. The PSD performance of early plastic scintillators was considered lower than that of organic crystals and liquid scintillators (Grodzicka-Kobylka et al., 2020), but their performance has been continuously improved with technological development. Eljen Technology's EJ-299 series of plastic scintillators has been continuously improved (Zaitseva et al., 2013). For instance, EJ-299-33G and EJ-299-33A have improved plasticity and PSD performance, while EJ-299-34 further enhances plasticity. EJ-276 introduced in 2018 has better physical hardness, long-term stability, and light yield, with significantly improved n/γ resolution performance, approaching the basic performance of liquid scintillators, making it more suitable for field applications. Plastic scintillators are increasingly used in on-site detection and have a promising development prospect.

Loaded Organic Scintillators

Traditional organic scintillators have low detection sensitivity to thermal neutrons or low-energy neutrons, and elements such as lithium (Li), boron (B), and gadolinium (Gd) are typically added to increase the neutron capture cross-section for thermal neutron detection (Pino et al., 2014). For example, ^{10}B plastic scintillators have application prospects in border detection and nuclear non-proliferation. Although EJ-339A boron-loaded scintillators have poor PSD performance, they meet many application requirements and have low chemical hazards (Dumazert et al., 2016).

Gadolinium-loaded liquid scintillators are used for solar neutrino detection and neutron measurement, and Gd-loaded organic scintillators can effectively detect and separate thermal neutrons, fast neutrons, and γ rays in a dual-scintillator system. However, the luminescence quenching effect of the loaded materials requires strict control of purity and dosage.

Conclusion

Organic scintillators are crucial for neutron-gamma discrimination, vital in nuclear energy, medical imaging, and high-energy physics. Different organic scintillators have strengths and improvement needs. Organic crystal scintillators have high luminous efficiency and stability but face large-size growth and isotropic response challenges. Liquid scintillators excel in light output and PSD but have toxicity and volatility issues. Plastic scintillators, with good processability and cost-effectiveness, are used in on - site detection, and ongoing optimizations boost their performance. Loaded organic scintillators detect thermal and low - energy neutrons, though luminescence quenching is a problem, solutions like surface modification show promise. Looking forward, organic-inorganic composite systems and perovskite-based organic scintillators have great potential. Composites combine organic processability and inorganic radiation resistance/stable energy levels. Perovskite-based ones, with crystallinity, tunable bandgaps, and high carrier mobility, enable fast response and high light output, and lead - free variants are non - toxic and radiation - stable, suitable for medical imaging and space detection. For future research, focus on three directions: develop multi-scale simulation tools for material design; advance scalable fabrication processes; establish standardized testing protocols for performance validation. This will drive organic scintillators' role in neutron detection and innovation in related fields.

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