

Advanced scintillators for neutron-gamma detection

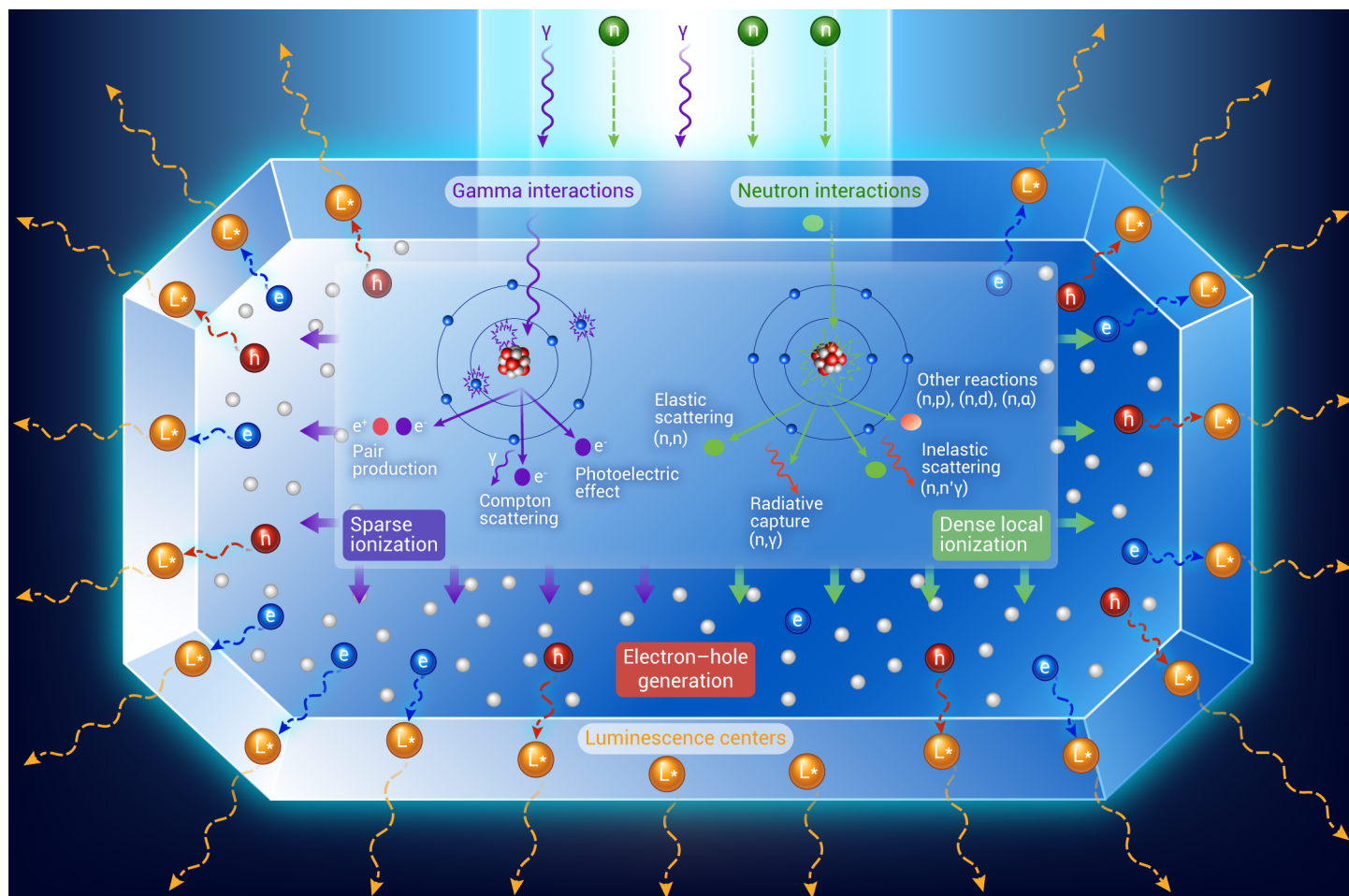
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- This review summarizes principles, materials, and pulse shape discrimination (PSD) for neutron detection.
- Advanced organic, crystal, and glass scintillators are evaluated for thermal and fast neutron measurements.
- Photodetectors, digitization, and AI algorithms are integrated to enhance neutron- γ PSD.
- Future perspectives cover scalable manufacturing, radiation hardness, and real-time mixed-field deployment.

Advanced scintillators for neutron-gamma detection

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Neutron- γ discrimination remains a central challenge in nuclear science, reactor instrumentation, homeland security, medical applications, and space radiation monitoring, particularly in environments where weak neutron signals must be extracted from intense γ backgrounds. Recent progress in scintillator development has significantly expanded the variety of materials, ranging from traditional liquid and plastic organic scintillators to Li-based halide crystals, Gd-loaded scintillators, and emerging neutron-sensitive glasses. This review summarizes the physical principles, material characteristics, and detector-level strategies that define neutron detection and neutron- γ discrimination across these materials. Special attention is given to the role of key conversion channels, including recoil processes, neutron capture in ^3He , ^{10}B , ^6Li , and gadolinium (^{155}Gd and ^{157}Gd), and the resulting pulse signatures exploited in modern detectors. We further compare major scintillator materials in terms of light yield, timing response, pulse shape discrimination capability, scalability, and suitability for thermal- or fast-neutron measurements. Beyond materials themselves, we emphasize that detector performance is increasingly shaped by the integration of photodetectors, waveform digitization, front-end electronics, and advanced data processing. In particular, simulation-guided optimization and AI-assisted pulse analysis are opening new opportunities for improving neutron- γ separation under low-energy, high-rate, and complex mixed radiation conditions. By connecting neutron interaction physics with material design and system engineering, this review outlines the main directions toward compact, robust, and application-oriented next-generation neutron scintillation detectors.

INTRODUCTION

Reliable neutron detection is of great importance in various fields, including science, industry, medicine, and security. In nuclear physics, the scattering of thermal and cold neutron beams, as well as neutron diffraction methods, make it possible to study the composition and structure of matter.^{1,2,3,4,5} Neutron measurements are required in the control and protection systems of nuclear reactors.⁶ In the security sector, neutron counting remains one of the primary methods for identifying explosives and radioactive materials; neutron detectors are used for screening carry-on luggage, baggage, mail, and personal belongings.^{4,7} In medicine, neutrons are used in radiation therapy; for example, thermal and epithermal neutrons are employed in boron neutron capture therapy (BNCT), which is based on neutron capture reactions in target nuclei.^{8,9,10} Neutrons are also an important background and diagnostic channel in high-energy and astroparticle experiments, where they can affect detector occupancy, induce activation, and contribute to delayed components of hadronic showers, motivating instrumentation that is efficient, robust, and selective.^{11,12,13}

The main difficulty in neutron detection is that neutrons almost never occur alone. In most practical settings, such as nuclear reactors, accelerators, and

many medical or industrial facilities, neutrons are accompanied by intense γ radiation. Because neutrons are electrically neutral, they do not directly ionize matter; instead, they must first be converted via nuclear interactions into detectable secondary products (charged particles, γ rays, conversion and Auger electrons, or fission fragments).^{2,14} Unlike neutrons, γ rays readily interact with matter through electromagnetic processes and can produce high count rates that overwhelm neutron signals. As a result, neutron detection is often limited not by the detector's intrinsic sensitivity to neutrons, but by false triggers, pile-ups, and misclassification caused by γ -induced events. Therefore, reliable neutron- γ discrimination is a fundamental requirement for most modern neutron detectors, especially when low neutron fluxes must be measured in a strong γ background or when compact geometries limit the use of extensive shielding.^{15,16,17}

Historically, the diversity of neutron-induced nuclear reactions and the strong energy dependence of their cross sections have driven the development of a wide range of neutron detectors. Fission chambers produce exceptionally large pulses from fission fragments and remain stable in high-radiation environments. For thermal neutrons, ^3He and BF_3 proportional counters have long been regarded as standard technologies because their efficiencies can be predicted accurately for many geometries and because they typically exhibit low sensitivity to γ radiation. Limited supplies of ^3He have further stimulated intensive development of alternative materials and technologies, including boron-lined proportional counters, ^6Li -based scintillators, and composite screens.^{4,18,19}

This review surveys the current landscape of neutron detection with emphasis on the coupling between interaction physics, scintillation materials, and discrimination strategies. We highlight the inherently system-level nature of performance: identical materials can yield markedly different efficiency and neutron- γ separation depending on moderation design, optical collection, photosensor choice, digitization, and analysis. We also discuss how modern waveform digitization and advanced (including data-driven) pulse-processing methods can exploit higher-dimensional pulse information, improving discrimination in low-energy regimes and under pile-up conditions where traditional PSD metrics often degrade. Finally, we summarize how Monte Carlo simulation and first-principles modeling increasingly guide material selection and detector optimization, linking microscopic scintillation mechanisms to macroscopic response functions and efficiency predictions.

MECHANISM OF NEUTRON DETECTION

Neutron interactions and energy ranges

Neutrons are electrically neutral and therefore do not directly ionize matter. Their detection relies on nuclear interactions that convert neutron energy into measurable secondary radiation such as prompt γ rays, conversion and Auger electrons, or heavy fission fragments.^{2,14} Detector selection is thus dictated mainly by neutron energy, source characteristics, and the required efficiency, timing performance, and background rejection. A brief summary of

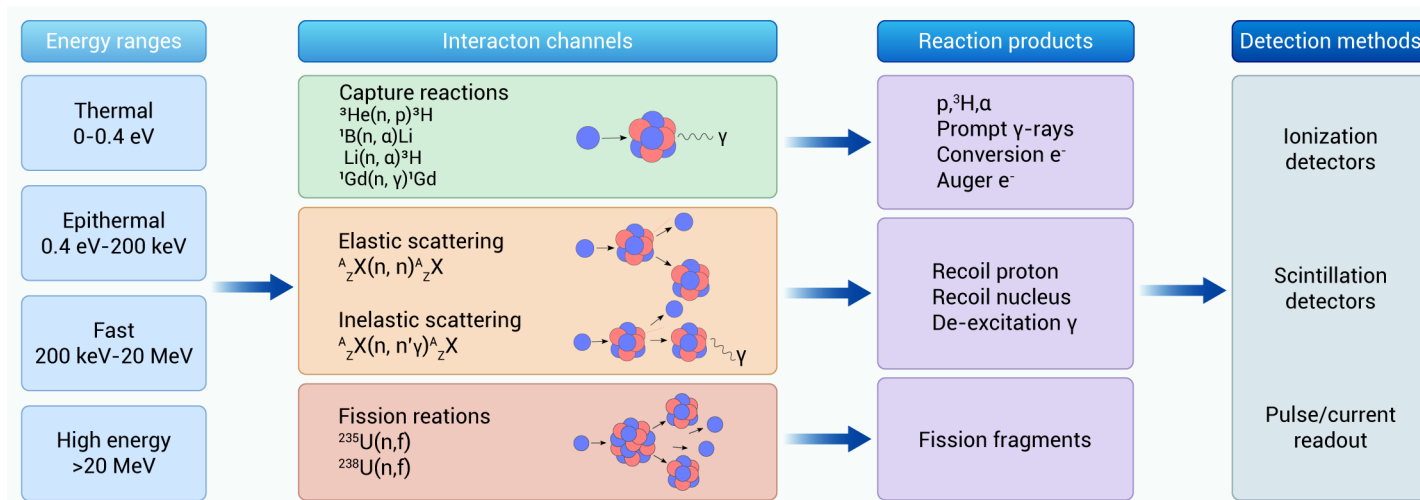


Figure 1. Brief summary of the neutron detection mechanism.

the neutron detection mechanism is shown in Figure 1.

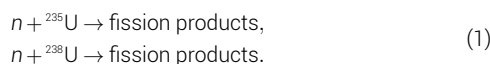
For practical purposes, the neutron energy spectrum is conventionally divided into four regions.⁵ The first region comprises thermal and low-energy neutrons (0 eV to 0.4 eV), extending from ultra-cold neutrons to the cadmium cut-off. Within this range, subcategories such as ultra-cold, cold, thermal, and hot neutrons are mainly distinguished by their equilibrium temperature and transport properties. The second region is the epithermal range (0.4 eV to 200 keV), in which many neutron-induced cross sections are characterized by a resonance structure. The third region corresponds to fast neutrons (200 keV to 20 MeV), which are typical of fission spectra and many accelerator-based sources, and are of particular importance for recoil-based detection techniques. The fourth region includes high-energy or relativistic neutrons (> 20 MeV), such as spallation neutrons and cosmic-ray secondaries, for which additional hadronic interaction channels become increasingly significant.

Neutron detection methods may also be classified according to the dominant interaction mechanism. For slow neutrons, the most widely used approach is based on neutron capture reactions, in which absorption of the neutron is followed by the emission of charged particles or prompt γ rays, as seen in reactions such as $^{10}\text{B}(n, \alpha)^7\text{Li}$ and $^3\text{He}(n, p)^3\text{H}$.

For fast neutrons, detection more commonly relies on scattering processes. In elastic scattering, the neutron transfers part of its energy to a recoil nucleus, which then produces the observable signal, whereas inelastic scattering leads to excitation of the target nucleus followed by characteristic de-excitation γ emission. A further important class of neutron detectors is based on fission reactions, in which neutron absorption by fissile materials generates highly ionizing heavy fragments, producing signals of exceptionally large amplitude.^{2,14}

Fission reaction

Physical principle and reaction cross-sections. Fission reactions represent a powerful mechanism for neutron detection due to the high Q -value of ~ 200 MeV per fission and the resulting heavy charged fragments with high stopping power. In the compound-nucleus picture, neutron absorption forms an excited nucleus that may overcome the fission barrier and split into fragments, creating intense ionization and large pulses, and enabling robust discrimination from many γ backgrounds. The reactions most widely exploited for detection are:



Fissile nuclides such as ^{235}U exhibit very large thermal fission cross-sections (~ 585 b at 25 meV) and resonances in the 1 eV to 1 keV region. In contrast, ^{238}U has a fission threshold near 700 keV and is mainly sensitive to fast neutrons (of the order of 1 b at ~ 10 MeV).²⁰ Fission-based detectors can be tuned to specific spectral ranges by selecting the converter isotope

and geometry.

Fission chambers. A fission chamber is a specialized ionization detector lined with a thin fissile layer (typically ^{235}U or ^{239}Pu) deposited onto an electrode.² Fission fragments ionize the fill gas (typically argon or argon-based mixtures), and the collected charge is measured either in pulse mode or in current mode. In both cases, the output is proportional to the fission rate, and thus to the incident neutron flux. Pulse mode is well suited to low and moderate fluxes where counting and timing are required.

At higher fluxes, current mode provides a robust flux monitor but sacrifices single-event information. In intense γ radiation, compensated ionization chambers use an additional non-fissile volume to subtract the γ -induced ionization. Detection efficiency can be improved by increasing the coated area or using multi-layer designs while keeping the self-absorption of fragments low. Practical issues include the intrinsic α activity of the fissile layer, handling and regulatory constraints, and the long-term stability of the coating under irradiation.^{2,21}

Elastic scattering

Physical principle and energy transfer. Fast-neutron detection often relies on elastic scattering, in which a neutron transfers part of its kinetic energy to a recoiling target nucleus. The charged recoil then deposits energy by ionization and excitation, producing scintillation light or an electrical pulse. The maximum recoil energy occurs for a head-on collision:

$$E_{\text{recoil}}^{\text{max}} = \frac{4m_A m_n}{(m_A + m_n)^2} E_n, \quad (2)$$

where m_A and m_n are the target and neutron masses, respectively, and E_n is the incident neutron energy.^{2,14} Light nuclei maximize the energy transfer; for hydrogen ($m_A \approx m_n$), nearly the full neutron energy can transfer to a recoil proton. In organic scintillators, the proton recoil light yield is notably reduced by ionization quenching compared to electron recoils of identical energy.²²

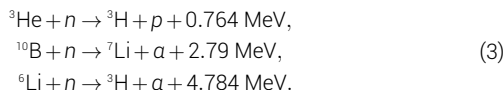
The role of hydrogen-enriched detectors. Hydrogen-rich media are central to recoil-based fast-neutron detection. Organic scintillators (liquids or plastics), composed mainly of C and H, provide fast timing performance and can be produced in large volumes. Gas-filled recoil detectors (proportional counters) commonly employ hydrogenous fills such as H_2 or CH_4 .

Recoil detectors are typically γ -sensitive: electron recoils from γ rays can heavily overlap neutron-induced pulses. In organic scintillators, this is mitigated by pulse shape discrimination (PSD), whereas most standard plastics show very weak PSD. The recoil signal provides the recoil proton energy E_p rather than the initial neutron energy E_n . For monoenergetic fast neutrons in hydrogen-rich scintillators, the recoil spectrum is continuous from 0 eV to E_n (the recoil continuum); therefore, accurate reconstruction of the incident spectrum generally requires response modeling or mathematical unfolding algorithms.^{23,24}

Neutron capture reactions

The principle of moderation and thermalization. Elastic scattering becomes inefficient for slow neutrons, so capture reactions dominate. A common strategy is to moderate fast neutrons through repeated scattering in a hydrogenous material (such as polyethylene) and then detect the resulting thermalized neutrons (~ 0.025 eV at room temperature) via capture. Thermalized neutrons then diffuse until captured or they escape. Moderation time and diffusion length depend on the moderator composition, geometry, and the initial neutron spectrum.^{2,14}

Key capture isotopes and their reactions (He-3, B-10, Li-6, Gd). Thermal neutrons can be detected efficiently using nuclides with large thermal capture cross sections (often following the $1/v$ law). Capture forms an excited compound nucleus that de-excites promptly by emitting charged particles or γ rays. Key reactions include:^{2,25}



The reaction with ${}^3\text{He}$ has the largest neutron capture cross section among the above reactions (~ 5300 b) and is commonly used in proportional counters or other ionization detectors. However, the low natural abundance of ${}^3\text{He}$ (about 1.4×10^{-4} %) has led to high costs and limited availability.^{26,27,28}

${}^{10}\text{B}$, with a neutron capture cross section of ~ 3800 b, is widely used due to the ready availability of boron-containing materials. Both gaseous materials such as BF_3 and solid materials such as boron oxide or boron carbide are employed using enriched boron (with a ${}^{10}\text{B}$ content greater than 96%) to increase detection efficiency. BF_3 proportional counters, first used to detect neutrons in 1939,²⁹ have low γ sensitivity, but a significant drawback of BF_3 is its high toxicity. Additionally, gas pressure and the presence of chemical impurities may impact the detector's baseline sensitivity.³⁰ Boron-lined detectors are another alternative that successfully avoids the use of toxic BF_3 gas.¹⁹

${}^6\text{Li}$ offers a lower capture cross section (~ 940 b) but a high energy release and good neutron- γ discrimination, since no prompt γ rays are produced. However, due to the lack of suitable gaseous lithium compounds, its use is restricted to solid-state materials, particularly scintillators such as ${}^6\text{LiF/ZnS}$, $\text{Cs}_2\text{LiYCl}_6\text{:Ce}$ (CLYC), etc.^{31,32}

Gadolinium is another notable target nucleus for neutron detection due to the extraordinarily large thermal neutron capture cross sections of its isotopes ${}^{156}\text{Gd}$ and ${}^{157}\text{Gd}$ (approximately 61 000 b and 254 000 b, respectively).^{25,33} These values are the highest among any stable nuclides. Neutron capture and subsequent de-excitation produce a complex cascade of high-energy γ rays with total energies of 7 MeV to 8 MeV, together with internal conversion and Auger electrons.³⁴ Even thin gadolinium layers absorb thermal neutrons very efficiently, making Gd-based converters highly attractive for compact or large-area detector geometries and completely complementary to boron-, lithium-, and helium-based technologies.³⁵

MATERIALS FOR NEUTRON DETECTION

Gaseous detectors

The "historical standard": BF_3 and ${}^3\text{He}$ proportional counters. Gas-filled proportional counters based on thermal-neutron capture in ${}^{10}\text{B}$ and ${}^3\text{He}$ have long been a standard technology for thermal neutron detection. In BF_3 counters, neutron capture produces energetic charged particles, such as α particles, which ionize the fill gas and generate a proportional pulse. In ${}^3\text{He}$ counters, the capture reaction produces secondary ions with a total kinetic energy of 764 keV, giving a characteristic capture peak.²

In proportional counters, charged reaction products create ion-electron pairs along their track in the gas. Under the applied electric field, electrons drift toward the anode and ions toward the cathode. Near the anode, the electric field becomes strong enough for electrons to produce secondary ionization, creating an avalanche. As a result, the total charge collected at the anode greatly exceeds the initial ionization charge. The ratio of collected to primary electrons defines the gas amplification factor, typically reaching 10^3 to 10^4 .

${}^3\text{He}$ tubes typically operate at several atmospheres of ${}^3\text{He}$ (from 4 atm to 8 atm) with a quench or stop gas such as CO_2 , whereas BF_3 tubes usually operate near atmospheric pressure, or up to about 4 atm in specialized high-sensitivity designs.^{36,37} The operating voltage determines the gain: increasing high voltage improves charge collection and pulse-height statistics up to an optimum, whereas excessive multiplication causes space-charge effects, nonlinearity, and system instability. Therefore, the operating voltage is chosen as a compromise between energy resolution, stability, and dead time.^{36,38} Gas composition and pressure are also critical, since higher stopping power better confines reaction products, reduces wall effects, sharpens the full-energy peak, and improves neutron- γ discrimination.³⁶

Key performance and neutron- γ separation. Neutron- γ separation in these detectors is usually based on pulse-height discrimination. Better confinement of the reaction products improves energy resolution and reduces overlap with γ -induced pulses.³⁶ BF_3 counters are widely used for thermal neutrons, and their efficiency can be calculated for many geometries and neutron energies.³⁷ ${}^3\text{He}$ counters can provide relatively uniform pulse amplitudes along the length of the tube.³⁹ In BF_3 counters, edge effects and wall effects can produce a low-energy tail in the pulse-height spectrum, so the measured efficiency depends on geometry and discriminator settings.⁴⁰

Under moderated ${}^{252}\text{Cf}$ tests, single ${}^3\text{He}$ tubes achieved 1.9 cps.ng $^{-1}$ to 3.1 cps.ng $^{-1}$, whereas a single BF_3 tube gave about 1.6 cps.ng $^{-1}$. Multi-tube assemblies reached 4.0 cps.ng $^{-1}$ for two ${}^3\text{He}$ tubes and 3.4 cps.ng $^{-1}$ to 3.8 cps.ng $^{-1}$ for four BF_3 tubes, with sub-linear scaling due to mutual shielding effects.³⁰ In general, ${}^3\text{He}$ detectors show higher neutron detection efficiency and better overall performance, while BF_3 detectors require higher operating voltages and are notably less sensitive.³⁷

Main constraints, limitations, and applications. The main limitation of ${}^3\text{He}$ technology is supply and cost, which have motivated the search for alternatives.^{41,18} BF_3 avoids dependence on ${}^3\text{He}$ but introduces safety and operational challenges because it is toxic and typically requires high voltage, increasing the risk of breakdown in humid environments.⁴¹ In mixed radiation fields, ${}^3\text{He}$ systems can remain stable at high γ dose rates (exceeding 200 rad h $^{-1}$), although pile-up and space-charge effects eventually limit performance.²⁷ Position-dependent efficiency losses ("edge effects") near tube ends can also shift pulses below threshold.²⁸ Despite these drawbacks, both BF_3 and ${}^3\text{He}$ counters remain important in portal monitors, scientific instrumentation, and neutron spectroscopy, and they continue to serve as benchmark technologies for alternative neutron detectors.

In summary, gaseous detectors and scintillation detectors address complementary needs in neutron detection applications. Gaseous proportional counters based on ${}^3\text{He}$ and BF_3 provide highly reliable thermal neutron counting with excellent intrinsic γ -ray rejection, making them vital for portal monitors, reactor instrumentation, and traditional neutron spectroscopy frameworks. However, their broader deployment is inherently constrained by limited time resolution, bulky form factors, low detection efficiency for fast neutrons, the toxicity of BF_3 , and the severe global shortage and rising cost of ${}^3\text{He}$ gas, alongside high operating voltages and power requirements.

To overcome these structural limitations, scintillation detectors offer an alternative approach by converting neutron-induced secondary particles or capture products into optical photons. This family of materials—encompassing liquids, plastics, inorganic crystals, and glasses—delivers several key advantages, including highly flexible and scalable geometries, superior timing resolution, high fast-neutron detection efficiency, and overall cost-effectiveness. Crucially, scintillation detectors enable real-time separation of neutron and γ -ray events through pulse shape discrimination (PSD). These attributes make scintillators exceptionally attractive for fast-neutron imaging, compact portal monitors, and deployment in demanding mixed-radiation fields, which are discussed in detail in the following subsections.

Liquid scintillators

Liquid organic scintillators are widely used for neutron detection due to their high hydrogen content, which provides efficient fast-neutron detection via elastic scattering on protons, while their scintillation kinetics often support pulse shape discrimination (PSD) between neutron- γ events.^{2,22} Their liquid form enables large detector volumes with uniform response, chemical tunability, and relatively low cost compared to many crystal scintillators.

Depending on the application, liquid scintillators can be used either as proton-recoil detectors for fast neutrons or as capture-gated detectors when loaded with thermal capture isotopes such as ^{10}B , ^6Li , or Gd .

Composition and traditional formulations. Traditional liquid scintillators consist of an organic solvent, a primary fluor, and often a secondary wavelength shifter. Common solvents include aromatic hydrocarbons such as toluene, xylene, pseudocumene (PC), di-isopropylnaphthalene (DIN), and linear alkylbenzene (LAB). Early successful applications in fast-neutron detection employed the xylene-based NE213 scintillator.^{42,43} Classical formulations such as BC-501A and its modern equivalents (e.g., EJ-301, EJ-309) remain benchmarks for fast-neutron detection, offering good light yield, fast time response, and excellent PSD capability.^{44,45,46}

Key performance and neutron- γ separation. A key advantage of many organic liquid scintillators is their intrinsic neutron- γ discrimination capability. This arises from differences in ionization density, which change the relative contributions of prompt and delayed scintillation components for recoil protons and electrons. This effect has been extensively exploited using analog and digital PSD techniques.^{47,48,49}

Boron-, lithium-, and gadolinium-loaded liquid scintillators. To extend sensitivity to thermal neutrons, liquid scintillators can be loaded with isotopes having large thermal-neutron capture cross sections, particularly ^{10}B , ^6Li , and Gd . In boron-loaded scintillators, neutrons are detected through the $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction after moderation in the hydrogenous medium. Boron loading can significantly increase neutron sensitivity while preserving strong neutron- γ discrimination, although the relatively low light output of the capture products and the presence of a competing γ branch limit performance.⁵⁰

Lithium-loaded scintillators provide an attractive alternative through the $^6\text{Li}(n,\alpha)$ reaction, which releases 4.78 MeV entirely in charged particles. This produces a compact, high-LET energy deposition and a well-defined capture signature. Capture-gated detection with ^6Li offers an effective prompt-delayed coincidence between recoil-proton signals and delayed neutron capture, enabling strong background suppression.⁵¹ Recent work has focused on stable lithium loading using microemulsions, surfactants, and lithium-6 salicylate, achieving improved optical transparency, preserved PSD capability, and reduced light-yield degradation.^{52,53}

Gadolinium-loaded liquid scintillators are mainly used when efficient thermal-neutron capture and a strong delayed signal are required. The isotopes ^{155}Gd and ^{157}Gd produce a characteristic ~ 8 MeV γ -ray cascade with capture times of tens of microseconds, making them highly effective in coincidence-based neutron tagging. Stable formulations based on LAB and organometallic gadolinium complexes have been extensively developed for large reactor neutrino experiments requiring long attenuation length, high light yield, and good chemical stability.⁵⁴ Unlike boron- or lithium-loaded scintillators, however, gadolinium capture produces only secondary γ rays, which cannot be separated from background γ interactions using only the PSD method.

Main constraints and applications. A central limitation of pure organic liquids is that they primarily detect fast neutrons via recoil protons. Sensitivity to thermal neutrons typically requires moderation and/or the introduction of a high-cross-section capture isotope. Operational constraints include flammability and toxicity (depending on the solvent), chemical compatibility, long-term stability, oxygen quenching, and impurity-related attenuation. Recently, neutron detection using liquid scintillators has expanded into areas such as reactor antineutrino measurements, nuclear-security alarm systems, neutron spectroscopy, and astrophysics.^{51,55,56} The efficiency of neutron detection can be further improved with advanced reflector and shielding designs.⁵⁷

Plastic organic scintillators

Plastic scintillators are composite materials fabricated by dispersing organic fluors within a polymer matrix. They combine fast fluorescence decay and tunable emission wavelengths with the ease of processing and large-volume molding capabilities of plastics.^{58,59} While widely used in traditional radiation detection, their current development is driven by the need for cost-effective, real-time neutron- γ discrimination, which is crucial for nuclear security, nuclear energy, fundamental physics, and space

exploration.⁶⁰

Composition and traditional formulations. Plastic scintillators are based on aromatic polymer matrices, primarily polyvinyltoluene (PVT) and polystyrene (PS) (see examples of plastic scintillators in Figures 2A-B). PVT is the industrial standard, offering $\sim 20\%$ higher scintillation efficiency than PS due to more effective exciton migration pathways.⁶⁷ Alternatively, polymethyl methacrylate (PMMA)-based matrices provide unique mechanical flexibility and enhanced transparency, though at the cost of significantly reduced light yield.⁶⁸

Because self-absorption in the polymer matrix can reduce the absolute light yield, plastic scintillators commonly employ a primary fluor together with a secondary wavelength shifter. The primary fluor converts matrix excitation into fluorescence, and the wavelength shifter shifts the emission to longer wavelengths where reabsorption is minimized and photodetector spectral matching is improved. Frequently used primary fluors include 2,5-diphenyloxazole (PPO) and p-terphenyl, while typical wavelength shifters include 9,10-diphenylanthracene, 1,4-bis(2-methylstyryl) benzene (bis-MSB), and 1,4-bis(5-phenyl-2-oxazolyl) benzene (POPOP).⁶⁹ Energy transfer in these materials is usually described by Förster resonance energy transfer (FRET) from the matrix to the fluor system.

Plastic scintillators achieve neutron- γ discrimination via pulse shape discrimination (PSD), based on distinct emission kinetics resulting from different ionization densities. Analyzing fast and slow pulse components enables effective neutron- γ separation. In 1960, Brooks developed early PSD plastics with nearly 100% counting efficiency for 2 MeV protons.⁷⁰ The EJ-299 series later became the first commercial PSD plastics, offering a density of 1.08 g cm^{-3} and a 56% anthracene light yield.⁷¹ Subsequently, Eljen introduced EJ-276 (Figure 2A), utilizing a combination of aromatic, chlorinated, and ketone solvents.⁷² This compositional modification enhances physical stability and allows higher dye loading, delivering superior PSD capability.⁷³

Application. For thermal-neutron detection, plastic scintillators are commonly loaded with capture isotopes such as ^6Li , ^{10}B , ^{157}Gd , or ^{155}Gd . In solid plastics, the main challenge is to introduce these inorganic additives while preserving optical transparency, light yield, and manufacturing scalability. Lithium-loaded plastics based on lithium methacrylate have shown promising optical quality and fast time response.^{74,75} Boron-loaded plastics can achieve relatively high loading fractions and improved thermal-neutron sensitivity.⁷⁶ For example, meta-carborane-doped plastics demonstrated a PSD figure of merit of 1.4 ± 0.03 in the 50 keV to 100 keV range.⁷⁷ Dumazert et al. proposed a gadolinium-core spherical scintillator, using capture-induced gammas for signal discrimination.⁷⁸ They also developed a dual-scintillator system (Gd-loaded and Gd-free) using non-linear signal smoothing and hypothesis testing algorithms, enabling robust thermal and fast neutron separation while improving signal-to-noise ratios.⁷⁹

Plastic scintillators are highly attractive for neutron imaging and localization as they can be fabricated in large plates, segmented arrays, or application-specific geometries. Chuirazzi et al. found that PVT-based scintillators with 2% Flrpic dye doping and black backing effectively doubled the neutron image resolution.⁸⁰ Heath et al. developed a pixelated, PSD-capable array coupled to position-sensitive PMTs for high-resolution neutron localization.⁸¹ He et al. fabricated large TPE-4Br@PVT scintillators achieving a spatial resolution of 2.03 lp mm^{-1} ,⁸² while Barr et al. demonstrated 3D-printed complex geometry detectors with a thermal neutron sensitivity of 30 photons MeV^{-1} .⁸³

Crystal scintillators

Organic fast-neutron crystalline scintillators. Organic crystalline scintillators constitute a vital class of recoil-based fast-neutron detectors, complementing capture-based inorganic thermal-neutron counters.^{84,85} Instead of specialized converting isotopes, fast neutrons are detected through elastic scattering on hydrogen nuclei, producing high-energy recoil protons.²² Because these proton recoils exhibit a significantly higher linear energy transfer (LET) than γ -induced secondary electrons, they generate a larger delayed scintillation component via triplet-triplet annihilation (TTA). This kinetic divergence provides the physical basis for pulse shape discrimination (PSD), enabling robust neutron- γ separation within mixed radiation fields.^{86,87}

Representative organic single crystals include anthracene, trans-stilbene, and p-terphenyl. Anthracene historically defines the reference light yield stan-

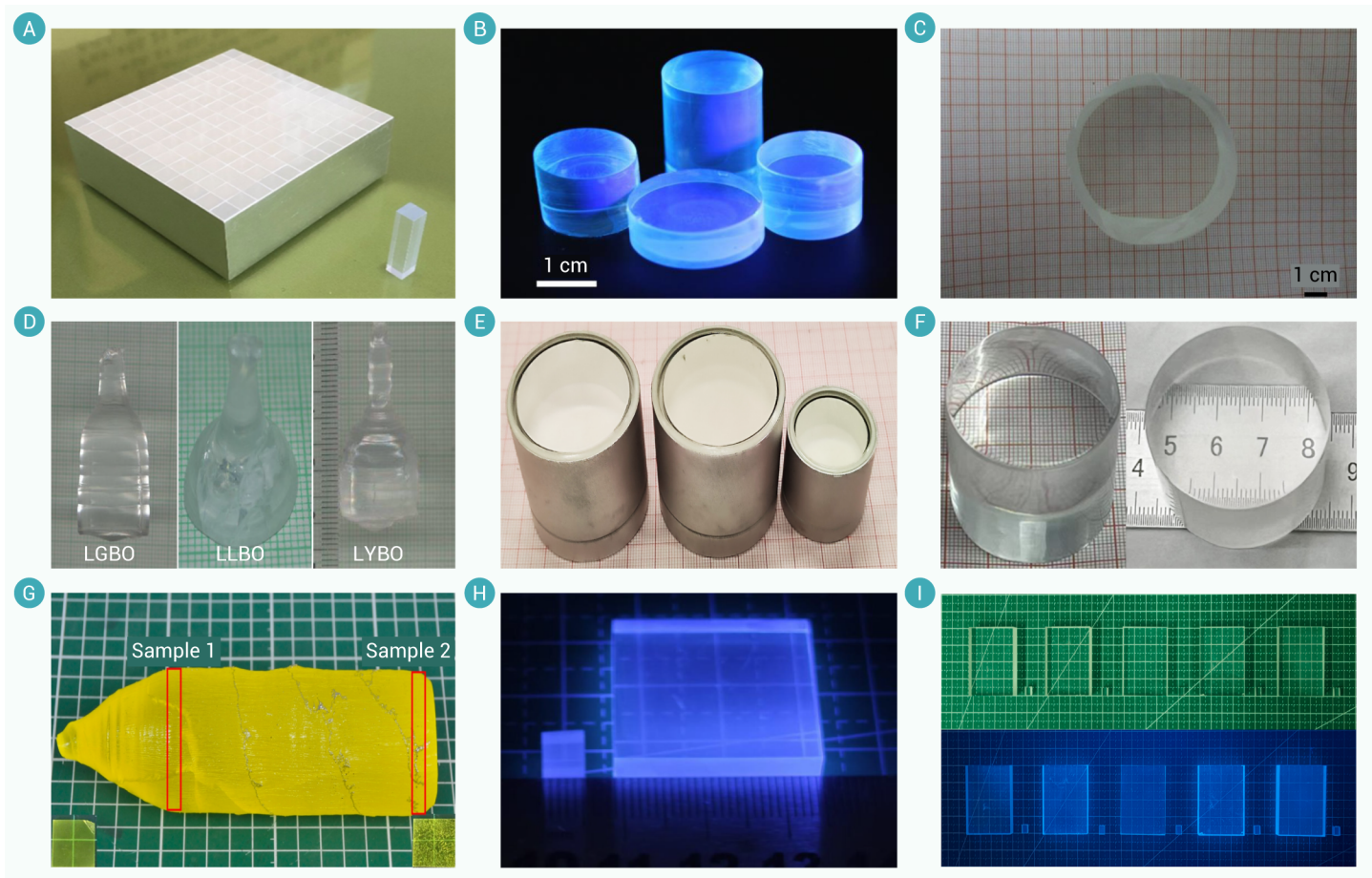


Figure 2. Photographs of representative neutron- γ scintillators (A) Plastic scintillator (EJ-276) array with a pixel size of 4 mm $\times$ 4 mm $\times$ 20 mm (Reproduced under the CC BY-NC-ND 4.0 license).⁵¹ (B) Examples of plastic scintillators based on triphenyl pyrazoline (PZ) and polyvinyltoluene (PVT) (Reproduced with permission.⁵² Copyright 2022, Wiley). (C) NaI:Ti,⁶Li crystal ingot (Reproduced with permission. Copyright 2026, Crystalab Co.). (D) LGBO, LLBO, and LYBO borate crystal samples (Reproduced with permission.⁵³ Copyright 2018, Wiley). (E) Packaged CLYC detector modules in 1" $\times$ 1" and 1.5" $\times$ 1.5" formats (Reproduced with permission. Copyright 2026, Crystalab Co.). (F) CLLB crystal ingots (Reproduced with permission. Copyright 2026, Crystalab Co.). (G) 50 mm $\times$ 120 mm GAGG:Ce crystal (Reproduced with permission.⁵⁴ Copyright 2021, Science Press). (H) Large-size ⁶Li-doped glass scintillator sample (Reproduced with permission.⁵⁵ Copyright 2025, IOP). (I) Large-size Gd-doped glass scintillator sample (Reproduced with permission.⁵⁶ Copyright 2026, Elsevier)

dard,²² while trans-stilbene remains the industry benchmark for fast-neutron spectroscopy due to its high hydrogen content, fast decay kinetics, and exceptional triplet transport dynamics.^{86,87} Recent scalable solution-growth techniques, replacing traditional melt growth, enable the commercial fabrication of large-volume, high-optical-quality stilbene single crystals at reduced cost. Solution-grown stilbene demonstrates superior low-energy PSD performance at thresholds < 100 keV_{ee} and enhanced scalability, making it highly attractive for high-efficiency spectroscopy systems.^{85,87}

Solid-state p-terphenyl crystals offer non-hazardous alternatives to liquid scintillators (e.g., NE-213 or BC501A) by eliminating toxicity, volatility, and flammability risks. Experimental measurements utilizing ²⁵²Cf and monoenergetic beams verified their applicability for fast-neutron spectroscopy, though their low-energy PSD can be slightly lower than that of optimized liquids.^{88,89} More recently, tetraphenylethylene (TPE) single crystals introduced dual-mode fast-neutron- γ discrimination via simultaneous PSD and pulse-height discrimination (PHD), showcasing novel molecular-design strategies.^{90,91} However, widespread field deployment of organic single crystals remains partially restricted by mechanical fragility along cleavage planes, anisotropic scintillation response, and manufacturing limits in large-scale geometries.

Inorganic conventional thermal-neutron crystalline scintillators. ⁶Li:Eu remains a representative thermal-neutron scintillator since the 1950s.^{92,93} The ⁶Li(n, α)t reaction produces a distinct neutron feature that is well separated in pulse-height spectra.⁹⁴ Typical datasheets report microsecond-scale decay and blue emission. Practical thermal-neutron stopping can be achieved with millimeter-scale thickness, enabling compact probes and phoswich designs in which neutron identification relies mainly on pulse-height separation from

the γ background.⁹⁵

Lithium co-doped NaI(Tl,Li) extends the familiar NaI platform toward combined γ spectroscopy and neutron sensitivity (see Figure 2C). A key engineering limitation is Li non-uniformity in large boules, which broadens γ peaks and can degrade PSD consistency.⁹⁶ Even so, NaI(Tl,Li) demonstrates practical neutron- γ PSD in a scalable host, with large-format studies typically reporting PSD FOM values around 2 to 4.⁹⁶ Hygroscopicity remains a packaging constraint, similar to ⁶Li:Eu. In addition, due to the low level of Li loading, the thermal-neutron detection efficiency is correspondingly limited.

Lithium-loaded composite screens are widely used when strong γ rejection and large-area coverage are prioritized over spectroscopy.³¹ The standard choice is ⁶LiF/ZnS:Ag (e.g., EJ-426, BC-704), where ⁶LiF converts neutrons and ZnS:Ag provides high light output with a pronounced slow component and afterglow. This long tail enables simple charge-comparison PSD and robust suppression of γ -induced events.⁹⁷⁻⁹⁹ For position-sensitive designs, the screen is commonly coupled to wavelength-shifting fibers (WLSF). Such dual-layer configurations have been applied to diffraction measurements, while optimization remains primarily an engineering problem of geometry, optics, and readout rather than energy spectroscopy.^{100,101}

Boron-bearing crystals provide another approach, often emphasizing chemical robustness via borate frameworks. A typical family is Li₆R(BO₃)₃:Ce (where R = Gd, Lu, Y), illustrated in Figure 2D.⁶³ Composition is used to balance timing and neutron response (e.g., fast timing in Lu-based compositions and enhanced neutron sensitivity in Gd-containing compositions), but relatively low light yield compared with leading halide crystals and mechanical brittleness still restrict broader deployment.¹⁰²

Elpasolite halide crystals. In mixed neutron- γ fields, Li-based Elpasolite halide scintillators are attractive because they integrate three capabilities that conventional neutron scintillators rarely deliver simultaneously: high thermal-neutron efficiency, strong neutron- γ discrimination, and γ -ray spectroscopy suitable for isotope identification.^{31,103,104} Representative materials include $\text{Cs}_2\text{LiYCl}_6 : \text{Ce}$ (CLYC) and $\text{Cs}_2\text{LiLaBr}_6 : \text{Ce}$ (CLLB), together with mixed-halide derivatives such as $\text{Cs}_2\text{LiLaBr}_{6-x}\text{Cl}_x : \text{Ce}$ (CLLBC).

Their core advantage is true dual-mode operation enabled by complementary physics in the same crystal: ^6Li capture provides a characteristic charged-particle signature for efficient neutron counting, while the high-Z host supports γ interaction and isotope identification from γ spectra, allowing compact detector architectures without separate neutron and γ modules.^{105,106,85} Figures 2E-F show photos of CLYC and CLLB crystals, respectively, illustrating practical detector-scale formats.

Within this family, composition provides clear performance differentiation. CLYC is often highlighted for strong neutron- γ discrimination because it exhibits an ultrafast γ emission channel associated with core-valence luminescence (CVL).^{107,108} This component increases γ pulse promptness and thus enhances neutron- γ pulse-shape contrast while preserving γ spectroscopy and high thermal-neutron response.¹⁰⁹ In addition, chlorine-related fast-neutron reactions ($^{35}\text{Cl}(n,p)^{35}\text{S}$ and $^{35}\text{Cl}(n,\alpha)^{32}\text{P}$) can generate charged-particle features that support fast-neutron response and, in suitable fields, spectrometric signatures rather than pure counting.¹¹⁰⁻¹¹²

CLLB is recognized for exceptionally high light output and excellent γ energy-resolution performance, making it well suited to applications where γ -emitter identification is the dominant requirement.^{113,114} However, the intrinsic time contrast between neutron and γ pulses in CLLB:Ce can be smaller than in CLYC, which can limit PSD robustness under demanding mixed-field conditions and may require trade-offs between discrimination and photon yield.

CLLBC extends the CLLB platform through mixed-halide engineering, where partial substitution of Br^- by Cl^- reshapes scintillation kinetics to strengthen PSD while retaining competitive γ spectroscopy.^{115,116} The presence of chlorine also introduces a $^{35}\text{Cl}(n,p)$ pathway that improves relevance in broader neutron fields.¹¹⁷ Reported behavior further suggests improved tolerance for discrimination-critical operation at elevated temperatures compared with CLLB, supporting more stable mixed-field performance when environmental conditions vary.¹¹⁸

Overall, CLYC, CLLB, and CLLBC constitute a differentiated Elpasolite portfolio for neutron- γ dual-mode detection: CLYC emphasizes PSD strength enabled by ultrafast γ emission, CLLB prioritizes maximum light yield and γ spectroscopy, and CLLBC uses mixed-halide tuning to balance discrimination, γ response, and broader neutron-field applicability.

GAGG. Gadolinium aluminum gallium garnet ($\text{Gd}_3\text{Al}_2\text{Ga}_3\text{O}_{12} : \text{Ce}$, GAGG) is a distinctive scintillator in which a single crystal can simultaneously function as a neutron converter, absorber, and light emitter. Owing to the presence of natural gadolinium, whose isotopes exhibit exceptionally large thermal-neutron capture cross sections, submillimeter-thick GAGG crystals are in principle capable of absorbing thermal neutrons with high efficiency (Figure 2G).¹¹⁹ Following neutron capture, excited compound nuclei are formed and subsequently de-excite through cascade transitions, releasing γ rays with a total energy of approximately 8.5 MeV, together with numerous internal conversion electrons and characteristic X-rays. This unique combination of neutron conversion and scintillation response provides the physical basis for the use of GAGG in compact and efficient neutron-sensitive detection platforms.

GAGG has a high density (6.6 g cm^{-3}) with high light output, making it highly suitable for γ -ray detection. More broadly, GAGG has attracted sustained attention because it combines a high effective atomic number, strong scintillation performance, good chemical stability, and resistance to moisture absorption. The potential of GAGG for γ -ray imaging has been demonstrated across a wide range of representative Compton-imaging scenarios. Early studies established the feasibility of GAGG-based medical Compton cameras for three-dimensional imaging of multiple radionuclides.¹²⁰ Subsequent work further extended its use to dual-photon emission coincidence imaging with crystals of different thicknesses,¹²¹ PET-Compton hybrid imaging,¹²² and 3D multimodal imaging.¹²³

Related developments have also included omnidirectional 4π Compton imaging systems for environmental monitoring, portable GAGG-based cameras deployable on unmanned aerial vehicles,^{124,125} three-layer portable Compton cameras for 1 MeV class γ rays,¹²⁶ and compact low-power instruments for γ -ray measurements in astrophysics.¹²⁷ Taken together, these studies show that GAGG is not merely a high-yield scintillator, but a practically validated platform for γ -ray imaging across nuclear physics, environmental monitoring, astronomy, and medical imaging.

Among these application directions, GAGG appears particularly attractive for next-generation PET, especially for high-resolution and small-animal systems. This interest arises from its favorable combination of high light yield, negligible intrinsic radioactive background, and optical compatibility with light-sharing readout architectures. A DOI resolution of 1.2 mm has already been reported for 20 mm-long GAGG crystals, corresponding to an almost twofold improvement over LYSO under comparable detector geometry.^{128,129}

This advantage is further exemplified in mixed LYSO/GAGG detector arrays with shared SiPM readout, where pulse shape discrimination enables crystal-by-crystal identification and allows GAGG edge pixels to be introduced for enhanced DOI encoding without compromising the high light output and timing performance of LYSO in the central region.¹³⁰ Accordingly, Ce-doped GAGG is being actively developed for PET detectors with continuous DOI encoding matched to submillimeter crystal pitch, providing an important route toward ultrahigh-resolution small-animal PET and whole-body PET with more spatially uniform resolution.^{128,131,132}

In addition to PET, related Gd-containing garnet scintillators have also been explored in CT, photon-counting CT (PCCT), and SPECT, where GGAG/GYGAG ceramics, GAGG-SiPM detector configurations, and GAGG-based γ cameras have demonstrated the broader applicability of this material family to high-resolution X-ray and γ -ray imaging, including BNCT dose monitoring and self-collimating SPECT architectures.¹³³⁻¹³⁸

Glass scintillators

^6Li -loaded glass scintillators. Research on glass scintillators for neutron detection commenced in the 1960s with the pioneering work of Ginther and colleagues. Initial efforts focused on Ce^{3+} -doped Al-B-Si glass systems, originally developed for γ -ray detection, which exhibited a light yield approximately 5% to 10% of that of NaI(Tl) crystals.^{139,140} A significant advancement came with the introduction of lithium into the Li-Mg-Al-Si glass system, which substantially enhanced the scintillation light output and shifted the research focus towards ^6Li -based glass scintillators.¹⁴¹

Optimal performance was achieved when the compositional ratio $(\text{Al} + \text{Li} + \text{Mg} + \text{Ce})/\text{Si} = 1$, with the Ce^{3+} concentration peaking at 0.3 mol% to 1 mol%. Exceeding this range led to performance degradation due to the quenching effect caused by the formation of Ce^{4+} . In the 1970s, the British team led by Spowart conducted systematic studies on Si-Al-Li-Mg lithium glasses with varying ^6Li contents (2.2 wt%, 6.1 wt%, and 11.6 wt%).¹⁴² Their work provided a foundational understanding of the temperature dependence of light yield, decay time, and energy transfer mechanisms within these amorphous materials.

Driven by growing demands from military and detection applications in the 1980s, intensified research and development efforts in the United States, United Kingdom, Russia, and Japan led to the commercialization of several lithium glass scintillator series (GS, NE, and KG series). Among these, the GS series of ^6Li -containing glasses, developed by Levy West Laboratory (now Scintacor), emerged as the mainstream commercial product (e.g., Figure 2H), establishing a standard for practical neutron detection applications. However, an inherent trade-off remains between achieving higher ^6Li content for better neutron capture and maintaining high optical transparency and light yield.

Recently, Ren et al. partially substituted oxygen ions with fluorine ions in a ^6Li -enriched Li-Mg-Al-Si glass system and demonstrated improved scintillation performance, yielding a neutron light yield of $\sim 7058 \text{ ph/n}$, which is about 1.18 times higher than the reported yield for GS20 glass.⁶⁵ The relative width (FWHM) of the thermal neutron peak is 10.5%, indicating good energy resolution.

While silicate glasses face limitations in Li loading and Ce^{3+} stability, phosphate glasses offer superior Li/Ce solubility and reduced issues with phase

separation. For applications requiring ultra-fast timing (e.g., fusion diagnostics), Pr^{3+} -doped fluoro-oxide glasses with sub-20 ns decay times present a promising alternative, despite their emission in the deep UV.¹⁴³

Future research directions need to optimize the content and distribution of neutron-absorbing nuclides (^6Li , ^{10}B) and activator ions, reduce energy quenching centers, improve radiation hardness, and deepen the fundamental understanding of energy transfer mechanisms within the glass matrix to enhance overall performance.¹⁴⁴

Gadolinium-loaded glass scintillators. Gadolinium is a key material for neutron detection due to its extraordinarily high thermal-neutron capture cross section. The two main isotopes, ^{155}Gd and ^{157}Gd , exhibit thermal neutron capture cross sections of approximately 60 700 b and 253 700 b, respectively.¹⁴⁵ When a thermal neutron is captured by a gadolinium nucleus, it forms excited states of ^{156}Gd and ^{158}Gd , which subsequently de-excite and release a series of secondary products, including prompt γ rays, internal conversion electrons (ICE), X-rays, and Auger electrons.

The total reaction Q-values are about 8.5 MeV and 7.9 MeV, respectively.¹⁴⁶ These secondary products, especially the prompt γ rays and internal conversion electrons whose energies are concentrated in the medium and low energy regions, provide an effective signal source for the indirect detection of neutrons.

Based on the requirements of future nuclear radiation detection for advanced glass scintillators, the High-density Glass Scintillator Collaboration (GS Group)¹⁴⁷ developed a Ce^{3+} -doped gadolinium-rich borosilicate fluoro-oxide glass (GFO:Ce), Figure 2I).^{66,148-150} The GFO:Ce glasses indicate a thermal neutron capture efficiency of approximately 78.48%, with each captured neutron producing on average about 4.45 prompt γ rays and 0.37 internal conversion electrons.^{151,152} In the low energy region (≤ 1 MeV), the internal conversion electrons are mainly concentrated in two energy ranges: 29 keV to 40 keV and 70 keV to 90 keV.¹⁵² The energy deposition of these secondary particles in the scintillator gives rise to characteristic peaks; the simulated deposition spectrum exhibits distinct peaks at 35 keV and 80 keV, providing key references for neutron energy spectrum measurements.

In experiments, the measured neutron energy spectrum shows a prominent characteristic peak at ~ 80 keV, which mainly originates from the prompt γ rays emitted during the de-excitation from the first excited state to the ground state after neutron capture by ^{155}Gd and ^{157}Gd (with energies of 88.9 keV and 79.5 keV, respectively). By comparing the scintillation light waveforms from an Am-Be neutron source and a ^{137}Cs γ -ray source, it was found that the neutron signals exhibit decay times of ~ 210 ns and ~ 2275 ns, while the γ signals show decay times of 221 ns and 1579 ns.¹⁵² This kinetic divergence provides a potential means for future neutron- γ discrimination. Additionally, the detection efficiency of GFO:Ce for a moderated Am-Be neutron source is estimated to be about 0.156 cps nv^{-1} .¹⁵²

Simultaneously, measurements of the fast-neutron response of GFO:Ce were carried out at the backward beam line of the China Spallation Neutron Source (CSNS). For fast neutrons above 30 MeV, the (n, p) and (n, α) reactions on ^{16}O and ^{27}Al have considerable neutron reaction cross sections. When the incident neutron energy is 14 MeV, several reaction channels—(n, p), (n, α), and (n, d)—on nuclides such as ^{16}O , ^{27}Al , ^{155}Gd , ^{157}Gd , and ^{10}B possess non-negligible cross sections. At a lower incident neutron energy of 1.9 MeV, the equivalent γ energy is below 1 MeV_{ee}; this contribution essentially comes from the Gd(n, γ) reaction.

The neutron energy spectrum of the GFO:Ce glass clearly exhibits two prominent neutron peaks, located at ~ 80 keV_{ee} and ~ 180 keV_{ee}, respectively. The ~ 80 keV_{ee} peak mainly arises from the prompt γ rays emitted during the transition from the first excited state to the ground state of ^{156}Gd and ^{158}Gd , while the ~ 180 keV_{ee} peak is primarily due to the γ rays released in the transition from the second excited state to the first excited state of the same nuclei.¹⁵³ Therefore, the above results demonstrate that GFO:Ce glass can effectively detect both thermal neutrons and fast neutrons.

Comparison of materials for neutron detection

Figures 2A-I present photographs of representative neutron- γ scintillators, encompassing plastic, liquid, inorganic crystal, and glass scintillators. Their typical performance parameters are systematically summarized in Table 1. Among these materials, plastic scintillators, liquid scintillators, and certain inorganic crystals exhibit a significant difference in scintillation kinetics—specifically in the decay times of neutron- and γ -induced signals. This distinct temporal response enables the application of pulse shape discrimination (PSD) for particle identification. The characteristic differences between neutron- and γ -induced pulse shapes, along with representative PSD-energy scatter plots, are illustrated for various materials: NaI:Li (Figures 3A & 4A), CLYC (Figures 3B & 4B), CLLB (Figures 3C & 4C), CLLBC (Figures 3D & 4D), BC532A2 liquid scintillator (Figures 3E & 4E), and EJ276 plastic scintillator (Figures 3F & 4F).

NEUTRON- γ DISCRIMINATION VIA PULSE SHAPE DISCRIMINATION
The physical basis of PSD

Pulse Shape Discrimination (PSD) is an analytical technique that distinguishes between different types of particles by analyzing the characteristic temporal profiles of scintillation light produced upon particle interaction with a scintillating material. The basis of this discrimination lies in the dependence of the scintillation mechanism on the linear energy transfer (LET), or ionization density, of the incident radiation. Particles with higher ionization density generate denser ionization tracks, which modify the excitation and relaxation pathways within the scintillator.

These inherent differences manifest as measurable variations in the

Table 1. Quantitative comparison of representative scintillation materials for neutron detection and neutron- γ discrimination.

Material	Density (g cm ⁻³)	Light Yield		ER @ 662 keV (%)	Decay Components (ns)	Max. Emission λ (nm)	Typical PSD FOM	Fast Neutron Capability	Hygroscopicity
		Thermal n (ph/n)	γ (ph/MeV)						
EJ-254 plastic scintillator	1.1	—	8600	—	13 / 35 / 270	~ 425	$\sim 1.2@100$ keV _{ee}	✓	No
EJ-301 liquid scintillator	0.874	—	12000	—	3 / 32 / 270	~ 425	$\sim 1.3@100$ keV _{ee}	✓	No
⁶ Li-doped glass	2.4	8500	3000	20.0	20 / 58 / 105	~ 395	PHD-based	×	No
Gd-doped glass	6.0	—	2000	25.0	60 / 500	~ 390	PHD-based	×	No
⁶ LiI:Eu	4.1	50,000	12,000	7.5	1400	~ 470	PHD-based	×	Yes
NaI:Tl, Li	3.66	60,000	35,000	6.3	230 / 1100	~ 415	2.0	×	Yes
⁶ LiF/ZnS:Ag	2.6	160,000	75,000	—	125 / 1000 / 10000	~ 450	—	×	No
Li ₆ Gd(BO ₃) ₃ : Ce	3.5	40,000	14,000	8.0	440 / 200 / 1000	~ 420	≤ 1.0	×	No
Cs ₂ LiYCl ₆ : Ce	3.3	70,000	20,000	3.9	1 / 50 / 1000	~ 370	4.2	✓	Yes
Cs ₂ LiLaBr ₆ : Ce	4.2	180,000	60,000	2.9	180 / 1080	~ 420	1.2	×	Yes
Cs ₂ LiLaBr _{6-x} Cl _x : Ce	4.0	160,000	55,000	3.0	115 / 500 / 1500	~ 410	3.5	✓	Yes

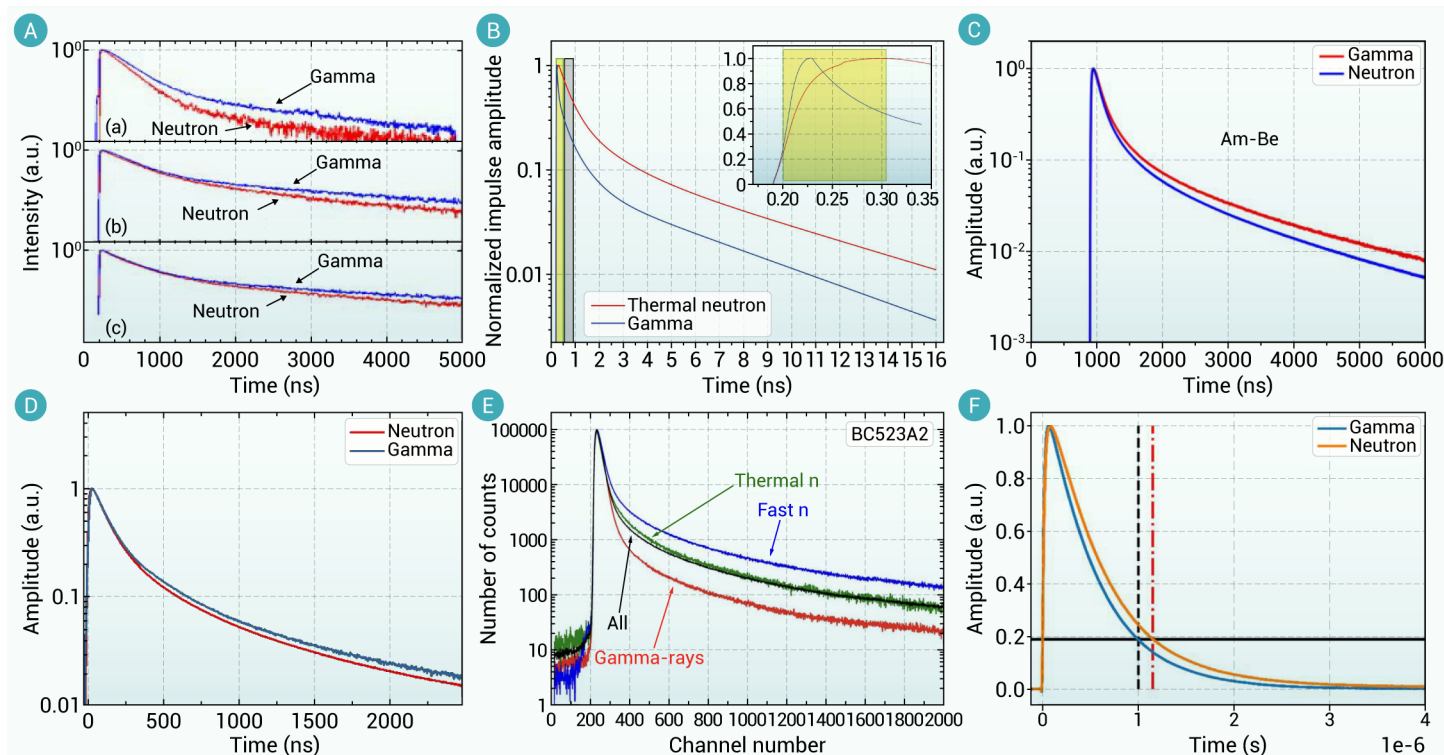


Figure 3. Typical differences between neutron- and γ -induced pulse shapes in neutron- γ detection scintillators (A) NaI:Li (Reproduced with permission.⁹⁶ Copyright 2018, Wiley). (B) CLYC (Reproduced under the CC BY-NC-ND 4.0 license.¹⁵⁴). (C) CLLB (Reproduced under the CC BY 4.0 license.¹⁵⁵). (D) CLLBC (Reproduced with permission.¹¹⁶ Copyright 2025, IEEE). (E) BC523A2 liquid scintillator (Reproduced with permission.¹⁵⁶ Copyright 2010, IEEE). (F) EJ276 plastic scintillator (Reproduced with permission.¹⁵⁷ Copyright 2024, Elsevier)

temporal shape of the emitted light pulse, thereby allowing reliable identification and classification of particles such as neutrons and γ rays. A brief illustration of the PSD methodology and its physical basis is shown in Figure 5.

Energy transfer mechanism and ionization density. The scintillation detector converts incident radiation energy into a measurable light pulse. γ rays and neutrons, however, interact via fundamentally distinct mechanisms.^{2,160} γ rays interact primarily with atomic electrons through the photoelectric effect and Compton scattering, with secondary electrons depositing energy via ionization and excitation.

In contrast, neutrons interact mainly with atomic nuclei, typically producing heavy charged particles such as protons or α particles. According to the Bethe formula,¹⁶¹ these heavy charged particles exhibit a much higher ionization density than electrons, leading to localized, dense energy deposition—a difference that critically influences scintillation kinetics. Exceptions include radiative capture processes in gadolinium-doped materials, where energy release occurs primarily via secondary γ emission cascades.

Scintillation kinetics. Scintillation materials with PSD capability exhibit distinct excitation and recombination dynamics based on the incident radiation's ionization density, yielding characteristic temporal light profiles that form the physical basis for PSD. Notably, the underlying kinetics differ fundamentally between organic and inorganic scintillators due to their electronic structures and energy transfer mechanisms.

Commercial PSD-capable organic scintillators comprise three main categories: single crystals (e.g., anthracene, stilbene, and p-terphenyl),^{86,162–164} liquid scintillators (e.g., BC501A, BC519, EJ-301, EJ-309),^{165–168} and plastic scintillators (e.g., EJ-276, EJ-299-33).^{169–171}

Their PSD mechanism centers on triplet–triplet annihilation (TTA),^{15,60,84,172} which generates delayed fluorescence. Radiative decay from the S_1 state to the ground (S_0) state yields prompt fluorescence on a nanosecond timescale. In contrast, direct radiative transition from the T_1 state to S_0 is spin-forbidden due to multiplicity selection rules. However, two T_1 excitons can undergo bimolecular TTA ($T_1 + T_1 \rightarrow S_0 + S_1$), generating delayed fluorescence extending from hundreds of nanoseconds to microseconds.

The microscopic origin of the higher density of T_1 excitons under neutron irradiation is directly linked to the high linear energy transfer (LET) of the

resulting heavy charged particles, such as recoil protons or α particles.² These highly ionizing particles create ultra-dense ionization tracks that favor electron–ion recombination processes rather than direct excitation. According to quantum spin statistics, random charge recombination natively populates triplet and singlet states in a 3:1 ratio, drastically multiplying the local T_1 exciton density.

In contrast, low-LET fast electrons induced by γ -ray interactions deposit energy more diffusely and primarily excite the medium via direct dipole-allowed transitions that selectively populate singlet (S_1) states. Consequently, neutron-induced heavy particles significantly enhance the TTA and delayed emission pathways, whereas γ -induced electrons yield predominantly prompt fluorescence, enabling highly effective pulse shape discrimination.

Among inorganic scintillators, $\text{Cs}_2\text{LiYCl}_6 : \text{Ce}$ (CLYC)¹¹⁰ is a prominent elpasolite crystal renowned for its excellent PSD capability, enabling the clear separation of neutron and γ -ray signals. This family of materials also includes related compounds such as $\text{Cs}_2\text{LiLaBr}_6 : \text{Ce}$ (CLLB),¹⁷³ $\text{Cs}_2\text{LiLaCl}_6 : \text{Ce}$ (CLLC),¹⁷⁴ $\text{Cs}_2\text{LiYBr}_6 : \text{Ce}$ (CLYB),¹⁷⁵ and mixed-halide $\text{Cs}_2\text{LiLaBr}_{6-x}\text{Cl}_x : \text{Ce}$ (CLLBC).¹⁵⁹

The superior PSD performance of these inorganic scintillators is fundamentally attributed to Core-to-Valence Luminescence (CVL),^{104,176,177} which is an ultra-fast radiative process that is selectively quenched by highly ionizing particles. Due to this localized quenching effect, the CVL component is substantially more suppressed in neutron-induced scintillation pulses than in those generated by γ rays. This alters the relative contribution of the prompt emission channel, resulting in distinct temporal pulse profiles and enabling effective particle discrimination.^{178,179}

Traditional PSD analysis methods

Zero-crossing and charge comparison are two well-established techniques for time-domain PSD in traditional analysis methods.^{180–182}

Zero-crossing method. The zero-crossing method is a robust, efficient, and well-established approach for neutron- γ discrimination, implemented through dedicated electronic pulse shaping. The procedure comprises three main stages:^{183–185} pulse shaping, zero-crossing detection, and classification.

First, the raw unipolar anode signal from the photodetector is processed by

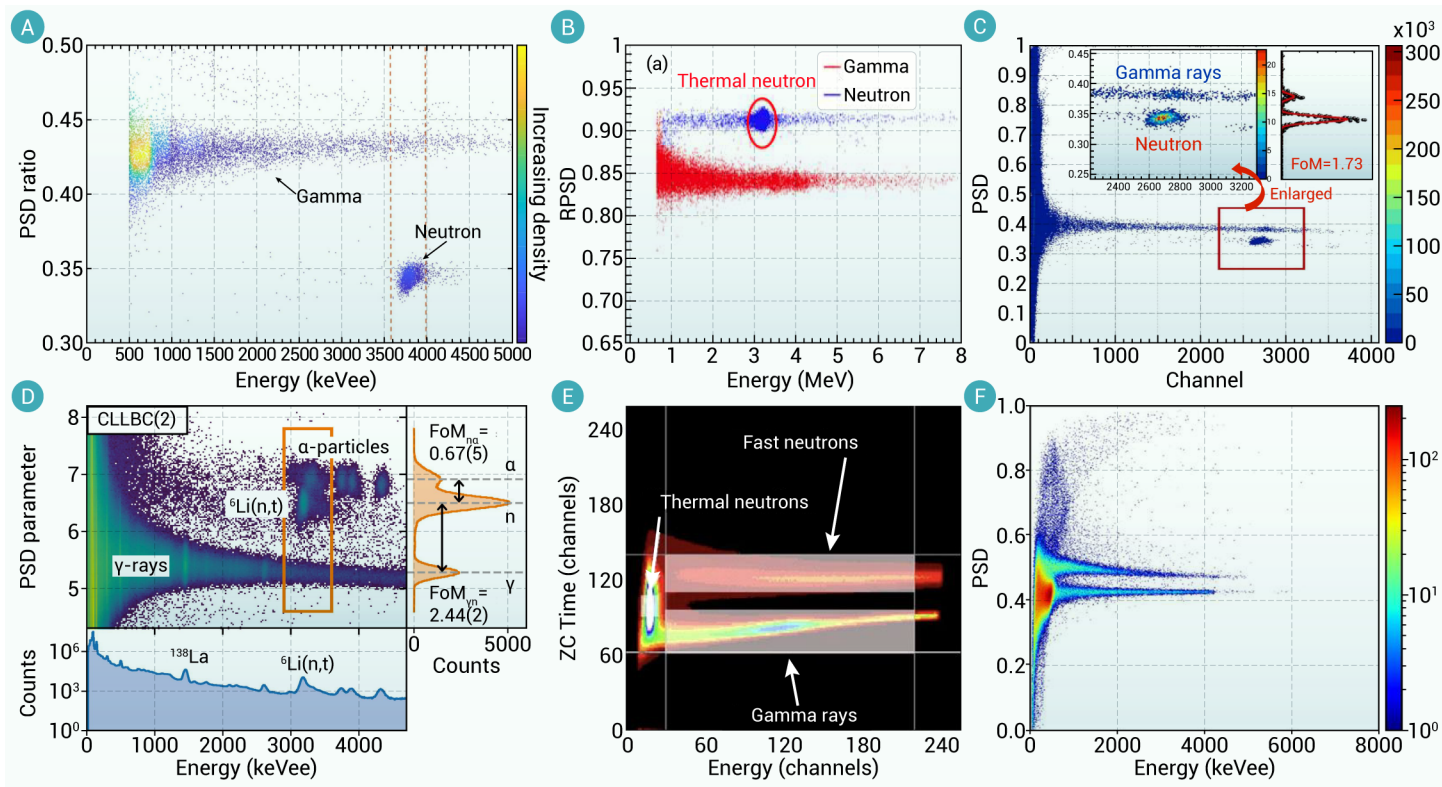


Figure 4. PSD–energy scatter plots of representative neutron– γ detection scintillators (A) NaI:Li (Reproduced under the CC BY 4.0 license.¹⁵⁸). (B) CLYC (Reproduced with permission.¹⁵⁹ Copyright 2024, IOP). (C) CLLB (Reproduced with permission.¹¹⁴ Copyright 2023, Elsevier). (D) CLLBC (Reproduced under the CC BY 4.0 license).¹¹⁷ (E) BC532A2 liquid scintillator (Reproduced with permission.¹⁵⁵ Copyright 2010, IEEE). (F) EJ276 plastic scintillator (Reproduced with permission.¹⁵⁷ Copyright 2024, Elsevier)

a CR - (RC)ⁿ shaping network—typically realized as a double differentiation circuit—which converts the pulse into a bipolar waveform. Subsequently, the shaped bipolar waveform crosses the baseline (zero-voltage line) at a specific time point. Owing to the longer decay tail characteristic of neutron-induced pulses, the corresponding bipolar signal remains in the negative phase for an extended duration. This results in a measurably later zero-crossing time compared to γ -induced events.

Finally, the measured zero-crossing time (T_{zc}) serves as the primary discrimination parameter. Events with longer T_{zc} values are classified as neutrons, whereas those with shorter T_{zc} are assigned as γ rays. This parameter is largely independent of pulse amplitude, rendering the method effective across a broad energy range.

The zero-crossing technique offers several practical advantages, including excellent performance at low energies, a wide dynamic range, reduced gain requirements, and compatibility with time-of-flight measurements. As a result, it remains a preferred choice for many applications in nuclear physics and radiation detection, where reliable neutron– γ separation is critical, particularly in compact or real-time detection systems.

Charge-comparison method. The charge comparison method represents another robust and widely employed PSD technique for neutron– γ discrimination.^{186,162} In its digital implementation, the method involves acquiring the full scintillation pulse waveform and performing numerical integration over strategically defined time intervals. The procedure generally consists of the following steps:^{45,187,188} pulse acquisition and alignment, charge integration, discrimination parameter calculation, and discrimination plot generation with thresholding.

First, the raw current pulse from the photodetector is digitized using a fast analog-to-digital converter (ADC). To ensure consistent integration windows, pulses are aligned either at their leading edge or at their peak amplitude. Subsequently, two charge integrals are calculated for each aligned pulse: the total integrated charge (Q_{total}), which captures the full pulse energy over a long gate, and the short-gate charge (Q_{short}), integrated over a shorter time window positioned to capture primarily the prompt (fast) light component. The precise start time and width of this short gate are critical parameters that

must be optimized for the specific detector system.

Next, the typical PSD parameter R is computed as the ratio of the short-gate charge to the total charge:

$$R = \frac{Q_{short}}{Q_{total}} \quad (4)$$

Finally, a two-dimensional scatter plot of R versus Q_{total} (or versus pulse amplitude) is constructed over a broad energy range. Two distinct bands typically emerge: an upper band with higher R values corresponds to γ -ray events, while a lower band with lower R values corresponds to neutron events. A discrimination threshold is then established between these bands to classify individual pulses as either neutron or γ -ray events.

The charge comparison method remains a cornerstone digital PSD technique owing to its conceptual simplicity, computational efficiency, and robust performance across a wide energy range. Although it establishes a strong baseline for neutron– γ discrimination, its performance can be surpassed by more advanced digital algorithms at the lowest energies and very high count rates. Nevertheless, the stability, ease of implementation, and well-understood behavior of the charge comparison method ensure its continued relevance in radiation detection systems.

Quantifying performance: The Figure of Merit (FOM)

The Figure of Merit (FOM) is a quantitative metric employed to evaluate and compare the performance of PSD techniques. It offers a standardized measure of the degree of separation achievable between these two pulse classes based on differences in their temporal profiles.

Definition of FOM. The most common definition, as established in the foundational PSD literature and consistently applied across comparative studies,^{2,181,185,188} is:

$$\text{FOM} = \frac{|\mu_n - \mu_\gamma|}{\text{FWHM}_n + \text{FWHM}_\gamma} \quad (5)$$

where μ_n and μ_γ denote the mean (or peak channel) values of the PSD parameter distributions—such as the zero-crossing time (T_{zc}) or the charge

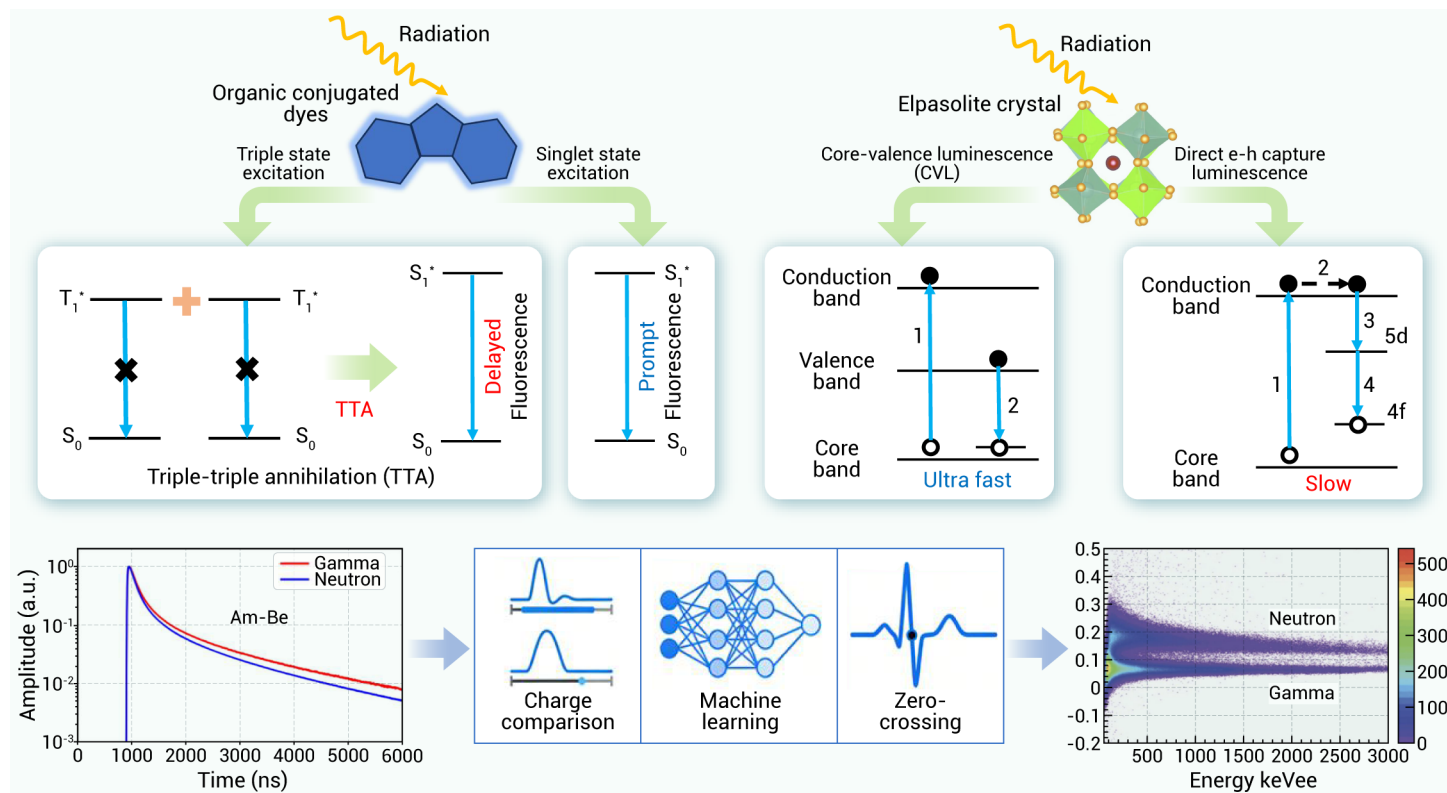


Figure 5. The physical basis and methodology of PSD.

ratio R —for neutron and γ -ray events, respectively. These distributions typically exhibit a Gaussian-like shape. FWHM_n and FWHM_γ represent the full widths at half maximum of the corresponding distributions.

This expression effectively normalizes the separation between the two populations (numerator) by their combined statistical spreads (denominator). A higher FOM corresponds to a greater degree of separation relative to the distribution widths, indicating superior discrimination capability.

Key factors affecting PSD performance. The performance of PSD in neutron- γ separation is governed by several main factors, including scintillator properties, event energy, photodetectors, electronics, and the PSD methodology employed.

The intrinsic PSD capability of a material arises from the difference in scintillation decay components induced by neutrons and γ rays. This difference is fundamentally linked to the scintillator type and its underlying scintillation kinetics.¹⁶³ A higher intrinsic light yield enhances PSD performance, particularly at low energies, by reducing statistical fluctuations in the PSD parameter (i.e., FWHM_n and FWHM_γ). However, discrimination typically degrades at low equivalent electron energies, and the threshold neutron energies for achieving a given FOM vary considerably across different scintillators.

The operating voltage and key performance parameters of the photodetector—such as photon detection efficiency, dark noise, and timing characteristics—significantly influence FWHM_n and FWHM_γ , and should be optimized experimentally.^{189–191} For timing-based methods like the zero-crossing technique, electronic pulse shaping parameters are critical for PSD performance.¹⁸⁵ In contrast, for waveform-sampling methods such as digital charge comparison, the sampling properties of the waveform digitizer are the primary determinants.¹⁹² Additionally, fast front-end electronics are essential in high-rate scenarios to effectively suppress pulse pile-up events.¹⁹³

Traditional PSD methods, such as charge integration and zero-crossing, operate in the time domain and are widely used as baseline approaches due to their simplicity and suitability for real-time systems. However, their effectiveness is limited under conditions of low particle energy and high noise levels. Frequency-domain methods demonstrate greater robustness to noise and pile-up compared to time-domain techniques, though they involve higher computational complexity and are less conducive to real-time implementation.

Meanwhile, machine learning methods have attracted increasing attention and generally deliver superior PSD performance. Nevertheless, these approaches require substantial computational resources, and their discrimination capability is often dependent on the size and quality of the training dataset.^{194–198} Systematic optimization not only enhances the accuracy and robustness of particle identification but also enables adaptation to varying detector characteristics and noise environments. Therefore, implementing a structured parameter optimization strategy is essential for achieving reliable, high-performance PSD in practical applications.^{185,199,200}

PHOTODETECTOR AND ELECTRONICS FOR PSD

Photodetection technologies

Photodetection technology encompasses devices and techniques that convert optical signals into electrical signals, primarily utilized in fields such as imaging, communication, and sensing.²⁰¹ The advancement of photodetection technology stands as a cornerstone of the information age. In nuclear radiation detection, photomultiplier tubes (PMTs) and silicon photomultipliers (SiPMs) serve as key core components, performing the critical function of photoelectric conversion.

PMTs are widely used in fields such as high-energy physics experiments,²⁰² astrophysics,²⁰³ and medical physics.²⁰⁴ Modern solutions are gradually shifting toward SiPMs, which employ dense arrays of micro avalanche photodiodes to achieve single-photon sensitivity, offering high gain, fast response, and strong resistance to magnetic interference. In medical imaging, the fast timing response of SiPMs, combined with rapid scintillation crystals such as LYSO, enables positron emission tomography (PET) systems to more accurately determine the time difference of arrival of annihilation photons.²⁰⁵

Key requirements for effective PSD. Pulse shape discrimination (PSD) serves to identify different particle types (e.g., neutrons versus γ rays) and requires joint optimization of the scintillator's intrinsic temporal luminescence and the photodetector's timing response. PSD is inherently a system-level optimization problem, not reducible to a single figure of merit. Birks' law provides a microscopic basis linking light-yield quenching to particle type and energy, thereby underpinning the physical basis of PSD.²²

Detector transit-time spread (TTS), rise time, and single-photon time resolution (SPTR) must be much shorter than the differences in scintillator decay

times; otherwise, intrinsic pulse shape contrasts will be obscured. The photon statistics and signal-to-noise ratio (SNR) require a sufficient photon yield to reconstruct the pulse shape reliably. If the fast-component photon fraction is small, its relative fluctuations increase, degrading the reconstruction of its arrival-time distribution.

In charge-comparison PSD, the discrimination parameter is expressed as the ratio of the short-gate charge to the total charge:

$$R = \frac{Q_{\text{short}}}{Q_{\text{total}}} \quad (6)$$

Therefore, the R distribution broadens and the FOM deteriorates as Q_{short} fluctuations grow. Caccia et al. quantified the minimum photon requirement for effective neutron- γ discrimination in SiPM-coupled systems.²⁰⁶

A low detector dark count rate, minimal afterpulsing, and low electronic noise are also required so that weak fast-component signals are not masked. Hence, a high scintillator light yield and a high detector SNR are essential for effective PSD.

Radiation-induced color centers increase self-absorption and reduce light yield, while structural defects introduce afterglow and non-radiative quenching, degrading neutron- γ discrimination.²⁰⁷ Co-doping and defect reduction sharpen recombination pathways and improve the PSD FOM; $\text{Zn}^{2+}/\text{Sb}^{3+}$ co-doping of dense frameworks has been shown to increase light output and optimize structural decay pathways.²⁰⁷ Ultimately, PSD systems require a global trade-off between environmental robustness and core timing performance.

PSD Performance of Ultra-Fast PMT and SiPM. PSD separates neutrons from γ rays via waveform features. The pursuit of ultrafast radiative signals (e.g., Cherenkov emission and cross-luminescence) drives two main detector paths: ultrafast PMTs (FPMTs) and SiPMs. FPMTs offer a single-photon TTS < 50 ps and a rise time < 500 ps. PMTs include dynode and microchannel plate (MCP) types, with 1 inch $\times$ 2 inch, proximity-focused MCP-PMTs providing compact, detector-friendly form factors. Figures 6A-H illustrate different types of optoelectronic devices.

The major manufacturers and developers of dynode-type and microchannel plate-type PMTs (e.g., Figures 6A-D) include Hamamatsu Photonics (Japan), ET Enterprises (UK), BURLE Industries (USA), MELZ (Russia), NNV (China), and PHOTONIS (France). SiPM products (e.g., Figures 6E-F) are primarily supplied by Hamamatsu Photonics (Japan), Onsemi (USA), Broadcom (USA), NDL (China), and Joinbon (China). Photodiode (PD) and APD products (e.g., Figure 6G) are mainly manufactured by Hamamatsu Photonics (Japan), Excelitas Technologies (USA), and Microphotons (China). Silicon drift detectors (SDDs) (e.g., Figure 6H) are primarily produced by Amptek (USA) and KETEK (Germany). Typical parameters of different types of photodetectors are presented in Table 2.

With organic scintillators (NE-213 or EJ-301) and fast dynode PMTs, charge integration PSD typically yields FOM $\approx$ 2.0, depending on the energy threshold and gate optimization.^{223,195,224} A 1 in CLYC scintillator with optimized gating and multiple PMTs achieved FOM > 1.9 ($\sim$ 2.0 for 1.5 MeV fast neutrons and $\sim$ 3.2 for thermal neutrons),²²⁵ and a 3 in NaI:TI crystal coupled with a fast Hamamatsu PMT reached FOM = 4.36 under 1 GHz waveform sampling.²²⁶

MCP-PMTs employing pulse stretching in the drift region realize $\approx$ 25 ps effective timing resolution (compared to $\approx$ 300 ps without stretching), enabling finer pulse edge sampling and significantly improving sampling-dependent digital PSD performance.²²⁷ SiPMs with fast ($\sim$ 10 ns) or ultrafast outputs are widely used for neutron- γ PSD in plastic, organic, and composite scintillators. SensL/Onsemi devices provide a dedicated fast output alongside a standard slow, high-charge output. Fixing per-event charge injection enables robust PSD even under conditions of partial charge collection, while a < 3 ns coincidence window between opposing detector ends effectively suppresses dark current and yields reliable particle discrimination.²²⁸

With optimized scintillator coupling, array architecture, and advanced front-end signal processing, ultrafast-output SiPM systems closely approach PMT-level single-photon performance while offering compact, low-voltage, and high-speed operation.

Electronic readout and signal processing

High-frequency digitizers. High-speed full-waveform digitizers have largely supplanted traditional analog PSD electronics by preserving complete time-amplitude pulse profiles. This enables flexible FPGA/CPU algorithms to execute real-time baseline restoration, gain correction, dynamic gating, high-frequency noise mitigation, and pile-up handling. Commercial digitizers now routinely reach thresholds from 10 GS s⁻¹ to 20 GS s⁻¹ with 12 bit to 14 bit resolution. Multi-ADC parallel architectures can even exceed 40 GS s⁻¹ with effective resolutions up to $\sim$ 16 bit, enabling direct, high-fidelity digitization of single-photon scintillation events.²²⁹

Wen et al. digitized $\text{LaBr}_3:\text{Ce}$ waveforms using a custom multi-ADC digitizer and a WavePro 404 HD oscilloscope; least-squares and linear discriminant analysis (LDA) classifiers proved highly robust to sampling-rate changes and provided excellent particle identification performance.²³⁰ Digital platforms easily support charge integration, linear discrimination, frequency-domain, and wavelet transform methods, permitting flexible offline or online optimization of integration gates and thresholds.^{231,232} This approach significantly improves low-energy pulse identification and pile-up separation performance in mixed neutron- γ radiation fields.¹⁹⁶ Consequently, GHz-class waveform digitization has driven the historic transition from analog to digital PSD systems.

PSD signal processing circuits. PSD circuits exploit scintillation pulse shape differences to separate neutron and γ -ray events, spanning analog, digital, hybrid, and machine learning approaches, each trading off architectural complexity, power consumption, and data throughput. Classical analog methods include zero-crossing RC differentiation,¹⁸⁰ dual-channel charge integration,¹⁸⁵ time-over-height topologies designed for degraded light collection scenarios,²³³ and high-speed charge integration with dynamic dead time to strictly limit misclassification at high count rates $\geq$ 100 kcps.²³⁴

Digital and hybrid schemes combine high-speed ADCs with FPGA-based digital signal processing (DSP) to implement dual-gate integration and related algorithms, achieving processing rates up to $\sim$ 2 Mcps with full-waveform storage capabilities.^{235,236} Alternative digital metrics include the evaluation of the cosine similarity of step responses.²³⁷

Feature-domain methods (such as Short-Time Fourier Transform [STFT], Continuous Wavelet Transform [CWT], and Haar wavelets) coupled with machine learning classifiers (e.g., logistic regression and decision trees) significantly improve discrimination accuracy and noise robustness compared to classical integration and frequency gradient analysis (FGA) methods.²³⁸⁻²⁴⁰ Meanwhile, an analog front-end combined with moderate DSP resource allocation offers a highly scalable, cost-effective instrumentation compromise.²⁴¹

End-to-end deep neural models (CNNs, Tempotron, and related architectures) consistently outperform traditional charge integration and wavelet benchmarks in terms of the area under the ROC curve (AUC) and FOM. They tolerate labeling noise exceptionally well, and with modern GPU/FPGA acceleration, they are rapidly maturing toward real-time field deployment.^{236,242-245}

Enhancing PSD performance through advanced electronics. Advanced front-end electronics and application-specific integrated circuits (ASICs) substantially boost PSD throughput and system energy efficiency by embedding processing elements directly onto the chip, thereby minimizing raw waveform data transfer. Examples include the Citiroc1A dual-shaper architecture designed for compact, high-channel-count detector arrays,^{246,247} a 430 μW CLYC-targeted System-on-Chip (SoC) that integrates full digital signal processing to deliver an FOM $\approx$ 1.36 for portable instrumentation applications;²⁴⁸ and SiPM-coupled ASICs developed for stilbene and EJ-276 plastics that achieve effective PSD down to thresholds of $\sim$ 100 keV.²⁴⁹

Precise analog mutual-exclusion circuits reduce event misclassification fourfold up to 100 kcps, and successfully implement charge-proportional dynamic dead times.²³⁴ Furthermore, pulse-duration/height-compensated analog topologies maintain a high FOM under degraded light collection conditions with a width uncertainty of < 1 ns.²³³ Mixed-mode designs combining analog signal conditioning with moderate DSP resources offer distinct cost and power advantages over full high-speed ADC instruments while retaining extensive algorithmic flexibility.²⁴¹

Digital pulse shaping combined with advanced charge comparison improves the CLYC neutron- γ FOM by $\approx$ 14% and effectively mitigates

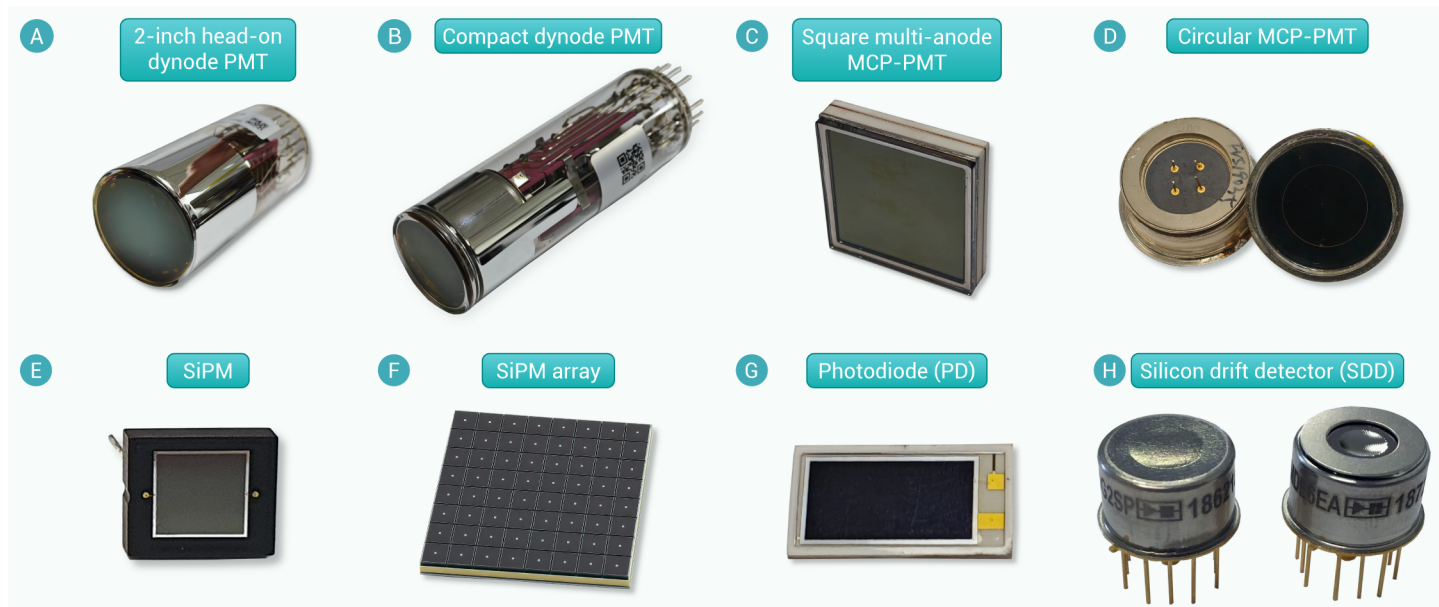


Figure 6. Representative architectures and form factors of optoelectronic devices used for photon detection. Photographs depict typical devices (A) 2-inch head-on dynode PMT (NNVT N4021). (B) Compact dynode PMT (NNVT N2013). (C) Square multi-anode MCP-PMT (NNVT N6021). (D) Circular MCP-PMT (NNVT N6015). (E) Single-channel SiPM (Hamamatsu S13360). (F) SiPM array (Hamamatsu S13361 series). (G) Photodiode (Hamamatsu S14605). (H) Silicon drift detector (Reproduced with permission. Copyright 2026, Amptek, Inc.)

severe pulse pile-up.²⁵⁰ Finally, Haar wavelet PSD executed within a tight 26 ns processing window attains an $FOM \approx 1.47$ with excellent pile-up tolerance, making it highly suitable for resource-constrained FPGA implementations.²⁴⁰

SIGNIFICANT IMPROVEMENT OF FOM VALUE WITH AI ASSISTANCE

With the rapid development of nuclear electronics technologies such as high-speed waveform sampling, detailed pulse waveform information can be acquired from scintillation detectors.²⁵¹ This technological progress provides the foundation for the application of artificial intelligence (AI)-assisted algorithms in neutron- γ discrimination. Compared with traditional pulse shape discrimination (PSD) methods, AI-based approaches can exploit more comprehensive waveform information and perform high-dimensional data analysis, leading to a significant improvement in discrimination performance, particularly in terms of the figure of merit (FOM) (Figure 7).

As reported in the literature, the FOM value of CLYC scintillators typically ranges from 1.0 to 5.0, depending on factors such as crystal properties, read-out electronics, energy threshold, and the selection of short and long integration windows. At low particle energies, neutron- and γ -induced signals tend to overlap strongly, resulting in a substantial degradation of the FOM. In this context, AI-assisted PSD methods have been demonstrated to be effective tools for enhancing neutron- γ discrimination performance.

Advantages of AI-assisted pulse shape discrimination

AI-assisted PSD methods have emerged as an effective solution to overcome the performance limitations of conventional neutron- γ discrimination techniques. By leveraging high-dimensional waveform information and powerful data-driven learning capabilities, AI algorithms significantly improve discrimination robustness and accuracy under complex measurement conditions.

Limitations of conventional PSD methods. Traditional neutron- γ discrimination techniques are mainly based on pulse shape discrimination methods such as the charge comparison method⁴⁵ and frequency gradient analysis.¹⁹⁵ These methods rely on manually extracted pulse features and predefined discrimination parameters, which inherently limits their operational performance.

In particular, conventional PSD methods exhibit poor adaptability in low-energy regions (typically below 200 keV_{ee}) and in high-noise environments, where neutron and γ signals tend to overlap strongly, leading to relatively low FOM values.^{252,253}

Moreover, traditional algorithms require manual optimization of param-

eters, such as integration windows and thresholds, for different experimental conditions. Their ability to handle complex scenarios, including pulse pile-up and dynamically changing radiation fields, is fundamentally limited. As a result, their generalization capability across different detector systems and operating conditions remains weak.

Multidimensional information extraction enabled by AI-based PSD. AI-based PSD methods effectively address the above limitations by enabling direct processing of raw pulse waveforms or high-dimensional feature representations. By eliminating the need for manual feature engineering, machine learning and deep learning algorithms can autonomously extract complex and subtle discriminative information embedded in pulse shapes.^{254,255}

Through high-dimensional feature learning and global optimization, AI algorithms are capable of capturing temporal, amplitude-related, and energy-dependent characteristics of scintillation signals. Dimensionality reduction techniques can further be applied to reduce data redundancy while preserving key waveform features relevant to neutron- γ discrimination.

As a result, AI-assisted PSD methods exhibit enhanced robustness against noise and improved discrimination performance, especially in low-energy regions where conventional PSD approaches are ineffective.²⁵⁶

AI algorithms for neutron- γ discrimination

A variety of AI algorithms have been applied to neutron- γ discrimination, demonstrating significant improvements in FOM across different scintillator systems and experimental conditions. These algorithms can be broadly categorized into traditional machine learning-based methods, deep learning-based methods, and specialized approaches for pulse pile-up scenarios.

Traditional machine learning-based methods. Early applications of AI in neutron- γ discrimination mainly focused on traditional machine learning techniques combined with manually extracted pulse features. Representative methods include filtering algorithms, principal component analysis (PCA),²⁵⁷ clustering algorithms, and support vector machines (SVM).²⁵⁵ These approaches typically operate on characteristic parameters derived from pulse waveforms and provide improved discrimination performance compared with conventional PSD methods.

In general, supervised learning methods achieve higher discrimination accuracy and FOM values, while unsupervised learning approaches offer better adaptability to complex and variable radiation environments. Although the performance improvement of traditional machine learning methods is limited by the quality of manually selected features, they remain highly attractive due to their relatively low computational cost and good inter-

Table 2. Typical performance parameters for different types of photodetectors.

Types	Typical models / series	Operating Voltage	PDE	Gain	Rise time	TTS	Dark current / counts	Magnetic resistance	Ref.
Dynode-PMT	Hamamatsu R6231	1500 V	~30% @ 380 nm	2.7×10 ⁵	8.5 ns	~1.0 ns	2 nA	Weak	208
	NNVT N2016	1500 V	~28% @ 380 nm	4.0×10 ⁶	1.9 ns	3.0 ns	2 nA	Weak	209
MCP-PMT	Hamamatsu R10754	2700 V	~25% @ 380 nm	1.0×10 ⁶	195 ps	70 ps	5 nA	Moderate	210
	PHOTONIS XP85112	2500 V	~24% @ 380 nm	1.0×10 ⁶	–	~40 ps	–	Moderate	211
	NNVT N6021	2500 V	~22% @ 410 nm	2.0×10 ⁶	300 ps	50 ps	500 Hz @ 0.2 p.e.	Moderate	212
	Hamamatsu S13360-6050PE	53 V	~40% @ 450 nm	1.7×10 ⁶	500 ps	350 ps	500 kcps @ 0.5 p.e.	Strong	213
SiPM	Onsemi J-60035	24 V	~50% @ 420 nm	2.9×10 ⁶	180 ps	–	0.45 μA	Strong	214
	Broadcom AFBR-S4N44P014M	12 V	~63% @ 420 nm	7.3×10 ⁶	–	–	0.5 μA	Strong	215
	NDL EQR20	27 V	~46% @ 420 nm	8.2×10 ⁵	–	–	500 kcps mm ⁻²	Strong	216
PD	Joinbon JSP-TP6050	~25 V	~35% @ 420 nm	2.1×10 ⁶	1 ns	–	140 kcps mm ⁻²	Strong	217
	Hamamatsu G6854	20 V	~0.95 A W ⁻¹ @ 1.55 μm	1	–	–	80 pA	Strong	218
	Excelitas VTP1012H	10 V	~0.60 A W ⁻¹ @ 960 nm	1	~1 μs	~1 μs	–	Strong	219
APD	Hamamatsu S5344	~140 V	~80% @ 620 nm	50	–	–	1 nA	Moderate	220
	Microphotons InGaAs-APD	39 V	~40% @ 620 nm	18	–	–	6 nA	Moderate	221
SDD	AMETEK SDD	< -100 V	>80% @ 10 keV	–	< 35 ns	–	–	Weak	222

pretability.

Deep learning-based PSD algorithms. With the availability of large-scale waveform datasets and increased computational power, deep learning-based PSD methods have attracted growing attention.²⁵⁸ By directly using raw pulse waveforms as inputs, deep neural networks can fully exploit the temporal structure of scintillation signals and achieve superior discrimination performance.

Hybrid models based on MobileNetV4 (MNv4) and Kolmogorov–Arnold Networks (KAN) have demonstrated remarkable improvements in FOM.²⁵⁹ For example, the FOM value obtained with the traditional charge comparison method for CLYC scintillators is ≈ 1.82, while MNv4- and KAN-based models achieve FOM values of 4.07 and 4.40, respectively, with discrimination accuracies of 99.7% and 98.6%. These results highlight the strong capability of deep learning models in capturing subtle waveform differences between neutron- and γ-induced events.

In comparison, the improved pulse-coupled neural network (XF-PCNN) achieves an FOM value of 1.10, outperforming the conventional charge comparison method with an FOM of 1.04. For organic scintillators such as EJ-276 coupled with silicon photomultiplier arrays, the traditional charge comparison method typically yields an FOM value of ≈ 1.13 at an energy threshold of 200 keV_{ee}, further illustrating the performance advantage of deep learning-based PSD approaches.²⁵²

AI-based discrimination under pulse pile-up conditions. Pulse pile-up poses a significant challenge for neutron–γ discrimination, particularly in high-count-rate environments. Overlapping pulses distort waveform shapes and severely degrade the performance of conventional PSD methods.²⁶⁰ AI-based algorithms demonstrate clear advantages in this scenario by learning the characteristic features of piled-up signals.

By training on simulated or experimentally measured piled-up pulse datasets, machine learning models can identify and discriminate individual pulse components within complex overlapped waveforms, achieving discrimination accuracies of up to 99%. Convolutional nuclear network (CNN)-based methods have been shown to be particularly effective in processing low-energy piled-up signals, leading to substantial improvements in discrimination performance in this challenging region.²⁶¹

Summary: physical mechanisms of FOM improvement and future perspectives

AI-assisted PSD algorithms significantly enhance neutron–γ discrimination performance by enabling multidimensional information extraction from scintillation pulse waveforms and performing global optimization in high-dimensional feature spaces. These capabilities lead to effective suppression of signal overlap, improved noise tolerance, and enhanced discrimination performance, as reflected by the substantial improvement in FOM values.

Looking forward, future research efforts are expected to focus on model lightweighting, few-shot and transfer learning strategies, and the deep integration of AI algorithms directly into readout electronics. These developments will further promote the practical deployment of AI-enhanced PSD systems in applications such as nuclear safety monitoring, space radiation detection, and real-time measurements in complex radiation fields.²⁶²

NEW NEUTRON DETECTION MATERIALS BY SIMULATION AND CALCULATION

The role of computational physics

Computational physics has evolved from an auxiliary tool for data analysis to a critical component in the design of high-performance neutron detection materials. Traditional material development relies heavily on empirical trial-and-error, involving iterative crystal growth, doping adjustments, and detailed characterization. This process is often time-consuming and costly, and it faces challenges in elucidating microscopic physical mechanisms, such as exciton energy transfer and non-radiative recombination.

To address these limitations, a cross-scale theoretical framework has been established, linking atomic-scale calculations to macroscopic device simulations. By integrating first-principles calculations with Monte Carlo transport simulations, researchers can predict material properties and detection performance prior to synthesis, thereby guiding experimental design and optimizing resource allocation.

Simulation tools. This research utilizes two primary computational methods: Monte Carlo simulations for particle transport and first-principles calculations for electronic structure analysis.

Radiation transport simulation: Geant4. Geant4 is a toolkit for the simula-

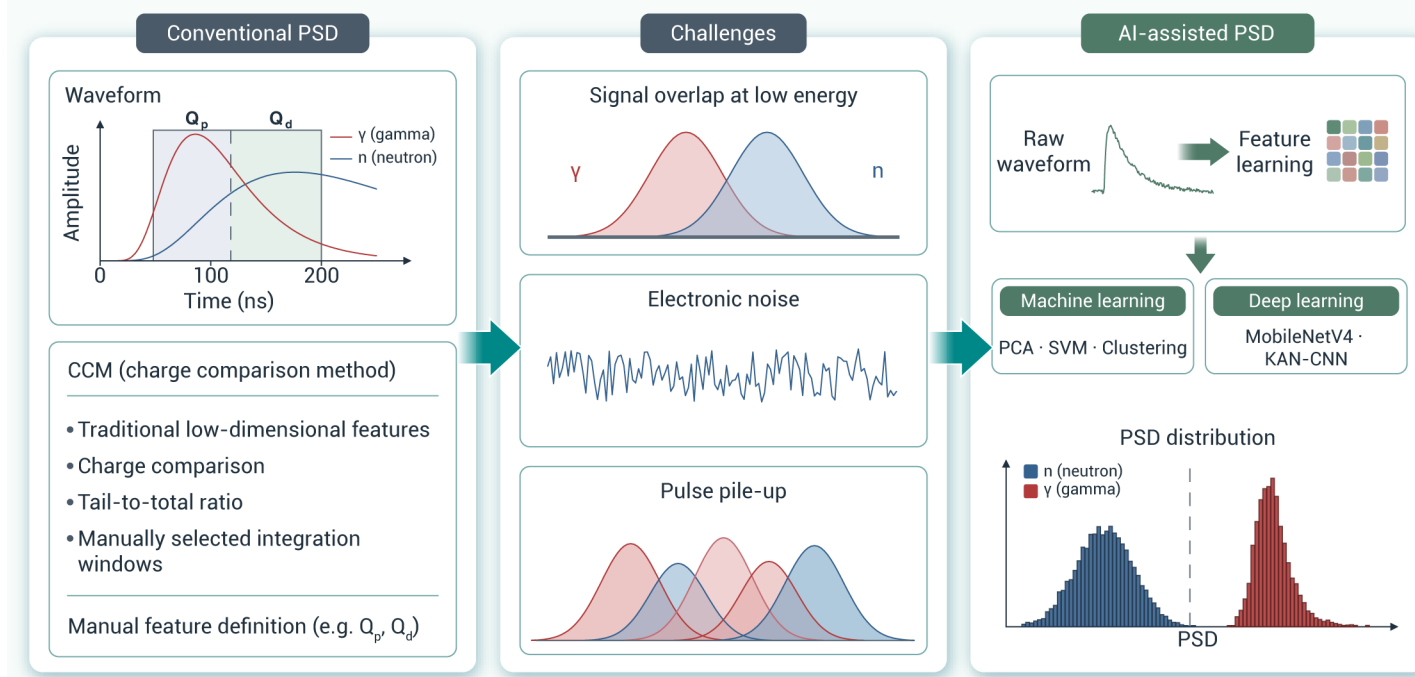
AI-assisted pulse shape discrimination for enhanced n- γ separation

Figure 7. Schematic architecture of AI-assisted pulse shape discrimination workflows.

tion of the passage of particles through matter, widely applied in high-energy physics and nuclear science.¹⁵¹ In this study, Geant4 is employed to evaluate detector geometries, validate nuclear physics models, and calculate detection efficiencies.

Accurate simulation of background radiation and calibration sources is essential for detector validation. Geant4 incorporates the Evaluated Nuclear Data File (ENDF)²⁰ to model radioactive decay pathways. The simulation successfully reproduces characteristic features, such as the 511 keV annihilation photons from ^{22}Na and the cascade γ rays from ^{60}Co (1173 keV and 1332 keV). Comparison between these simulated spectra and experimental data serves as a rigorous method to verify the energy response and resolution of the detector models.

First-principles calculation. At the microscopic scale, electronic structure calculations are performed using the Vienna Ab initio Simulation Package (VASP) based on Density Functional Theory (DFT).²⁶³ Using the projected augmented wave (PAW) method, VASP calculates the electronic band structure and density of states (DOS) of the scintillator host. A key parameter derived from these calculations is the bandgap (E_g), which is inversely proportional to the theoretical light yield limit ($LY \propto 1/E_g$).²⁶⁴

Consequently, DFT calculations enable the screening of host materials with high light yield potential. Furthermore, these calculations can predict the energy levels of dopants (e.g., Ce^{3+} 5d states) relative to the conduction band, providing insight into thermal quenching mechanisms, and emission wavelengths.

Theoretical calculations. The combination of DFT and Geant4 creates a comprehensive evaluation chain. First-principles calculations determine fundamental optical properties—such as refractive indices and absorption coefficients—which are then input into the optical transport modules of Geant4. This integration enables the simulation of light collection efficiency (LCE) and pulse shape discrimination (PSD) performance.

Theoretical models can estimate the electron-hole pair density generated by high-LET particles (neutrons) versus low-LET particles (γ rays), providing a physical basis for designing materials with enhanced PSD capabilities, such as elpasolite halides and composite scintillators.

Guiding principles for material design

Based on the predictive capabilities of first-principles calculations and

Monte Carlo simulations, systematic design strategies have been established. These strategies aim to optimize light yield, timing response, and neutron- γ discrimination capabilities, addressing specific challenges in complex radiation fields.

Engineering materials with decay time constant differences. PSD relies on the distinct fluorescence decay kinetics induced by particles with different Linear Energy Transfer (LET).

Theoretical models indicate that high-LET particles, such as protons or α particles from neutron capture, generate a significantly higher density of electron-hole pairs compared to low-LET γ rays. This high ionization density enhances non-radiative recombination and bi-molecular quenching processes.²² Consequently, material design should target host lattices that exhibit competitive kinetics between fast activator transitions (e.g., Ce^{3+} 5d-4f) and slower processes involving Self-Trapped Excitons (STE). By engineering the energy barrier for STE formation, the slow component of the neutron pulse can be relatively enhanced, improving the discrimination Figure of Merit (FOM).

Furthermore, Core-to-Valence Luminescence (CVL) offers a mechanism for sub-nanosecond timing. Band structure calculations can identify compounds where the energy difference between the valence band maximum and the outermost core level is less than the bandgap ($E_{vc} < E_g$). This transition is sensitive only to low-LET radiation (γ rays) and is suppressed under high-LET neutron excitation due to rapid quenching.²⁶⁵ Exploiting this physical "switching" effect allows for the temporal separation of neutron and γ signals.

Dopants and crystal defects. Microscopic defects and impurity levels critically influence carrier transport and afterglow. First-principles calculations guide the selection of activators and the management of defects. Simulations predict the energy levels of rare-earth ions (e.g., Ce^{3+} and Eu^{2+}) within the host bandgap. To avoid thermal ionization quenching, the lowest 5d excited state must maintain a sufficient energy barrier relative to the conduction band minimum.

Additionally, aliovalent co-doping strategies are optimized through defect formation energy calculations. For example, in oxide scintillators like $\text{Gd}_3(\text{Al}, \text{Ga})_5\text{O}_{12} : \text{Ce}$ (GAGG), the introduction of divalent ions (Mg^{2+} or Ca^{2+}) creates hole centers that compensate for intrinsic defects. This approach effectively suppresses shallow electron traps responsible for slow decay

Table 3. Horizontal comparison of application-specific performance requirements across advanced neutron- γ detection frontiers.

Requirement	Nuclear security & Isotope ID	BNCT monitoring	High-count-rate fields	Space exploration
Neutron energy range	Thermal to fast neutrons	Thermal and epithermal neutrons	Fast to high-energy neutrons	Epithermal to fast neutrons
Count-rate condition	Low to moderate (~ 10 kcps)	Moderate to high (~ 100 kcps)	Extreme (≥ 1 Mcps); severe pulse pile-up	Low to moderate; long-term stable
γ background intensity	Variable; potentially strong	Intense mixed radiation fields	High-intensity transient bursts	Variable orbital or solar backgrounds
Scintillator metrics	Dual-mode response; high- γ host for γ spectroscopy (e.g., elpasolites)	High light yield; excellent imaging linearity and spatial resolution	Ultrafast decay time; low afterglow; high radiation tolerance	High radiation hardness; compact volume; extreme thermal stability
PSD & electronics	Robust real-time PSD coupled with isotope-ID libraries	Real-time waveform integration; stable dose-reconstruction calibration	GHz digitization; fast baseline restoration; pile-up correction	Ultra-low-power ASICs; autonomous in-orbit gain-drift calibration
Compactness & priority	Handheld or portal forms; fast low-false-alarm decisions	Integrated clinical layouts; accurate repeatable dose mapping	Facility-scale arrays; maintaining dynamic range under peak rates	Strict mass-volume-power budgets; high space-grade reliability

components and afterglow.²⁶⁶ By stabilizing the Ce^{4+} valence state, co-doping significantly improves the timing response required for high-count-rate neutron detection.

Exploring composite and heterostructure scintillators. For background suppression, multi-layer heterostructures are modeled to utilize spatial energy deposition differences. Simulations optimize layer thickness precisely, ensuring thermal neutrons deposit energy mainly in a specific capture layer (e.g., ${}^6\text{LiF}$), while background γ rays penetrate to a separate veto layer, significantly enhancing the signal-to-noise ratio in mixed radiation fields.¹⁴⁸

Heterogeneous composite crystals (e.g., BGO/GAGG and $\text{PbWO}_4/\text{GAGG}$) enable efficient neutron- γ discrimination by coupling γ -sensitive, fast-decay oxide crystals (BGO or PbWO_4) with Gd-rich, high thermal-neutron capture GAGG crystals, using their intrinsic scintillation decay-time difference to break the single-crystal PSD bottleneck.²⁶⁷ GAGG, with ultra-high thermal-neutron capture cross-sections from ${}^{155}\text{Gd}$ and ${}^{157}\text{Gd}$, achieves nearly 100% absorption in sub-millimeter slices¹¹⁹ but cannot realize effective PSD alone due to similar neutron and γ -ray waveforms.

BGO and PbWO_4 , with strong γ -absorption and fast decay, amplify PSD waveform contrast when combined with GAGG.²⁶⁷ Experiments confirm PbWO_4 -GAGG achieves clear separation ($\text{FOM} = 3.33$),²⁶⁷ synergizing GAGG's detection efficiency and BGO/ PbWO_4 's γ -rejection, with no complex fabrication, excellent scalability, and great potential as a compact ${}^3\text{He}$ alternative.

Computational design of organic scintillation materials

In organic scintillators, neutron- γ discrimination is governed by coupled processes of ionization, singlet and triplet exciton dynamics, intermolecular energy transfer, and delayed emission.⁶⁰ Therefore, computational screening serves as a powerful guideline to identify molecular candidates and optimize host-guest combinations prior to synthesis. Key calculated descriptors include singlet and triplet excited-state energies, singlet-triplet splitting (ΔE_{ST}), oscillator strength, photoluminescence quantum yield, triplet mobility, and spectral overlap for Förster or Dexter energy transfer.^{268,269} Recent progress in organic phosphorescent materials further highlights the importance of triplet-state engineering for controlling delayed emission processes.²⁷⁰

One important direction is the simulation-guided design of plastic scintillators utilizing thermally activated delayed fluorescence (TADF) dyes. TADF molecules harvest dark triplet excitons via reverse intersystem crossing (RISC), producing enhanced prompt and delayed components. Accurate calculation of ΔE_{ST} is vital since this parameter controls triplet-to-singlet conversion rates, directly affecting light yield and PSD performance.^{271,272} However, an extremely small ΔE_{ST} does not automatically optimize discrimination; a calculated balance between light yield, delayed fluorescence lifetime, and optical transparency is required.

Another strategy relies on triplet-energy matching in multiple-dye plastic or nanostructured polymeric matrices. Calculations show that when the energy gap between the first triplet levels of two fluors is small, heterogeneous triplet migration accelerates triplet-triplet annihilation (TTA), enhancing delayed

light output.²⁷³ Conversely, a large mismatch traps excitations and suppresses delayed channels. Similar concepts guide nanostructured polymer architectures, where liquid-like nanodomains are engineered to maximize triplet diffusion and TTA efficiency.⁶⁰

Furthermore, modeling energy-level configurations facilitates the selection of organic single crystals like tetraphenylethylene (TPE) for dual pulse shape and pulse height discrimination, establishing a rational route for accelerating the development of scalable organic neutron detectors.⁹⁰

NEW PROSPECTS, CHALLENGES, AND FUTURE DIRECTIONS

Application frontiers

Based on the systematic discussions of neutron interaction mechanisms, scintillation materials, detector architectures, and pulse shape discrimination methods presented in the preceding sections, it is evident that modern neutron- γ detection performance is governed by the combined effects of material response, detector geometry, readout electronics, and signal-processing strategies. Different application scenarios impose distinct constraints on radiation environments and operational conditions, leading to application-specific technical requirements. Representative examples are discussed below.

New-generation nuclear security and identification. To address the severe global shortage of ${}^3\text{He}$, the nuclear security sector is actively shifting toward high-performance devices capable of simultaneous neutron counting and radionuclide identification. Based on the Elpasolite crystals (e.g., CLYC and CLLBC) discussed herein, next-generation handheld detectors can acquire both neutron signals and high-resolution γ -ray spectra within a single compact module. Combined with deep learning algorithms for efficient pulse shape discrimination (PSD), these devices can rapidly distinguish between legitimate medical isotopes and controlled special nuclear materials in customs screening and Radiation Portal Monitoring (RPM), significantly reducing false-alarm rates and enhancing the mobility of field inspections.

Precision monitoring in boron neutron capture therapy (BNCT). BNCT requires real-time characterization of neutron flux, the energy spectrum, and spatial dose gradients under mixed neutron- γ radiation fields,^{9,10} where small measurement deviations can critically affect treatment efficacy and patient safety. Self-collimated SPECT systems based on high-light-yield and chemically stable GAGG crystals maintain a stable energy response and spatial resolution under intense radiation conditions, enabling high-fidelity spatial imaging of neutron-related radiation.

Combined with AI-assisted waveform analysis and multiparameter signal-processing methods, these systems effectively suppress γ -induced interference and separate neutron-related signal components, achieving sub-centimeter dose reconstruction. The integration of digital signal processing and intelligent algorithms improves measurement consistency and repeatability during long-term clinical operation, enabling real-time dose evaluation and control in BNCT treatments.

Neutron detection at high count rates. In fusion devices, neutron detection is mainly used to measure the instantaneous neutron yield, energy spectra, and their temporal evolution, which directly correspond to fusion power,

ion temperature, and plasma burn dynamics. During high-power discharges, neutron fluxes can reach extremely high levels within short time intervals, imposing stringent requirements on system dynamic range and timing resolution.²⁷⁴

Under high-count-rate operation, pulse pile-up, baseline fluctuations, and electronic saturation lead to severe spectral broadening and temporal distortion, degrading ion temperature inference and transient analysis. High-speed waveform digitization combined with multiparameter time-correlation analysis enables the reliable separation of overlapping pulses and dynamic baseline correction, successfully preserving spectral integrity and timing performance. Together with radiation-tolerant detector structures and online calibration, reliable neutron yield and spectral measurements can be maintained during long-term, high-load operation.

Neutron- γ detection systems for space applications. In space missions, neutron and γ -ray detection is mainly used for in-situ measurements of hydrogen abundance and elemental composition on planetary surfaces and shallow subsurfaces, as well as for monitoring the harsh radiation environment along spacecraft orbits. These measurements support landing site selection, resource assessment, and radiation shielding design. Such systems operate under direct exposure to cosmic rays and solar energetic particles without the benefit of additional shielding.^{274,275}

During on-orbit operation, high-energy particle irradiation and thermal cycling induce gain drift and spectral response variations, which affect compositional inversion accuracy. Stable scintillation materials, compact detector architectures, and digital readout systems enable continuous monitoring and correction of response changes, maintaining spectral consistency. Combined with low-power electronics and robust in-orbit calibration schemes, space neutron- γ detection systems can continuously acquire quantitative data for planetary science and radiation risk assessment under long-term, unattended operation.

Summary of application requirements. To provide a systematic synthesis of the discussed operational landscapes, the specific requirements and technical constraints of each application frontier are systematically synthesized in Table 3. While nuclear security prioritizes low false-alarm thresholds under moderate count rates, clinical monitoring in BNCT demands strict dose repeatability within intense mixed fields. Conversely, high-count-rate diagnostics require ultrafast scintillation decay to mitigate severe pulse pile-up, whereas space-based platforms are heavily governed by strict mass, volume, and power budgets. This comparative matrix highlights how detector specifications must be selectively optimized for the distinct constraint vector of each deployment scenario.

Overcoming key challenges

Operation in extreme radiation environments. A major challenge for advanced neutron- γ scintillators is stable operation in reactors, accelerators, BNCT facilities, and space missions, where prolonged irradiation can degrade light yield, timing response, afterglow, and PSD performance. Recent irradiation studies on GAGG and CLYC, together with radiation-characterization work on SiPMs, show that system reliability depends not only on scintillator hardness itself, but also on photosensor tolerance, thermal stabilization, and online gain calibration.^{276,277}

Cost reduction and scalable manufacturing of advanced crystals. Another important challenge is the affordable production of large-scale, optically uniform detector materials. Many high-performance scintillation crystals remain difficult to grow at large sizes and are highly sensitive to internal defects, compositional inhomogeneity, or hygroscopicity. Therefore, recent research increasingly focuses on scalable alternatives such as ^6Li -glass composites, transparent inorganic composites, and transparent ceramics, which can successfully preserve attractive neutron sensitivity while reducing fabrication complexity and improving manufacturability.^{278,279} In this context, generative deep-learning frameworks developed for composition-property optimization in amorphous solids provide a useful methodological reference for future data-driven screening of glass, composite, and ceramic scintillator compositions.²⁸⁰

Development of hybrid AI/traditional systems for real-time PSD. Real-time neutron- γ discrimination remains a challenging task in the low-energy region, at high count rates, and under severe pulse pile-up conditions. Classi-

cal PSD methods such as charge comparison remain highly attractive for fast electronic implementation. However, recent studies show that hybrid strategies, which systematically combine conventional PSD methods with neural networks or direct FPGA deployment, can noticeably improve separation performance while preserving computational efficiency and practical interpretability.^{198,281-283} More broadly, physical reservoir computing and edge-AI concepts provide useful references for developing low-power, hardware-efficient signal-processing architectures suitable for embedded real-time neutron- γ discrimination systems.²⁸⁴

CONCLUSION

The evolution of neutron- γ detection is no longer driven by scintillator composition alone, but by the coordinated design of the entire detection chain. The materials reviewed here show that no universal scintillator exists for all operating regimes. Gas-filled ^3He and BF_3 detectors remain benchmark technologies for thermal neutrons, but their practical limitations continue to motivate solid-state alternatives. Liquid and plastic scintillators remain highly effective for fast-neutron detection and large-area instrumentation, especially where recoil-based response and scalable geometries are required.

Li-based crystal scintillators, such as CLYC, CLLB, and related elpasolites, are particularly attractive for dual-mode neutron and γ detection, whereas GAGG and Gd-loaded glass scintillators offer promising routes toward compact, high-density, non-hygroscopic detectors with strong thermal-neutron sensitivity and expanding fields of application. Across all of these basic materials for neutron detection, the final detector performance is determined not only by neutron interaction cross sections or scintillation light yield, but also by emission kinetics, optical transport, photodetector response, front-end electronics, digitization architecture, and the waveform analysis strategy. Consequently, recent progress in scintillator research is increasingly inseparable from parallel advances in SiPMs, high-speed acquisition systems, digital PSD methods, and simulation-assisted detector design.

The most important current trend is the convergence of advanced materials, fast electronics, and data-driven analysis. High-speed waveform digitization, ASIC-based front ends, FPGA-capable digital PSD, and AI-assisted classification are successfully extending neutron- γ discrimination into regimes where conventional charge comparison methods degrade, particularly at low deposited energies, under severe pulse pile-up, and at high count rates. At the same time, simulation and first-principles modeling are becoming essential tools for guiding material composition, defect control, and detector architecture before fabrication.

Future progress will therefore depend on several coupled priorities: improving radiation hardness and long-term stability, reducing cost and enabling scalable manufacturing, establishing fair benchmarking under realistic mixed radiation conditions, and developing interpretable hybrid AI / traditional processing methods for real-time field deployment. Continued advances along these directions should enable the next generation of compact, robust, and application-specific neutron detectors for nuclear science, security, medicine, nuclear fusion, and space instrumentation.

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AUTHOR CONTRIBUTIONS

A.S., S.Q., P.H., and F.G. conceived and designed the research. A.S. wrote the "INTRODUCTION," "MECHANISM OF NEUTRON DETECTION," "Gaseous detectors," "Liquid scintillators," and "Overcoming key challenges" sections. H.H. wrote the "Plastic organic scintillators" section. X.Z. wrote the "Crystal scintillators" section, with Z.L. contributing the "GAGG" subsection. J.R. and Z.H. wrote the "Glass scintillators" section. P.H. wrote the "NEUTRON-GAMMA DISCRIMINATION VIA PULSE SHAPE DISCRIMINATION" section. R.S. wrote the "PHOTODETECTOR AND ELECTRONICS FOR PSD" section. J.H. and X.W. wrote the "SIGNIFICANT IMPROVEMENT OF FOM VALUE WITH AI ASSISTANCE" section. J.R. and Y.H. wrote the "NEW NEUTRON DETECTION MATERIALS BY SIMULATION AND CALCULATION" section. F.G. wrote the "Application frontiers" section. Z.C., H.L., B.L., and T.W. participated in reviewing and revising the manuscript. All authors reviewed and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data sharing is not applicable to this article as no new raw data were created or analyzed in this review study.