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Progress in the Design of New Gas-Based Neutron Detectors: A Critical Review

Kreusch Filho[a], D.; Caetano[a], L. L.; Azevedo[a], A. M.; Nunes[a*], W. V.

[a] Instituto Militar de Engenharia, 22.290-270, Rio de Janeiro, Rio de Janeiro, Brazil.

*Correspondence: vallory@ime.eb.br

Abstract: The detection of neutrons through gas detectors has been an established practice for decades, with significant applications in nuclear reactors and monitoring by international organizations responsible for safeguarding the use of nuclear energy. Historically, these detectors utilized Helium-3 (He-3) as the ionization gas due to its reliability, safety, ease of use, insensitivity to gamma radiation, and high efficiency in thermal neutron detection. However, the scarcity in the supply of He-3 has created an urgent need to develop new gas-based neutron detectors which do not rely on this isotope. Although significant technological advances have been made, challenges remain, particularly in improving the sensitivity and resolution of detectors and enhancing their ability to discriminate between neutrons and other forms of radiation, such as gamma radiation. In response to these demands, the present study aims to review recent advancements in the development of gas-based neutron detectors that can replace Helium-3-based detectors. The review focuses on the advantages of these new technologies, particularly in terms of neutron capture efficiency and linear response over a wide range of energies. This analysis was conducted through a critical review of the scientific literature, focusing on articles published in scientific journals between 2015 and 2024. The evolution of gas detectors is examined, from the technologies available in 2015 to the most recent innovations in gas neutron detectors. The findings highlight substantial improvements in detection efficiency and detector resolution, along with advances in particle discrimination. There is also a growing trend towards miniaturization of devices and the exploration of new doping techniques to increase sensitivity and reduce costs. It is concluded that, despite the significant advances achieved in the development of gas-based neutron detectors, there remains considerable room for further improvement. Areas such as device miniaturization, the use of new dopants, cost-benefit analysis, and the application of these detectors in new fields still offer substantial opportunities for innovation and development.

Keywords: Neutron detection, gas detectors, helium-3.

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Progresso no Design de Novos Detectores de Nêutrons Baseados em Gás: Uma Revisão Crítica

Resumo: A detecção de nêutrons por meio de detectores gasosos é uma prática consolidada há décadas, com aplicações significativas em reatores nucleares e no monitoramento por organizações internacionais responsáveis pela salvaguarda do uso da energia nuclear. Historicamente, esses detectores utilizavam Hélio-3 (He-3) como gás de ionização devido à sua confiabilidade, segurança, facilidade de uso, insensibilidade à radiação gama e alta eficiência na detecção de nêutrons térmicos. No entanto, a escassez na oferta de He-3 criou uma necessidade urgente de desenvolver novos detectores de nêutrons baseados em gás que não dependam desse isótopo. Embora avanços tecnológicos significativos tenham sido alcançados, ainda existem desafios, particularmente na melhoria da sensibilidade e resolução dos detectores e no aprimoramento de sua capacidade de discriminar entre nêutrons e outras formas de radiação, como a radiação gama. Em resposta a essas demandas, o presente estudo tem como objetivo revisar os avanços recentes no desenvolvimento de detectores de nêutrons baseados em gás que possam substituir os detectores baseados em Hélio-3. A revisão foca nas vantagens dessas novas tecnologias, especialmente em termos de eficiência de captura de nêutrons e resposta linear em uma ampla faixa de energias. Esta análise foi conduzida por meio de uma revisão crítica da literatura científica, com foco em artigos publicados em periódicos científicos entre 2015 e 2024. A evolução dos detectores gasosos é examinada, desde as tecnologias disponíveis em 2015 até as inovações mais recentes em detectores de nêutrons gasosos. As conclusões destacam melhorias substanciais na eficiência de detecção e na resolução dos detectores, juntamente com avanços na discriminação de partículas. Há também uma tendência crescente para a miniaturização dos dispositivos e a exploração de novas técnicas de dopagem para aumentar a sensibilidade e reduzir os custos. Conclui-se que, apesar dos avanços significativos alcançados no desenvolvimento de detectores de nêutrons baseados em gás, ainda há muito espaço para melhorias. Áreas como miniaturização de dispositivos, uso de novos dopantes, análise de custo-benefício e aplicação desses detectores em novos campos ainda oferecem oportunidades substanciais para inovação e desenvolvimento.

Palavras-chave: Detecção de nêutrons, detectores gasosos, hélio-3.

1. INTRODUCTION

Neutron detection plays a crucial role in nuclear safeguards, homeland security, scientific research, and nuclear energy generation. For decades, helium-3 gas-filled proportional counters have been the gold standard for neutron detection due to their high efficiency, gamma-ray insensitivity, and long-term stability. However, a severe shortage of helium-3 gas that emerged in the late 2000s has driven an urgent need to develop alternative neutron detection technologies [1, 2]. This shortage threatens to impact critical applications in nuclear nonproliferation monitoring, border security screening, and neutron scattering science [3].

In response to the helium-3 shortage, extensive research and development of alternative neutron detection technologies have been conducted over the past decade [4]. International efforts, including collaborative workshops and benchmarking exercises, have been organized to evaluate and compare these alternative technologies against reference ^{3}He-based systems [4]. These initiatives have helped to assess the performance of various alternatives in terms of efficiency, gamma-ray discrimination, and overall system capabilities for nuclear safeguards applications [4].

Despite advances, several key challenges remain. Long-term stability and reliability of alternative detectors over many years of operation has not been fully demonstrated [4]. Optimizing neutron detection efficiency while maintaining gamma-ray insensitivity comparable to helium-3 detectors is still an ongoing effort for many alternatives [5].

Developing effective alternatives to helium-3 detectors is fundamental to ensure continuity in nuclear safeguards, security screening, and scientific applications that rely on neutron detection [6]. As helium-3 supplies continue to dwindle, alternative technologies must be matured and validated to meet the stringent requirements of these fields [7]. Advancing gas-based alternatives leverages existing expertise with proportional counters while potentially offering improved performance in some areas [8]. A thorough review of progress in this area is important to guide future research priorities and development efforts.

This review paper presents a comprehensive overview of recent advances in gas-based alternatives to helium-3 neutron detectors, with a focus on technologies relevant to nuclear safeguards applications. We examine developments in gas-based neutron detectors, covering improvements in detection efficiency, gamma-ray discrimination, and overall system performance. We also discuss remaining challenges, ongoing research efforts, and the potential for gas-based alternatives to meet or exceed helium-3 detector capabilities in specific use cases. By synthesizing recent progress, this review aims to provide a roadmap for further development of gas-based neutron detectors to address the critical helium-3 shortage.

2. METHODOLOGY

This systematic literature review, following Kitchenham and Charters [9] guidelines, examined advancements in gas-based detection technologies from 2015 to 2024, focusing on alternatives to Helium-3 detectors.

2.1. Search Strategy and Selection Process

Searches were conducted in Science Direct and Scopus using a string with Boolean operators that encompassed the main keywords used in the field, as "gas-based", "neutron detection", "gas detector", among others.

Inclusion criteria comprised gas-based neutron detection studies (excluding Helium-3), review articles, and relevant technologies. Exclusion criteria were non-neutron detection studies, non-gas-based technologies, and Helium-3 detector studies. The selection process involved initial screening of titles/abstracts followed by full-text evaluation.

2.2. Quality Assessment and Data Extraction

A rigorous quality assessment was conducted using a checklist of 8 questions. Each question was scored on a scale of 0 ("No"), 0.5 ("Partially"), or 1 ("Yes"). Studies scoring 2.0 or below were excluded from further analysis, ensuring only high-quality, relevant research informed our review.

For studies meeting the quality threshold, a comprehensive data extraction process was implemented. Key information extracted included: Detector type and gas(es) used; Performance metrics (efficiency, sensitivity, resolution); Comparative aspects with Helium-3 detectors; Key findings and intended applications; Challenges, limitations, and suggested improvements.

This systematic approach to quality assessment and data extraction ensured the inclusion of only the most pertinent and robust studies in our analysis, providing a solid foundation for drawing meaningful conclusions about advancements in gas-based neutron detection technologies.

2.3. Data Synthesis and Analysis

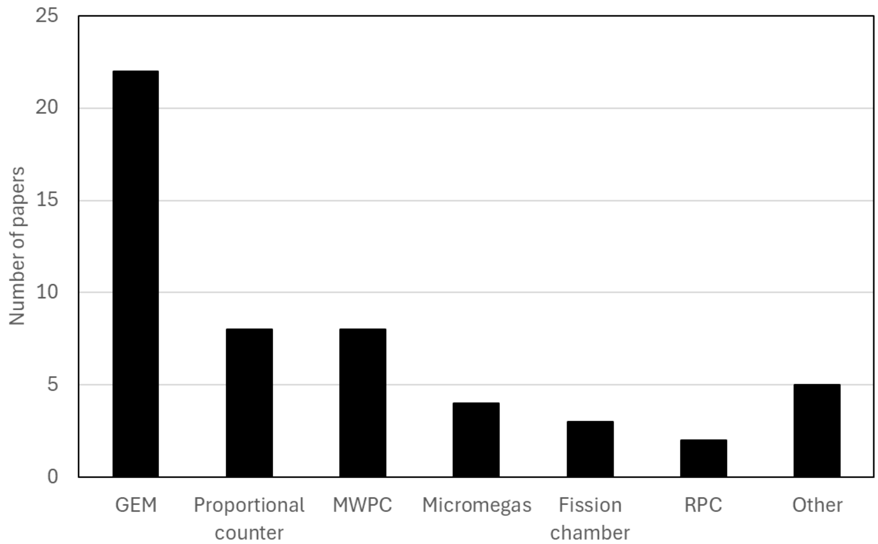
Data synthesis employed a narrative approach with quantitative analyses where appropriate. Information was thematically organized to identify trends, patterns, and research gaps. A critical analysis evaluated the robustness of evidence, considering internal/external validity, methodological reliability, and potential biases.

3. RESULTS AND DISCUSSIONS

The systematic literature search yielded, after removing duplicates, a total of 313 articles from the selected databases and remained for initial screening. Application of the inclusion and exclusion criteria during the title and abstract review resulted in the elimination of 249 articles, leaving 64 potentially relevant studies for quality of the full-text assessment. Upon thorough examination of the full texts, a further 9 articles were excluded based on the predefined criteria for quality assessment. Ultimately, 55 high-quality articles were included in this systematic review, forming the basis for our analysis and discussion of findings.

An analysis of the selected articles reveals a heterogeneous distribution of research focus across various neutron detector technologies, as is shown in Figure 1. The graph clearly demonstrates a predominance of studies centered on Gas Electron Multiplier (GEM) technology. This category, encompassing configurations such as Boron Array Neutron Detector-GEM (BAND-GEM) and neutron GEM (nGEM), constitutes the primary focus of 22 articles, either as the central subject or as a key component in achieving research objectives.

Figure 1: Number of papers that used each type of gas-based detector.



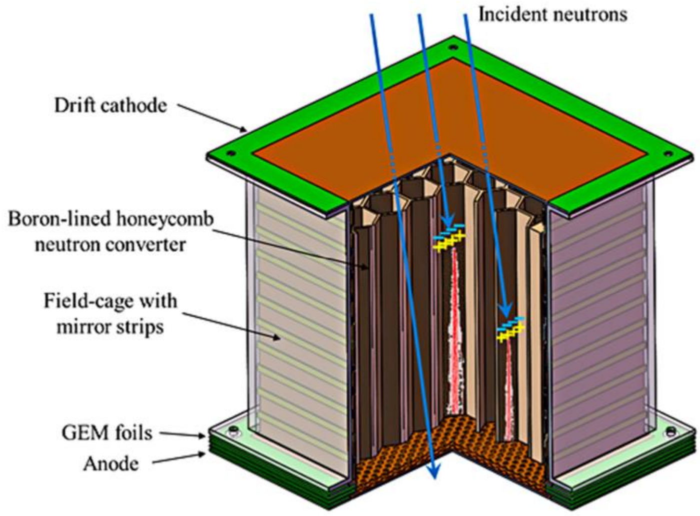
Source: The authors, 2024.

Boron-based detectors were the most studied GEM detectors and have been explored by Jamil *et al.* (2015)[10], Kim *et al.* (2015)[11], Celentano *et al.* (2015)[12], Aza *et al.* (2015)[13], Flierl *et al.* (2016)[14], Li *et al.* (2016)[15], Albani *et al.* (2016)[16], Santoni *et al.* (2018)[17], Croci *et al.* (2019)[18], Zhou *et al.* (2020)[19], Fang *et al.* (2020)[20], Albani *et al.* (2020)[21], Zhou *et al.* (2021)[22], Zhou *et al.* (2022)[23], and Yang *et al.* (2022)[24].

Aza *et al.* (2015)[13] reported on a triple GEM capable of detecting both thermal and fast neutrons. The detector demonstrated efficiencies ranging from 4.2 ± 0.2% for thermal neutrons to an average of 0.013 ± 0.001% for fast neutrons (2-20 MeV). Notably, it exhibited high photon rejection (around 10^{-7} at a chamber gain of 300) and good spatial resolution (around 8 mm, corresponding to pad size). Zhou *et al.* (2020)[19] advanced the field with a GEM detector using boron-coated foils as converters. This design achieved a remarkable 54 ± 2% detection efficiency for neutrons with a 4.9 Å wavelength, while maintaining excellent spatial resolution with a full width half-maximum (FWHM) of 2.94 ± 0.01 mm.

Detector geometry and layout were among the areas studied for improving performance. Albani *et al.* (2016)[16], Croci *et al.* (2019)[18], Edwards *et al.* (2018) [25], and Fang *et al.* (2020)[20] explored various configurations, including 3D converters, an improved BAND-GEM (I-BAND-GEM), and honeycomb converter, for either single anode-wire proportional counter and for GEM (shown in Figure2). The boron-lined honeycomb geometry improves neutron detector performance by providing a large surface area for neutron conversion, enabling efficient electron migration, and simplifying the detector structure. This design enhances detection efficiency and spatial resolution while improving overall robustness.

Figure 2: Schematic of honeycomb converter-based detector and neutron detection process.



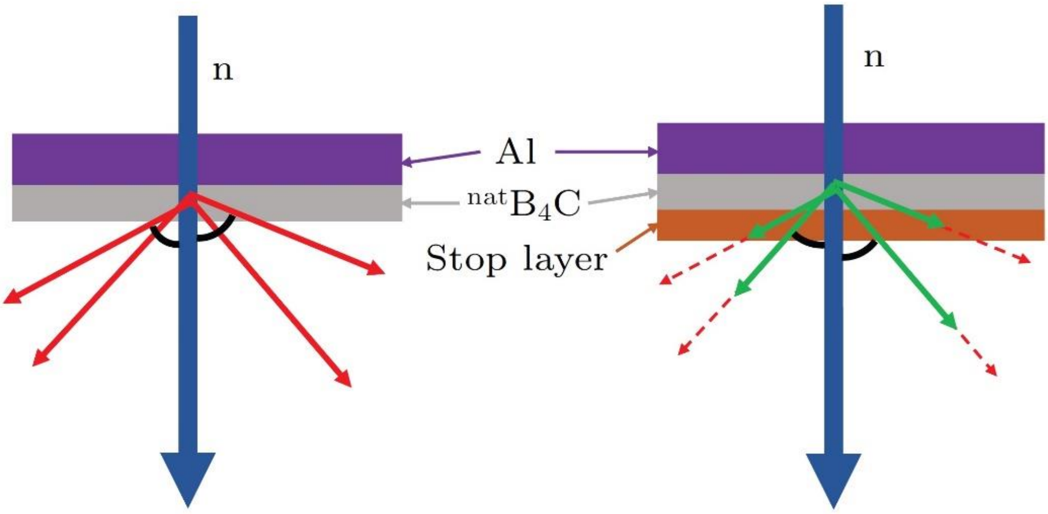
Source: Fang *et al.*, 2020 [20].

Supporting technologies have also seen significant advancements. Jamil *et al.* (2015)[10] and Kim *et al.* (2015)[11] utilized GEANT4 MC and FLUKA-MC simulations to enhance boron-based GEM detector development. Flierl *et al.* (2016)[14] demonstrated sub-millimeter spatial resolution by implementing a time-projection-chamber (TPC) concept for GEM readout. Celentano *et al.* (2015)[12] introduced an e-beam technique for depositing ^{10}B on Al_2O_3 substrates, potentially improving neutron capture efficiency.

While boron-based GEM were the most extensively researched for neutron detection, several studies explored alternative converter materials and configurations, showcasing the versatility of GEM technology in this field. Muraro *et al.* (2019) [26] explored the directionality properties of an nGEM detector using a plastic cathode to convert fast neutrons into protons via elastic scattering on hydrogen. This detector, designed for the Close-contact Neutron Emission Surface Mapping (CNESM) diagnostic system in the SPIDER experiment, showed promising results in discriminating neutron incidence angles. Anjomani *et al.* (2017) [27] developed a multi-element gaseous microdosimetric detector based on Thick Gas Electron Multiplier (THGEM) technology, aimed at measuring neutron and gamma-ray dose rates in weak neutron-gamma radiation fields. Their prototype incorporated 21 tissue-equivalent plastic sub-elements to increase neutron detection efficiency. Vahsen *et al.* (2015) [28] investigated a miniature Time Projection Chamber (TPC) with GEM-based charge amplification and pixel readout for 3-D tracking of millimeter-scale ionization trails. While primarily focused on directional dark matter detection, their work also demonstrated the potential for fast neutron detection and source localization, showcasing the adaptability of GEM technology for various particle detection applications.

Recent research has introduced stopping layers as a new concept in neutron detection. Zhou *et al.* (2022)[23] and Yang *et al.* (2022)[24] have explored this approach to improve the spatial resolution of GEM detectors. Their primary function is to reduce the deviation between the true position of the incident neutron and the position where the resulting ions are detected. This discrepancy often occurs due to a high angle of neutron incidence and the stopping layer can prevent alpha particles with high angle of incidence from entering the drift region, as can be seen in Figure 3. This technique offers a fresh perspective on enhancing GEM detector performance and may have applications in other types of neutron detectors as well. While still in its early stages, the use of stopping layers represents an interesting development in the ongoing efforts to improve neutron detection technologies.

Figure 3: Schematic of the operation of the stopping layer.

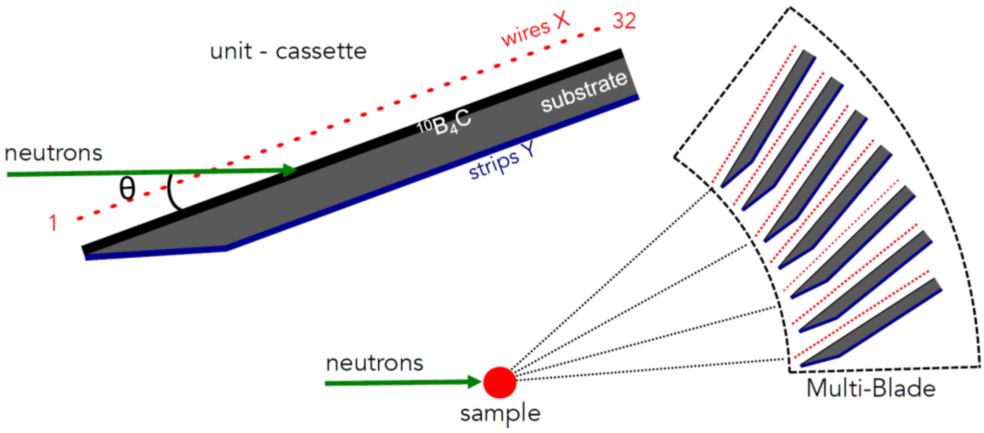


Source: Zhou *et al.*, 2022 [23].

The second most prevalent type of detectors investigated is shared equally between Multi-wire proportional counters (MWPC) and other types of proportional counters, each represented in 8 articles. MWPC exhibit diverse architectural approaches, including boron-lined and lithium-foil-based designs, while the broader category of proportional counters demonstrates a wide range of design concepts, including BF_3-based systems, boron-coated architectures, spherical geometries, and innovative approaches utilizing nanoparticle aerosols. This dual focus underscores the ongoing refinement of established technologies alongside the exploration of novel designs to meet specific application requirements.

Among the various MWPC configurations, the Multi-Blade detector has emerged as a promising solution for high-flux applications, with potential for both thermal and fast neutron detection. The Multi-Blade detector (a stack of MWPC, as shown in Figure 4) has undergone significant development, as reported by Piscitelli *et al.* (2017) [29] with an optimized design that improved thermal neutron detection efficiency to 56 ± 2% at 4.2 Å wavelength, increasing to 65 ± 2% at 5.1 Å. Mauri *et al.* (2018) [30] reported that the Multi-Blade can be used to detect fast neutrons, however, it's important to note that the fast neutron detection efficiency is approximately 4 orders of magnitude lower compared to thermal neutrons. Additionally, this detector also demonstrated impressive gamma sensitivity below 10^{-8} for a 100 keV threshold, which gives its ability to discriminate neutron detection from gamma radiation.

Figure 4: Schematic of the Multi-Blade detector.



Source: Piscitelli *et al.*, 2017 [29].

Those boron-lined MWPC utilizing grazing angle geometries, such as the multi-blade design, were comprehensively simulated and optimized by Qiu *et al.* (2020) [31]. Their study revealed that using neutron grazing incident geometry can significantly increase neutron detection efficiency compared to normal incidence structures. For a configuration with 4 layers of $^{10}B_4C$, each 1 μm thick, the neutron detection efficiency reached 54.56%, 49.17%, and 44.36% for neutron incident angles of 6°, 8°, and 10°, respectively. The researchers also determined that the width of the cathode plane is a crucial parameter affecting the detector efficiency, as it influences the total number of boron converter layers the neutron beam passes through. Additionally, their simulations using Garfield software provided insights into signal formation, time resolution, and gas gain uniformity, especially for curved detector geometries, which are often used in neutron scattering applications to minimize parallax errors.

Liu *et al.* (2023) [32] developed an innovative neutron beam monitor MWPC using Atomic Layer Deposition (ALD) to realize an ultra-thin boron layer to minimize the auto-attenuation within the converter layer. This monitor demonstrated noteworthy effectiveness in detecting thermal neutrons, achieving an efficiency of up to 0.12% for 1.8 Å neutrons.

Spherical proportional counters are also a promising technology for neutron spectroscopy. Bougamont *et al.* (2017) [33] investigated neutron spectroscopy using a Spherical Proportional Counter based on nitrogen gas, demonstrating the flexibility of this detector design in detecting both thermal and fast neutrons, using ^{14}N as a converter. Building on this work, Giomataris *et al.* (2023) [34] explored the capabilities of these detectors for neutron energy spectrum measurements, highlighting their potential to provide detailed information about neutron energy distributions ranging from thermal to fast neutrons.

In the scope of nuclear reactor monitoring, Teimoory *et al.* (2024) [35] reported on the development and characterization of fission chamber neutron detectors for use in the Isfahan miniature neutron source reactor. Their work showed that using a layer of 1.5 µm of 60% enriched uranium as converter has an acceptable linear response in the range of the used neutron flux and the spectrum can be related to the neutron flux.

The graph in **Figure 1** also showcases a range of other detector technologies with varying levels of research activity. Micromesh-gaseous structure (Micromegas), fission chambers, and Resistive Plate Chambers (RPC) were studied in 4, 3, and 2 papers each, among others less studied. These technologies represent a spectrum of research interest, potentially indicating specialized applications or emerging areas of study within the field of neutron detection.

One of these innovative approaches was proposed by Giovanetti *et al.* (2022) [36] with a novel thermal neutron detector called uRANIA (μ-RWELL Advanced Neutron Imaging Apparatus) based on micro-Resistive WELL (μ-RWELL) technology. This detector utilizes a thin layer of $^{10}B_4C$ on the cathode surface for neutron conversion, combined with the reliable and cost-effective μ-RWELL amplification stage. The researchers explored various converter layouts, including flat cathodes with different $^{10}B_4C$ thicknesses, a grooved aluminum cathode, and a metallic mesh coated on both sides. Through a combination of experimental measurements and simulations, they achieved thermal neutron (25 meV) detection efficiencies ranging from 3% to 10%.

In subsequent work, Giovanetti *et al.* (2024) [37] present further advancements in the uRANIA-V project. This study explores two Micro-Pattern Gaseous Detector (MPGD) technologies: the μ-RWELL and the surface-Resistive Plate Counter (sRPC). Both detectors utilize $^{10}B_4C$ converters for thermal neutron detection. The μ-RWELL, a compact resistive detector with a single amplification stage, demonstrated thermal neutron detection efficiencies of 4-8% for a single detection layer, depending on the converter configuration. The sRPC, a novel iteration of the Resistive Plate Counter technology based on surface resistivity, showed promise particularly in its hybrid layout, combining a boron-coated cathode with a float glass anode. This design offered good stability at high voltages and sufficient separation between neutron sensitivity and cosmic ray detection. The researchers highlight the potential for both technologies to be stacked, potentially achieving efficiencies of tens of percent, making them suitable for various applications.

The evolution of MPGD has continued with several groups conducting specialized research on Micromegas detectors, aiming to optimize their performance for neutron-related applications. Tsiledakis *et al.* (2017) [38] developed a novel large high-efficiency multi-layered Micromegas thermal neutron detector, which utilized several $^{10}B_4C$ thin layers mounted inside the gas volume. Their simulations and prototype tests demonstrated that five $^{10}B_4C$

layers of 1-2 µm thickness could lead to a detection efficiency of 20-40% for thermal neutrons with sub-mm spatial resolution. Diakaki *et al.* (2018) [39] introduced an innovative segmented mesh Micromegas detector with embedded XY strip structure, obtained by segmenting both the mesh and the anode in perpendicular directions. This design resulted in a low-mass device with good energy and spatial resolution capabilities, making it ideal for in-beam neutron measurements and quasi-online neutron beam profiling. Qi *et al.* (2020) [40] developed two variants of a Micromegas-based neutron detector to measure the beam spot distribution at the Back-n white neutron facility of the China Spallation Neutron Source. Their detector, using either ^{6}Li or ^{10}B as a neutron converter, demonstrated good performance in reconstructing neutron beam profiles and showed agreement between experimental data and Monte Carlo simulations for the measured beam spot distribution. Building on these Micromegas developments, Lee *et al.* (2023) [41] further advanced neutron detection systems at the Nuclear Data Production System (NDPS) of RAON, including a Micromegas detector with a ^{232}Th converter. Their Micromegas design showed good separation of fission fragments from background noise, particularly when using a GEM foil.

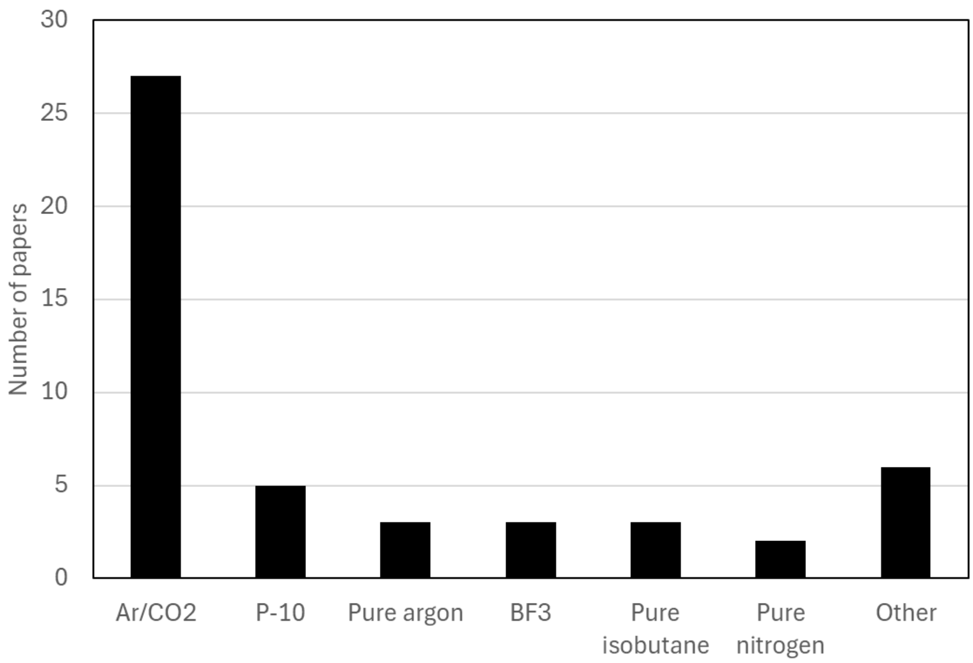
In addition to Micromegas, Lee *et al.* (2023) [41] also explored another MPGD technology for neutron detection - the Parallel Plate Avalanche Counter (PPAC). Their PPAC design, also incorporating a ^{232}Th converter, demonstrated excellent time resolution of about 1 ns FWHM and showed promising results in neutron detection during beam tests.

Zhang *et al.* (2018) [42] investigated the track identification and reconstruction capabilities of MPGD in fast neutron detection. Their work demonstrated the potential of these detectors to provide detailed information about neutron interactions, which is valuable for applications requiring precise neutron tracking and energy determination.

Advancements in Resistive Plate Chambers (RPC) have also contributed to the field of neutron detection. Margato *et al.* (2023) [43] developed timing RPC for thermal neutron detection with 3D position sensitivity. This innovation demonstrates the versatility of RPC technology and its potential to provide high-resolution spatial and temporal information in neutron detection applications. In a related development, Moon *et al.* (2024) [44] reported on the creation of a fast neutron monitoring detector for the NDPS neutron Time-of-Flight (TOF) facility using PPAC. This work showcases the adaptability of gaseous detectors for specialized neutron detection tasks, particularly in time-of-flight applications.

Building upon the discussion, **Figure 5** provides insight into the various gas mixtures employed in these detectors. Ar/CO_2 mixtures emerge as the dominant choice, featured in 27 papers. These mixtures are used with distinct ratios, typically ranging from 70/30 to 90/10 (Ar/CO_2). This flexibility in composition allows researchers to fine-tune detector performance for specific applications. The significant emphasis on Ar/CO_2 mixtures stems from their favorable properties for neutron detection, such as good electron drift characteristics and overall stability in detector operation.

Figure 5: Number of papers that used each gas/gas-mixture.



Source: The authors, 2024.

The choice of detector gas mixture plays a crucial role in neutron detection performance. Dian *et al.* (2017) [45] studied neutron activation and prompt gamma intensity in Ar/CO_2-filled neutron detectors at the European Spallation Source. Their work provides valuable insights into the behavior of common gas mixtures under high-intensity neutron fluxes, which is essential for designing detectors for next-generation neutron sources.

P-10 gas (a mixture of 90% argon and 10% methane) is represented with 5 papers. The continued research interest in P-10 relates to its well-established performance characteristics in certain detector configurations, particularly in proportional counters.

The graph shows equal representation of pure argon, pure isobutane, and BF_3 gases, with 3 papers each dedicated to their study. This indicates ongoing interest in these gases for specific neutron detection applications. BF_3, in particular, has historically been used in neutron detectors due to its high neutron capture cross-section for boron, but its high toxicity prevents it from broader usage.

Even with this limitation, Nasir *et al.* (2018) [46] conducted an experimental and theoretical study on the response of BF_3 detectors to thermal neutrons in reflecting materials. Their findings contribute to a better understanding of how detector surroundings can influence neutron detection efficiency, which is worthy for accurate neutron flux measurements in various applications.

Pure nitrogen appears in 2 papers, suggesting a more specialized application or potentially novel approaches in neutron detection using this gas.

Other mixtures are accounted for by 6 papers. This category encompasses a variety of exotic gases or combinations tailored for specific detector designs or performance requirements, like R-14, pure xenon, R134a, and other mixtures. The size of this category underscores the ongoing innovation and diversification in the field of neutron detection gas mixtures.

This division of research focus reflects a field that balances the refinement of well-established gas mixtures like Ar/CO2 with exploration of alternative compositions. This approach facilitates both the optimization of proven technologies and the development of novel gas mixtures that may offer unique advantages for specific applications in neutron detection.

The distribution of focus in neutron detection across three categories of energy was also evaluated, these being detection of thermal neutrons, fast neutrons, and both. The analysis reveals a clear predominance of research focused on thermal neutron detection, with 36 articles dedicated to this category. This significant emphasis on thermal neutron detectors reflects their widespread applications in fields such as neutron scattering, materials research, fission reactors, and homeland security. The higher interaction cross-sections for thermal neutrons with many converter materials contribute to this focus, as it allows for more efficient detection.

Fast neutron detection, while less prevalent, is the subject of 9 articles. This smaller but notable portion of research addresses specialized applications in nuclear physics experiments, fusion research, and high-energy physics. The challenges associated with fast neutron detection, such as lower interaction cross-sections, contribute to the fewer number of studies in this area.

Another 8 articles discuss detectors capable of detecting both thermal and fast neutrons. This category represents research into versatile detection systems that can operate effectively across a wide energy range, potentially offering broad-spectrum detection capabilities. While thermal neutron detection dominates the research landscape, there is an ongoing effort to improve detection efficiencies and capabilities across the entire neutron energy spectrum, as evidenced by the studies on fast neutron detection and dual-purpose systems.

Converters play a key role in neutron detectors by addressing a fundamental challenge in neutron detection. Neutrons, being electrically neutral particles, do not directly ionize materials and are therefore difficult to detect using conventional methods. The converter primary function is to transform incoming neutrons into detectable secondary particles, typically charged particles or photons. This conversion process allows for the indirect detection and measurement of neutrons. Common converter materials include boron-10, lithium-6, and helium-3, which have high neutron absorption cross-sections. When neutrons interact with these materials, nuclear reactions occur, producing charged particles that can then be detected by the detector. The choice and efficiency of the converter significantly influence the overall performance of the neutron detector, affecting its sensitivity, energy resolution, and ability to discriminate between neutrons and other types of radiation. Thus, the converter is an essential component that enables the practical application of neutron detectors.

Besides the prominent preference for boron, improvements in other converter materials have contributed significantly to advances in neutron detection. ^{6}Li has emerged as an effective neutron converter material due to its high thermal neutron cross-section and the energetic reaction products produced. Montag *et al.* (2018)[47] reported on the development of Li foil MWPC, which have demonstrated high neutron detection efficiencies. These detectors utilize suspended ^{6}Li foil sheets between anode wire banks, allowing reaction products to escape from both sides of the foil. The authors achieved over 55% thermal neutron detection efficiency with five layers of 75 µm thick ^{6}Li foils, with the potential to increase efficiency above 70% using ten 96% enriched ^{6}Li foil layers. Nelson *et al.* (2015)[48] further explored this concept, constructing large-area Li foil MWPC with five layers of 75 µm thick ^{6}Li foils spaced 1.63 cm apart. Their modular system demonstrated an efficiency of 13.9±0.03% for a bare ^{252}Cf source, with good angular response and gamma-ray rejection. Edwards *et al.* (2018) [49] investigated an alternative approach using suspended foil microstrip neutron detectors (SFMND) with ^{6}Li foils, achieving intrinsic thermal neutron detection efficiencies of 12.58±0.15% for a single foil and 29.75±0.26% for five foils.

Gadolinium (Gd) has also been used as converter material due to its exceptional thermal neutron capture cross-section. Song *et al.* (2020) [50] developed a gas electron multiplier (GEM) detector with a gadolinium cathode to explore its potential as a neutron detector. Their design consisted of three standard-sized (10 x 10 cm^2) GEM foils and a thin gadolinium plate as the cathode, serving as the neutron converter. Using a thermal neutron source at the Korea Research Institute of Standards and Science (KRISS), they measured a neutron detection efficiency of 4.630 ± 0.034(stat.) ± 0.279(syst.)% for their gadolinium GEM detector. The authors noted that while Gd-GEM detectors may not completely replace ^{3}He and BF_3 neutron detectors, they show great promise for large-area neutron-beam monitors and neutron imaging devices. Dumazert *et al.* (2018)[51] provided a comprehensive review of Gd use in neutron detection, highlighting its exceptionally high thermal neutron capture cross-section of around 255,000 barns, which is an order of magnitude larger than other commonly used converter materials. They discussed various detection schemes utilizing different aspects of the Gd(n,γ) capture reaction, including low-energy electron signatures in gaseous detectors, medium-energy gamma-ray and electron signatures in small-volume solid-state detectors, and high-energy gamma-ray signatures in large-scale liquid and solid detectors. These studies demonstrate the versatility and potential of gadolinium-based neutron detectors across various applications and detection configurations.

Another promising converter material is High-density polyethylene (HDPE), that can be used for fast neutron detection due to its high hydrogen content. Wang *et al.* (2015)[52] developed a high-efficiency fast neutron detector prototype based on a triple GEM detector coupled with a novel multi-layered HDPE neutron-to-proton converter. Their study compared traditional single-layered HDPE converters with novel multi-layered designs, finding that the multi-layered approach significantly improved neutron detection efficiency.

When using 38 layers of HDPE, the relative detection efficiency was approximately four times higher than that of the traditional single-layered method. This multi-layered conversion technique opens up new possibilities for enhancing neutron detection in practical applications. Croci *et al.* (2015)[53] likewise explored the use of HDPE in neutron detection by developing a medium-size area nGEM detector for neutron beam diagnostics. Their detector utilized a cathode composed of a 150 μm thick polyethylene (CH_2) film coupled with a 50 μm thick aluminum layer. This design allowed for the conversion of fast neutrons into recoil protons through elastic scattering processes. The nGEM detector demonstrated good performance in reconstructing neutron beam profiles and showed excellent gamma rejection capabilities. These studies highlight the potential of HDPE-based converters in improving the efficiency and versatility of neutron detectors for various applications, including fusion-relevant experiments and spallation source beam monitoring.

Even though solid converters are the most used, one of their biggest issues is auto-attenuation of the ionized particles produced. Liu *et al.* (2024) [54] proposed a novel method to enhance the stability of detection efficiency in grazing angle incidence boron-lined neutron detectors that can be used for any solid converter. Their approach involved the addition of a nickel layer, which effectively reduced the detector's sensitivity to surface roughness. This innovation resulted in a marked improvement in both the stability and reproducibility of detector performance, addressing key challenges in neutron detection technology and potentially broadening its applications in various scientific fields.

Another novel concept in neutron detection to reduce auto-attenuation has also been proposed by Amaro *et al.* (2017)[55], introducing a proportional counter filled with ^{10}B nanoparticle aerosol, which transforms a standard proportional gas mixture into a neutron-sensitive aerosol. This approach showed promise, with experimental results achieving a detection efficiency of 4% at V_{GATE}= -50 V. The adjustment of V_{GATE}, which controls the detector operating voltage, enables the application of energy discrimination techniques.

Meanwhile, Monte Carlo simulations were conducted for single B_4C particles of various radii, rather than for multiple layers of coating, providing insights into the detector behavior at the particle level. Duarte *et al.* (2019) [56] further investigated the operational properties of this concept using B_4C microparticles dispersed in P-10 gas (Ar-CH_4, 90/10%). They found that the presence of B_4C particles caused a 36% decrease in gas gain and a 15% degradation in energy resolution. The intrinsic energy resolution worsened from 15% to 32% with the inclusion of microparticles. Despite these effects, the detector remained operational without electrical discharges or severe instabilities, validating the potential of fine powder aerosols as radiation detection media in proportional counters.

Advancements in readout and signal processing techniques have also been verified. Mufti *et al.* (2016)[57] developed pulse shape discrimination techniques to effectively separate neutron signals from gamma-ray backgrounds in high-temperature fission chambers. Wang *et al.* (2015) [58] compared Wedge-and-Strip Anode (WSA) and delay line readouts for large-area neutron-sensitive microchannel plate detectors, finding WSA performance degraded in larger assemblies while delay line readouts achieved superior spatial resolution and throughput. Key factors improving spatial resolution were identified, including increased voltages and decreased MCP-to-delay line distance.

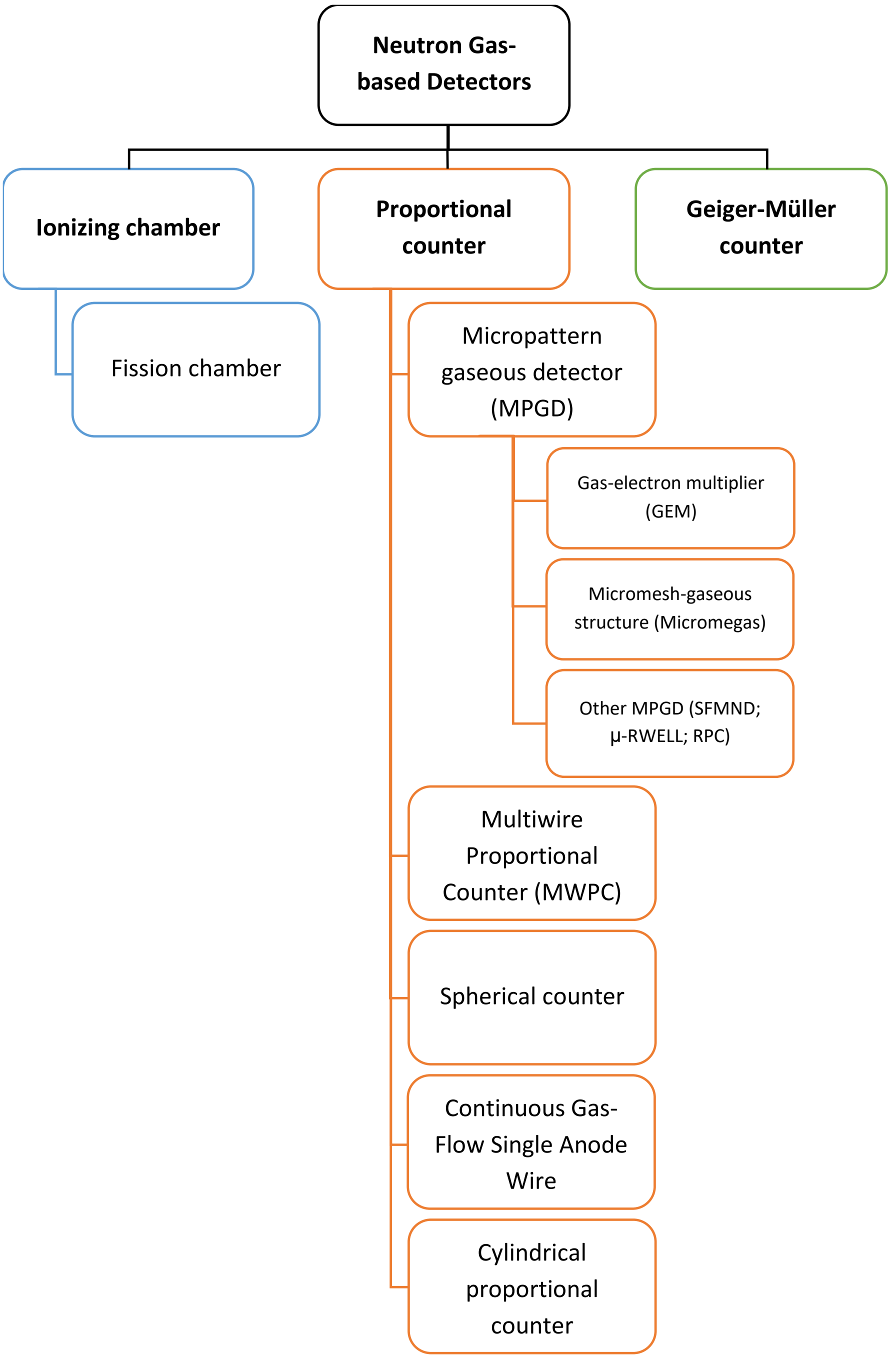
Yu *et al.* (2018) [59] presented a multiplexing readout method for large-scale neutron detectors, reducing the number of readout channels while maintaining high spatial resolution. Lab tests with simulated MWPC signals achieved position resolution better than 35 μm at 2 MHz event rate, while a joint test with a GEM detector demonstrated 400 μm resolution.

The practical aspects of neutron detector development are crucial considerations addressed in many of the articles. Cost-effectiveness is a recurring theme, particularly in light of the ^3He shortage. For example, Zhou *et al.* (2021)[22] discuss the use of available materials and manufacturing techniques to reduce costs in their lithium-based detectors. Reliability and long-term stability are emphasized in several studies, such as Li *et al.* (2016)[15], who report on a sealed ceramic nTHGEM (neutron Thick GEM) detector demonstrating good long-term counting rate stability. Ease of manufacturing and scalability are addressed by researchers like Höglund *et al.* (2015)[60], who explore thin film deposition techniques for large-area boron carbide coatings. Operational considerations, such as gas handling and pressure requirements, are discussed in articles like the one by Desai & Rao. (2021)[61], which examines the temperature sensitivity of BF_3 detectors. Safety concerns, particularly regarding toxic materials like BF_3, are noted in several papers, driving research into safer alternatives. Many articles, including Nelson *et al.* (2015)[48], discuss the importance of gamma-ray discrimination capabilities in practical applications. The challenge of achieving high detection efficiency while maintaining good spatial and temporal resolution is a common thread, with various approaches proposed to balance these often-competing requirements. Additionally, several papers, such as Reichenberger *et al.* (2016)[62], address the need for structures capable of operating in high-radiation environments or under extreme conditions like those found in nuclear reactors. These practical considerations reflect the complex interplay of technical, economic, and operational factors that influence the development and adoption of new neutron detection technologies in real-world applications.

The harsh environments present in nuclear reactors pose unique challenges for neutron detectors. Galli *et al.* (2020) [63] addressed this issue by designing a new discriminating high-temperature fission chamber filled with xenon for sodium-cooled fast reactors. Their innovative approach demonstrates the ongoing efforts to develop robust neutron detection solutions for advanced reactor designs. In a similar vein, Hamrita *et al.* (2017) [64] focused on the rejection of partial-discharge-induced pulses in fission chambers designed for sodium-cooled fast reactors, further illustrating the importance of signal discrimination in challenging detector environments.

Summarizing, each approach has been classified within the three classical gas-detector categories—ionization chambers, proportional counters and Geiger–Müller counters (however there were no studies accounted for Geiger-Müller counters)—to illustrate how recent innovations extend established detection principles. Figure 6 presents the corresponding schematic classification for each design approach, and Table 1 assigns papers studied to each category alongside its specific design approach.

Figure 6: Classification for the design approaches presented.



Source: The authors, 2024.

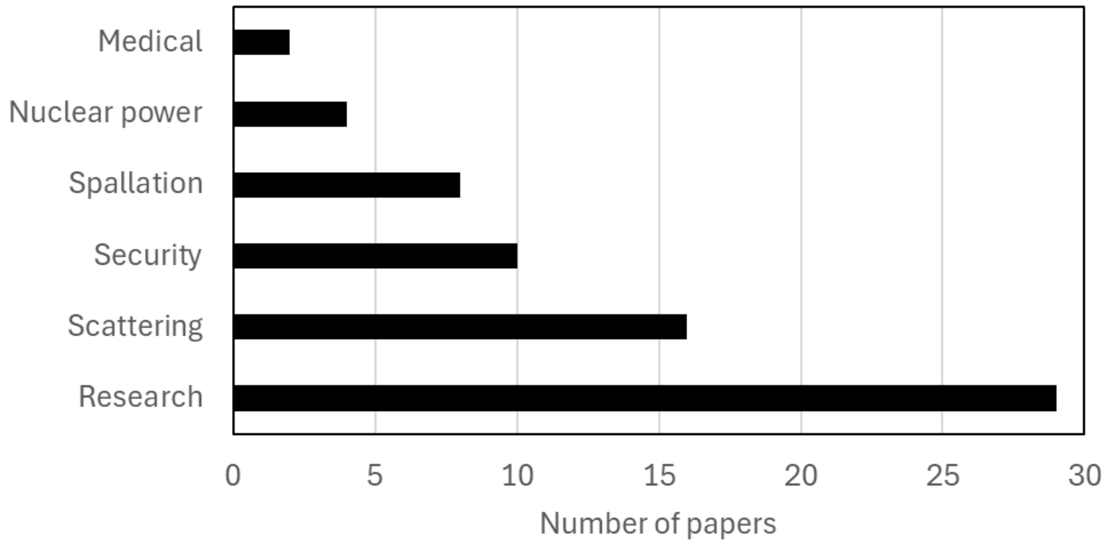
Table 1: Categories of gas-detectors studied in each paper.

Category	Design Approach	Papers
Ionizing Chamber	Fission Chamber	[35], [63]-[64]
Proportional Counter	GEM	[10]-[24], [26]-[28], [50], [52]-[53]
	Continuous Gas-Flow Single Anode Wire	[25]
	MWPC	[29]-[32], [47]-[48]
	Spherical counter	[33]-[34]
	Other MPGD	[36]-[37], [43]-[44], [49], [58], [62]
	Micromegas	[38]-[42]
	Cylindrical proportional counter	[46], [55]-[57], [61]

Source: The authors, 2024.

The articles in the dataset cover a diverse range of applications for neutron detectors, reflecting the broad utility of these devices across various scientific and technological fields, and are shown in Figure 7. Research applications dominate the dataset with 28 papers, indicating the significant role of neutron detectors in scientific studies. Scattering experiments account for 18 papers, representing the second most common application. Security applications are mentioned in 11 papers, highlighting the importance of neutron detection in safety and surveillance contexts. Spallation facilities are the focus of 9 papers. Nuclear power applications are discussed in 5 papers, demonstrating the relevance of neutron detection in the energy sector. Medical applications appear in 2 papers, suggesting a smaller but notable presence in healthcare or medical research. This distribution of applications underscores the versatility of neutron detection technologies across multiple fields, from fundamental research to practical applications in energy, security, and medicine.

Figure 7: Number of papers for each purpose.



Source: The authors, 2024.

4. CONCLUSIONS

The field of neutron detection has witnessed remarkable progress over the past decade, driven by the pressing need to develop alternatives to ^{3}He-based systems and the growing demand for enhanced performance across various applications. This comprehensive review has illuminated several significant advancements that have shaped the landscape of neutron detection technology.

Gas Electron Multiplier (GEM) detectors, particularly those incorporating boron-10 converters, have emerged as one of the most promising alternatives to ^{3}He detectors. These systems have demonstrated impressive capabilities, achieving thermal neutron detection efficiencies of up to 54%, spatial resolutions with FWHM as low as 2.94 mm, and robust gamma rejection capabilities. The exploration of novel converter materials, including lithium-6, gadolinium, and high-density polyethylene, has significantly expanded the toolkit available to detector designers, each offering unique advantages for specific neutron energy ranges and applications.

Innovative detector concepts have pushed the boundaries of neutron detection technology. The Multi-Blade detector has shown great promise for high-flux applications, while the use of nanoparticle aerosols in proportional counters and the implementation of stopping layers in GEM detectors have opened new avenues for detector design. Advancements in readout techniques, such as time projection chambers and multiplexing methods, coupled with sophisticated pulse shape discrimination algorithms, have further enhanced detector performance and expanded their capabilities.

A notable trend in the field is the growing emphasis on miniaturization and portability, paving the way for new applications in field-deployable systems. This development holds significant potential for expanding the use of neutron detectors in various practical scenarios, from environmental monitoring to security applications, especially using MPGD.

Despite these advancements, several challenges persist in the field of neutron detection. Balancing high neutron detection efficiency with effective gamma-ray discrimination continues to be a significant hurdle, particularly for thermal neutron detection. The development of cost-effective detectors that can match or exceed the performance of ^{3}He-based systems while remaining viable for large-scale deployment remains an ongoing challenge. Additionally, creating detectors capable of long-term stable operation in extreme environments, such as those found in nuclear reactors or space applications, presents considerable difficulties. While progress has been made, efficient and cost-effective fast neutron detection with good energy resolution remains an area requiring further research and development.

Looking to the future, several promising research directions emerge. The continued exploration of advanced materials, including novel converter materials and nanostructured designs, holds the potential to enhance neutron capture efficiency and reaction product detection. The integration of machine learning techniques for improved signal processing, background rejection, and data analysis represents a fertile area for innovation. The development of hybrid detector systems that can efficiently detect neutrons across a wide energy range merits further investigation.

Quantum sensing techniques offer intriguing possibilities for ultra-sensitive neutron detection, while environmental considerations call for a focus on sustainable materials and energy-efficient designs. In the medical field, research into biocompatible detectors and high-resolution imaging systems could open new avenues for neutron-based diagnostics and therapy monitoring. Furthermore, the potential for large-scale, networked neutron detection systems presents exciting opportunities for applications in environmental monitoring, nuclear safeguards, and fundamental physics research.

In conclusion, while significant strides have been made in gas-based neutron detection technologies, there remains substantial room for innovation and improvement. The field is poised for further advancements that will not only enhance existing applications but also open up new possibilities across a wide range of disciplines, from fundamental nuclear physics to homeland security and medical imaging. Continued investment in research and development in this area is crucial to meeting the evolving challenges of neutron detection in the 21st century. As we look ahead, the synergy between materials science, advanced electronics, data processing, and quantum technologies promises to drive the next generation of neutron detectors, further expanding our capabilities in this critical field of scientific instrumentation.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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