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Full Length Article

Concept development of an active fast neutron backscatter imaging technique for planetary subsurface studies

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ABSTRACT

Active neutron interrogation techniques that integrate Gamma-Ray and Neutron Spectroscopy (GRNS) with Associated Particle Imaging (API) offer a highly promising approach for achieving three-dimensional (3D) bulk geochemical analysis of planetary shallow surfaces. While API-GRNS using prompt γ -rays has been explored previously, the complementary use of backscattered fast neutrons within the API framework remains comparatively underexplored. Most prior fast neutron API demonstrations are based on forward scattering measurements in a transmission geometry, whereas planetary surface deployments require a backscatter geometry in which neutrons are measured after being scattered from the target.

This study presents a proof-of-concept laboratory demonstration of API-based backscattered fast neutron imaging for material discrimination, with emphasis on distinguishing hydrogen-rich from hydrogen-deficient targets relevant to planetary exploration. Experiments were conducted using a D-T neutron generator-based API system at Lawrence Berkeley National Laboratory (LBNL), employing ^6Li -activated CLYC ($\text{Cs}_2\text{LiYCl}_6:\text{Ce}$) and EJ-309 scintillators for coincident detection of alpha particles and fast neutrons. The system successfully imaged contrasting materials with high and low mass number (A) based on their neutron scattering characteristics, investigating the feasibility of backscattered fast neutron imaging as a complementary diagnostic to API-based γ -ray spectroscopy and as a method to distinguish hydrogen-bearing materials.

Monte Carlo simulations using GEANT4 provide insight into the observed image contrast, highlighting the roles of elastic and inelastic scattering kinematics, macroscopic cross sections, and detector timing resolution. While quantitative hydrogen retrieval and depth sensitivity analyses are beyond the present scope, this work establishes a foundation for future studies aimed at extending API-based fast neutron imaging toward hydrated minerals and water, depth profiling, and integration with other GRNS sensors for planetary shallow subsurface exploration.

1. Introduction

Active neutron interrogation techniques have emerged as powerful tools for subsurface compositional analysis in applications ranging from security screening to *in situ* planetary exploration. Among these, Associated Particle Imaging (API) enables volumetric mapping by tagging neutrons with coincident detection of associated charged particles from fusion reactions. While API using prompt γ -ray spectroscopy and its use in planetary studies has been investigated [e.g. 1–3], the potential of detecting backscattered fast neutrons within the API framework remains underexplored. This proof-of-concept study investigates the fundamental feasibility of fast neutron based API for discriminating materials

with different neutron interaction properties, with particular attention to hydrogen-rich versus hydrogen-deficient substances, a distinction of significant importance for planetary geochemical analysis.

For decades, Gamma-ray and Neutron Spectroscopy (GRNS) from orbital platforms has been instrumental in mapping elemental abundances and hydrogen distribution across the Moon, Mars, Mercury, and asteroids, revealing large-scale geochemical patterns and potential volatile reservoirs [4–8]. These passive techniques rely on detecting secondary radiation produced by galactic cosmic ray (GCR) interactions with the planetary surface. While orbital GRNS provides global context, *in situ* measurements are necessary for detailed characterization and localization of resources at specific landing sites.

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Active nuclear techniques, which employ onboard neutron sources, offer major advantages for surface measurements. By actively interrogating the subsurface, these instruments enable controlled measurement conditions and higher sensitivity, spatial resolution, and depth penetration than passive GCR-induced methods [9,10]. The Dynamic Albedo of Neutrons (DAN) instrument on the Mars Science Laboratory (MSL) Curiosity rover exemplifies this approach, using a pulsed neutron generator (PNG) to map variations in subsurface hydration along the rover's traverse [9,11–15]. The upcoming Dragonfly mission will also employ an active GRNS system (DraGNS) with a neutron source on board [16,17]. In addition, several prototype instruments are in development, including the system investigated in this work [18–20].

Despite these advances, most active neutron and γ -ray instruments primarily detect bulk variations in hydrogen content. A significant gap remains in our ability to generate high-fidelity, 3D maps of subsurface hydrogen and other elements at centimeter scales. Such spatially resolved information can help distinguishing between different forms of volatiles with higher resolution and interpreting their geological context.

Building on the foundation of active neutron sensing, the API technique has been proposed as a means to achieve volumetric compositional mapping [2,3,21]. API systems typically employ a deuterium-tritium (D-T) neutron generator that produces neutrons along with associated charged particles — α particles ($^4\text{He}^{2+}$) — from the D-T fusion reaction. Alternatively, deuterium-deuterium (D-D) generators can produce neutrons and $^3\text{He}^{2+}$ ions. Detecting the associated particle in coincidence with a neutron scattered or prompt γ -ray generated during inelastic neutron scattering within the irradiated sample allows precise determination of the primary neutron's emission direction and timing. This coincidence information enables accurate time-of-flight (ToF) measurements and 3D reconstruction of interaction points within the target, effectively producing volumetric maps of elemental distributions [1,2,21,22]. The technique inherently suppresses background signals and has demonstrated strong potential for identifying major rock-forming elements using prompt γ -ray spectroscopy [3,21,23,24].

Despite the API based γ -ray spectroscopy being effective in detecting many major elements such as C, Si and O, direct detection of hydrogen via prompt γ -rays in the API framework is not feasible, as hydrogen lacks excited nuclear states that produce characteristic prompt γ -rays from inelastic scattering. Although recent work has explored indirect inference of hydrogen content using spectral variations and machine learning methods [25], these approaches remain indirect. Hydrogen's only notable gamma emission arises from thermal neutron capture at 2.223 MeV, but these delayed events fall outside the short (tens of nanoseconds) coincidence window of API systems [21]. Although the system can detect thermal neutrons, the API technique relies on the directional correlation between the emitted alpha particle and the associated neutron. Once a neutron undergoes scattering and thermalization, this correlation is lost. Therefore, only epithermal and fast neutrons contribute to the API signal of interest, which defines and limits the effective timing window.

This limitation motivates the exploration of alternative API detection modes, specifically those that focus on the neutrons themselves. Hydrogen's nearly equal mass to the neutron allows for exceptionally large fractional energy losses per collision, up to 100%. This makes hydrogen-rich materials highly effective moderators, strongly influencing the transport, energy, and spatial distribution of fast neutrons. By detecting backscattered fast neutrons in coincidence with their associated α particles, one can, in principle, reconstruct the spatial distribution of scattering centers and infer hydrogen presence indirectly.

Experiments were conducted using an API system based on a D-T neutron generator at LBNL, integrating two neutron-sensitive scintillator detectors: ^6Li -enriched CLYC ($\text{Cs}_2\text{LiYCl}_6\text{:Ce}$) and EJ-309. CLYC is an inorganic dual-mode scintillator capable of detecting both γ -rays and neutrons (thermal and fast), offering good energy resolution ($\sim 4\%$ at 662 keV) and pulse shape discrimination (PSD) performance, with flight

heritage on LunaH-Map [26,27] and selection for Lunar-VISE [28]. EJ-309, an organic liquid scintillator with dual-mode, serves as a benchmark for fast neutron sensitivity due to its high light yield, excellent PSD, and fast timing. However, it does not have any flight heritage and it is not suited for γ -ray spectroscopy, but gross counting and separation of fast neutrons and γ -rays.

The primary goal of this work was to assess the utility of the API technique using the neutron channel, i.e., neutrons that exit the target and are detected in the CLYC (along with the system's inherent sensitivity to prompt γ -rays). In practice, the detector records any particle that reaches it; therefore, the measured neutron signal includes both elastically backscattered primary neutrons and secondary neutrons arising from non-elastic processes (e.g., inelastic scattering and reaction channels such as $(n,2n)$), while the γ -ray channel is dominated by prompt emission from inelastic interactions. In this study, our simulation-based interpretation focuses on the backscattered fast neutron population resulting from both elastic and inelastic interactions within the ToF/energy range selections used in the analysis. This assessment could be readily performed with equipment that was already on-hand that, while not optimal, was nonetheless adequate for the intended purpose.

The primary objectives of this proof-of-concept study are:

- To experimentally demonstrate that an API system can produce spatial images based on coincident detection of backscattered fast neutrons, using well-characterized reference materials (Delrin vs. stainless steel) with contrasting hydrogen content.
- To evaluate the system's capability in terms of spatial contrast and material differentiation within the API coincidence window.
- To compare the response of CLYC and EJ-309 detectors for coincident fast neutron imaging.
- To employ Monte Carlo simulations to interpret the experimental results, elucidate the contribution of individual elements (notably hydrogen, carbon, and iron), and analyze the underlying scattering kinematics.

This investigation represents an initial step toward applying API-enabled backscattered fast neutron measurements to planetary surface studies, rather than establishing the underlying proof-of-principle of fast neutron API imaging itself in general, which has been demonstrated previously [29–31]. Here we evaluate the feasibility and limitations of a backscatter geometry relevant to field/rover deployment by analyzing the spatial distribution of coincident fast neutrons emerging from the target. This configuration introduces distinct constraints for hydrogen sensing because n-H kinematics strongly limit single scatter backscattering for near equal masses. We therefore evaluate the feasibility and limitations of rover/field-relevant backscatter API by analyzing the spatial distribution of coincident fast neutrons emerging from the target, establishing a foundation for future planetary surface geochemical and volatile prospecting applications.

2. Apparatus and settings

The experimental setup at LBNL centers around an API system illustrated in Fig. 1 that is designed for volumetric elemental analysis. The core components include a sealed-tube deuterium-tritium (D-T) neutron generator (Adelphi Technology DT108.1-API), a position-sensitive alpha detector, and the scintillator detectors under investigation. The D-T generator produces monoenergetic 14.1 MeV neutrons, along with coincident 3.5 MeV alpha particles via the reaction $^2\text{H} + ^3\text{H} \rightarrow ^4\text{He} + n$ where ^2H is deuterium (D), ^3H is tritium (T) and ^4He is an alpha (α) particle.

The associated α particles are detected using a Yttrium Aluminum Perovskite (YAP:Ce) scintillator coupled to a 16×16 pixelated multi-anode photomultiplier tube (MAPMT, Hamamatsu H13700-300). The YAP:Ce detector in our setup is positioned 6.7 cm away from the neutron generator along the +z direction. A four-corner resistive readout

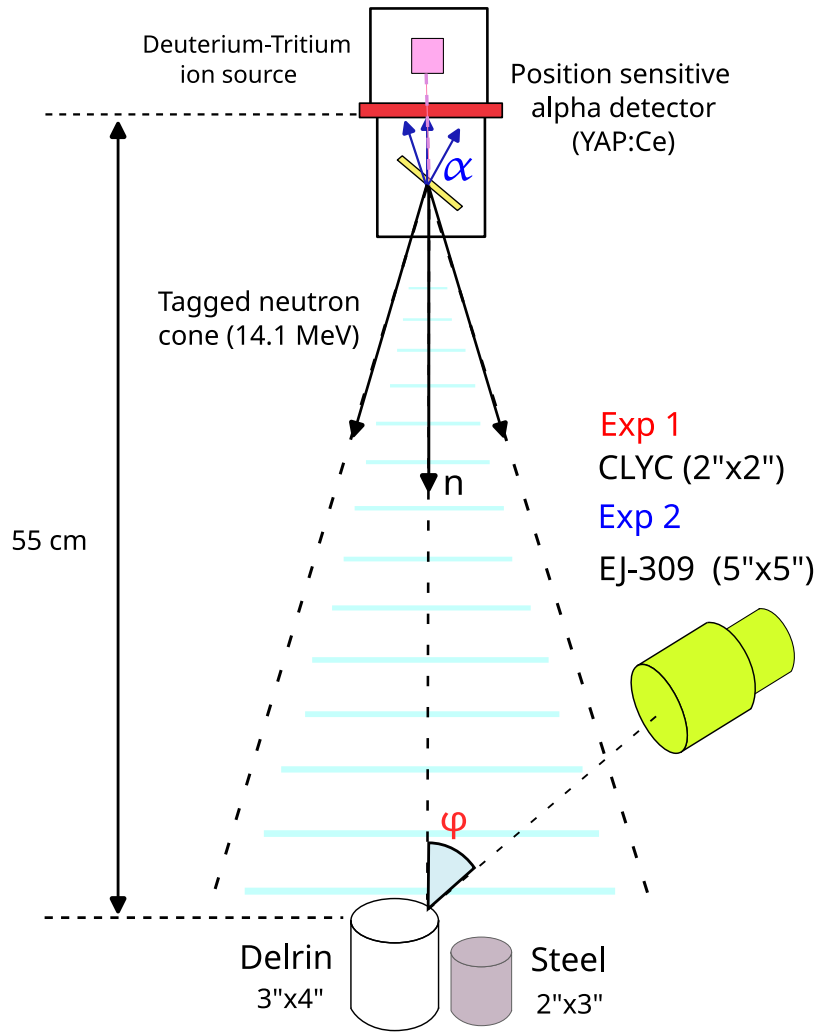


Fig. 1. Schematic illustration of the API system and experimental geometry, including the D–T neutron generator, the position sensitive YAP:Ce alpha detector, and the tagged neutron cone (14.1 MeV) directed toward the sample region located at a stand-off distance of ~ 55 cm. Only one scintillator detector was operated at a time: the CLYC ($2'' \times 2''$) was used in Exp. 1, and the EJ-309 ($5'' \times 5''$) was used in Exp. 2 after replacing the CLYC at the same detector position (i.e., detectors were swapped between runs, not used simultaneously). The cylindrical targets consist of Delrin (polyoxymethylene; white cylinder, $3''$ diameter) and stainless steel (gray cylinder, $2''$ diameter). The angle φ denotes the net scattering angle for neutrons undergoing scattering interactions within the target(s).

network connected to the MAPMT allows for the reconstruction of the alpha particle interaction position on the scintillator surface [21]. This position information, together with the known geometry of the neutron generator target, defines a cone of possible trajectories for the coincident neutron, rather than a single path. The precise timing signal from the α detection provides the start time (t_0) for neutron ToF measurements.

For detecting the secondary radiation consisting of scattered neutrons and induced γ -rays resulting from the interaction of primary neutrons with the sample, we employed two different scintillator detectors in separate experimental runs. The first detector was a $2'' \times 2''$ cylindrical ${}^6\text{Li}$ -enriched CLYC ($\text{Cs}_2\text{LiYCl}_6:\text{Ce}$) crystal from Radiation Monitoring Devices (RMD), Inc., coupled to a Hamamatsu R6233-100 photomultiplier tube (PMT). CLYC offers dual-mode detection capabilities for both neutrons and γ -rays, good energy resolution for gamma spectroscopy ($\sim 4\%$ at 662 keV), and excellent pulse shape discrimination (PSD) for n/γ separation [32]. Thermal neutrons are detected via the ${}^6\text{Li}(n, \alpha)t$ reaction ($Q = 4.78$ MeV), producing a distinct signature around 3.2 MeV gamma-equivalent energy (MeV_{ee}). Fast neutrons interact via scattering and reactions such as ${}^{35}\text{Cl}(n, p)$ and ${}^{35}\text{Cl}(n, \alpha)$.

The second detector was a larger $5'' \times 5''$ cylindrical EJ-309 organic liquid scintillator from Eljen Technology. EJ-309 is optimized for fast

neutron detection through elastic scattering on hydrogen (proton recoil), providing superior fast neutron sensitivity and excellent PSD capabilities, albeit with poor energy resolution for γ -rays and no sensitivity to thermal neutrons. Key properties of both scintillators relevant to this application are summarized in Table 1. During the measurements, both scintillators were positioned at a height of 25 cm above the sample plane and 30 cm from the center of the sample configuration. The detector positioning at $\sim 55^\circ$ from the incident neutron beam was determined by the experimental setup constraints at LBNL. This angle places the detector outside the direct neutron beam path while maintaining sufficient solid angle coverage for adequate counting statistics.

The data acquisition (DAQ) system employed a PIXIE-16 digital platform (XIA, Inc.) equipped with 14-bit analog-to-digital converters (ADCs) sampling at 500 MS/s [33]. The system digitizes full waveforms from both the alpha-detector readout channels and the scintillator PMT signals. Energy and timing are calculated in real time using onboard FPGA-based charge integration and digital constant-fraction discrimination algorithms, respectively. PSD and coincidence analysis between the α detector and scintillator events are performed offline during post-processing using custom analysis routines.

The coincidence window for correlating α particles with detected backscattered neutron or prompt γ -ray was set to roughly 80 ns, a value

Table 1
Comparison of key properties for CLYC and EJ-309 scintillators relevant to API applications.

Property	CLYC	EJ-309
Physical Form	Inorganic crystal	Organic liquid
Density (g/cm ³)	~3.3	~0.96
Light Yield (photons/MeV)	~20,000	~12,000
Gamma Energy Resolution (@ 662 keV)	~4%	Poor (>10%)
Neutron Sensitivity	Thermal (⁶ Li) + fast	Fast only (p-recoil)
Primary Fast Neutron Interaction	Scatter + (n,p), (n, α)	Elastic scatter (n,p)
Timing Resolution (ns)	~1–2	~0.5–1
Scintillation decay components (ns)	Multi-component (material-specific)	~3–4 (fast) + ~30–40 (slow)
PSD basis (n/ γ)	Different component weights (pulse shape)	Fast/slow weight differs (p-recoil tracks)
PSD Capability (n/ γ)	Excellent	Excellent
Space Heritage/Suitability	Yes (LunaH-Map, Lunar-VISE)	No heritage; not suited for γ -ray spectroscopy

chosen based on both experimental geometry and neutron ToF considerations. In the API system, each deuterium–tritium (D–T) fusion event emits a 14.1 MeV neutron nearly back-to-back with a 3.5 MeV alpha particle. The alpha particle is detected within 4–5 ns after being released from the source, initiating the timing sequence. The corresponding neutron travels toward the target material, where it may scatter before reaching the detector. For a typical source-to-detector distance of 30–50 cm, 14.1 MeV neutrons require approximately 7–12 ns to reach the detector, depending on the path length and scattering geometry. In the PIXIE-16 each α event was configured to open a 60 ns timing window and each gamma or neutron event created a 20 ns windows. When these windows overlapped a coincidence trigger was created that was used to validate events in the list mode data stream. The API coincidence window provides a margin to include events with slight delays due to scattering angles or moderation while excluding uncorrelated background to a significant degree. This window was empirically studied in previous experimental studies using the same instrumentation coupled with a LaBr₃ detector [3,21,34]. However, the optimization of the PIXIE parameters for different scintillators is still ongoing work.

3. Experiments

To evaluate the fast neutron imaging capabilities of the API system with CLYC and EJ-309, we conducted a series of experiments using two cylindrical targets with distinct compositions: Delrin (a type of polyoxymethylene) and stainless steel (SS 304). The two cylinders differ not only in composition but also in size. The Delrin cylinder has a diameter of 3" (ϕ 76.2 mm) and a height of 4" (h 101.6 mm) cylindrical Delrin, whereas the steel cylinder has a diameter of 2" (ϕ 50.8 mm) and a height of 3" (h 76.2 mm). The cylindrical samples are placed in the same plane under the neutron beam, with the surface of the Delrin cylinder positioned ~55 cm away from the neutron generator. The composition of these materials are summarized in Table 3. Delrin (CH₂O)_n, composed of 53.29% O, 40.00% C and 6.73% H by weight, served as the H-rich target. Stainless steel, an alloy primarily composed of Fe (~75%), Cr (~18%), and Ni (~4%), represented a dense, hydrogen-poor material dominated by higher-Z elements. The contrasting neutron interaction properties of hydrogen (high elastic scattering cross section, efficient moderation) versus heavier elements like Fe and C (lower elastic cross section, significant inelastic scattering potential at 14.1 MeV) make these materials suitable for testing the system's ability to differentiate composition based on fast neutron signals.

During the measurements, the Delrin and stainless steel cylinders were placed simultaneously in a diagonal arrangement relative to the neutron-beam axis, as shown in Fig. 2 and the overall API setup in Fig. 1, with the tagged neutron cone directed downward. The neutron generator was operated at 90 kV. Data were acquired using one detector at a time: in Experiment 1 (Exp.1), the CLYC detector was operated for 3 h. The measurement was then repeated in Experiment 2 (Exp.2) by replacing the CLYC with a 5"×5" (ϕ 127 mm, h 127 mm) EJ-309 liquid scintillator positioned at the same detector location relative to

the cylinders as shown in Fig. 1. Because the two detectors required different readout and operating settings (PIXIE configuration and detector power supply), simultaneous acquisition was not performed. The EJ-309 run used the same generator voltage (90 kV; ~10⁷ n/s) and a 3 h acquisition time to ensure comparable neutron fluence. These measurements enabled a systematic comparison of detector responses (CLYC vs. EJ-309) for fast neutron coincidence imaging of the two contrasting materials.

4. Simulations

To complement the experimental measurements and gain deeper insights into the neutron interactions governing the observed signals, we performed Monte Carlo simulations using the GEANT4 toolkit (version 10.7) [35–37]. The simulations aimed to model the neutron transport within the sample materials, the detector response, and to help interpret the experimental fast neutron images, particularly regarding the contributions from hydrogen versus other elements. The main goal was to find out what the fraction of neutrons from different nuclei were based on neutron scattering physics, not a full API simulation.

The simulation geometry included the D–T neutron source modeled as an isotropic point source emitting 14.1 MeV neutrons with 10° beam angle, the sample cylinders (Delrin and stainless steel), and a 2"×2" cylindrical CLYC detector placed at the experimental position. The model did not include the walls, the frame supporting the system components and other objects in the room. For accurate modeling of neutron interactions across the relevant energy range, we employed a comprehensive physics list including standard electromagnetic processes (G4EmStandardPhysics), particle decays (G4DecayPhysics), high precision neutron physics including elastic and inelastic scattering, capture, and fission down to thermal energies using evaluated data libraries (G4HadronPhysicsQGSP_BERT_HP), specific modeling for low-energy neutron elastic scattering (G4HadronElasticPhysicsHP), and thermal neutron scattering (G4ParticleHPThermalScattering).

In the simulations, we tracked neutron interactions within the cylindrical samples and their subsequent interactions in the detector. For each primary neutron, we recorded the type and coordinates of each scatter (both elastic and inelastic) event inside the samples, the number of scatters along its trajectory, its kinetic energy and ToF upon arrival at the detector, as well as the first and last recoil nuclei encountered. The last recoil nucleus prior to detection was used to calculate the net scattering angle by comparing the neutron's trajectory at emission with its entry coordinates at the detector.

The simulated data was recorded as if the system DAQ was in list mode, hence the α -neutron correlation based on applying time gate is established later during the analysis. In the simulations, a detection event in the scintillator is defined as a neutron interaction with the detector material, followed by energy deposition from a cascade of secondary particles produced during the interaction. Each simulation launched 10⁸ neutrons uniformly within a 10° cone to reduce the computation time. This corresponds to the fraction of an isotropic

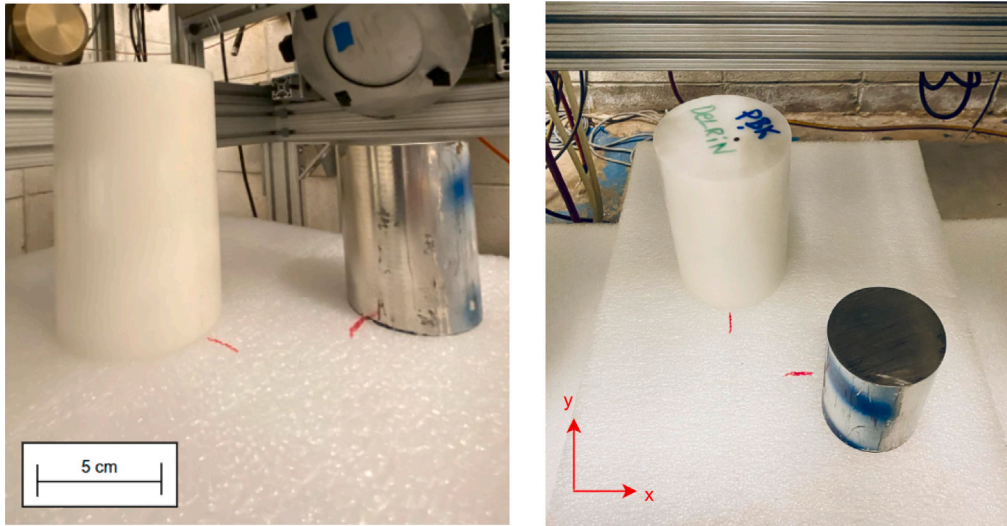


Fig. 2. Cylindrical samples made of Delrin (left) and stainless steel (right) and their placement under the neutron beam.

emission of 3.5×10^9 neutrons over 4π steradians that would fall within a 10° cone. The neutrons recorded at the detector are those originating from interactions of the primary neutrons within the irradiated sample materials. This setup enables accurate reproduction of both the physical scattering processes and the resulting detector signals. However, the simulations do not incorporate a full detector response model including energy-dependent intrinsic efficiency and they exclude background contributions.

Unlike the experimental API system, no coincidence window between associated α -particles and detected backscattered neutrons and prompt γ -rays was applied during the simulations. Instead, the image was reconstructed from simulated events meeting four criteria: (1) scattering in the sample via elastic or inelastic interaction, (2) particle type restricted to neutrons, (3) neutron arrival energy $E_{\text{arrival}} \geq 0.6$ eV, and (4) arrival at the detector within 80 ns. This configuration isolates the effect of scattering kinematics without additional API timing constraints.

To address both the experimental validation and the fundamental material contrast mechanisms underlying fast neutron API imaging, we carried out two complementary sets of simulations:

Validation of the experiment: To first establish the validity of our simulation framework, we replicated the experimental geometry. The diagonal configuration with both 3"×4" (ϕ 76.2 mm, h 101.6 mm) cylindrical Delrin and 2"×3" (ϕ 50.8 mm, h 76.2 mm) cylindrical stainless steel samples were placed under the simulated neutron beam. Background features present in the laboratory environment were excluded from the model to isolate and focus on signals originating solely from the samples. This comparison allowed us to validate the simulation's physics models and CLYC detector hits by confirming that it could reproduce the observed spatial contrast between the materials. The comparison is qualitative and semi-quantitative in terms of relative trends, rather than an absolute validation.

Material Comparison Study: To study the influence of material composition from geometric effects, we performed a systematic comparison of neutron scattering properties. Simulations were run with single cylinders of different materials positioned centered at the propagation direction of neutron beam on the XY plane 55 cm away from the source. In addition to Delrin ($(\text{CH}_2\text{O})_n$, 1.41 g/cm³) and stainless steel (7.87 g/cm³), we included graphite (C_n , 1.70 g/cm³), water (H_2O , 1.00 g/cm³) and high density polyethylene (HDPE, $(\text{C}_2\text{H}_4)_n$, 0.94 g/cm³) for comparison (see Table 3 for material properties). All cylinders in this study had the same dimensions (ϕ 76.2 mm, h 101.6 mm). We isolated and compared the effects of composition (H vs. C vs. O vs. Fe) on the detected fast neutron counts. These simulations also

helped us investigate the effect of relative macroscopic cross section (Σ) on neutron elastic and inelastic scattering behavior described by the scatter angle and the arrival time to the detector to differentiate the contributions of H from C, O, and Fe.

By analyzing the spatial distribution of interaction points within the samples that led to detected neutrons within 80 ns relative to the source emission, we generated simulated images analogous to the experimental API reconstructions.

5. Data processing

The raw data acquired from the PIXIE-16 system consists of digitized waveforms for each event detected in coincidence by the α detector and the scintillator (CLYC or EJ-309). Post-processing involves several steps to extract relevant physical information, including energy deposition, particle/radiation type, and interaction timing, culminating in the reconstruction of spatial images.

5.1. Pulse shape discrimination (PSD) ratio

A critical step for analyzing data from scintillators like CLYC and EJ-309 in mixed n/ γ fields is PSD analysis. This technique exploits the difference in the scintillation light decay profiles induced by different types of interacting particles. γ -rays typically produce faster decaying pulses compared to neutrons (see Fig. 3), which induce recoil protons in EJ-309 or heavier charged particles via reactions in CLYC. We employed the charge integration method to quantify this difference.

For each digitized pulse waveform, two charge integrals were computed: a prompt charge Q_{prompt} and a tail charge Q_{tail} , with integration windows defined relative to the aligned trigger time ($t = 0$). The prompt gate length was 0.14 μs (from -50 to $+90$ ns) and the tail gate length was 0.38 μs (from $+90$ to $+470$ ns). For CLYC, the PIXIE-16 QDC values (charge sums over predefined gates) were used to form $Q_{\text{total}} = \sum_{i=1}^7 \text{QDC}_i - C_1 \text{QDC}_0$, $Q_{\text{prompt}} = \sum_{i=1}^5 \text{QDC}_i - C_2 \text{QDC}_0$, and $Q_{\text{tail}} = Q_{\text{total}} - Q_{\text{prompt}}$. Here, QDC_0 is a pre-trigger baseline gate spanning approximately -7 μs to -0.05 μs relative to the trigger, and it was scaled by C_1 and C_2 to match the widths of the total and prompt integration windows, respectively. For EJ-309, the integration windows were applied directly to the saved waveforms, as illustrated in Fig. 3. The PSD ratio was then calculated as

$$\text{PSD} = 1 - \frac{Q_{\text{prompt}}}{Q_{\text{tail}}} \quad (1)$$

Plotting the PSD ratio against the total energy (proportional to Q_{total}) reveals distinct bands corresponding to γ -ray and neutron events

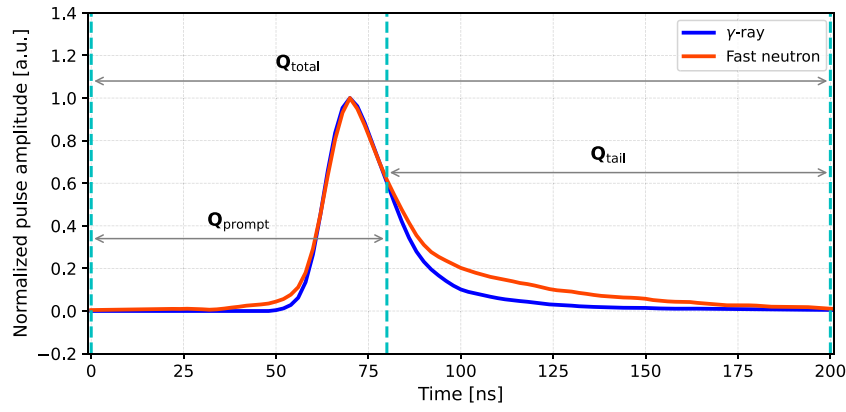


Fig. 3. Illustration of the charge integration method for PSD using EJ-309 waveforms. Average values of fast neutron (red) and γ -ray (blue) pulse traces. Prompt (Q_{prompt}), tail (Q_{tail}) and total (Q_{total}) charge) integration windows used in calculating PSD ratio is annotated (cyan).

(see Figs. 4A and 5A). The quality of separation is quantified using the Figure of Merit (FOM):

$$FOM = \frac{|m_n - m_\gamma|}{FWHM_n + FWHM_\gamma} \quad (2)$$

where m_n and m_γ are the centroids of Gaussian fits to the neutron and gamma PSD distributions at a specific energy slice, and $FWHM_n$ and $FWHM_\gamma$ are their respective full widths at half maximum. A higher FOM indicates better separation. For both CLYC and EJ-309, the entire energy range in the PSD plots (Figs. 4A and 5A) were used to calculate FOM see in Figs. 4B and 5B.

For EJ-309, a parabolic discrimination curve was applied on the data shown in Fig. 5A to separate the neutron and γ -ray continuum spectra. The discrimination boundary was optimized to maximize separation. The wiggles at higher energies (channels $> 8e4$) are due to saturation effects caused by the preamp range. In the inset plot inside Fig. 5A is the cleaner version of the PSD plot with energy cut off applied where our preamp starts to distort the signal. PSD performance is similar in both cases, however when reconstructing images using fast neutrons and γ -rays, we applied a cut off to the PSD data to exclude events at high energies. For CLYC, PSD required a more nuanced treatment because the detector exhibits a prominent thermal neutron capture peak in addition to the fast neutron and γ -ray continua. Fast neutrons and γ rays were separated using the same parabolic curve cut as shown in Fig. 4, while thermal neutrons were isolated by fitting a 2D Gaussian to the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ capture-peak region in Fig. 4, which peaks near ~ 3.2 MeVee. Neutron events were first selected with a PSD ratio band cut (the neutron band in Fig. 4), forming df neutrons, and then subdivided by energy into (i) *thermal neutrons* within the capture window $3.1 < E < 3.6$ MeVee, and (ii) *fast neutrons* outside this window, $E \notin [3.1, 3.6]$ MeVee. A low energy threshold and an upper energy bound were additionally applied to suppress near-threshold artifacts. Gamma-ray events were defined as those outside the neutron PSD selection within the same energy bounds. Although the 2D-Gaussian approach provides effective thermal neutron isolation, a small fraction of fast/epithermal neutrons can still fall within the capture peak region.

5.2. Image reconstruction

The API technique enables spatial reconstruction by correlating the emission time and initial direction of a tagged neutron — inferred from the coincident detection time and position of the associated α particle — with the subsequent detection time of radiation measured in the scintillator. Because only neutrons emitted within the tagged “API cone” have a corresponding α signal, untagged primary neutrons do not contribute to the reconstructed image. Accordingly, the neutron events used for imaging in this work are backscattered neutrons, i.e., source

neutrons that have undergone one or more interactions in the sample and/or surrounding materials before reaching the detector. In addition, a subset of events are random coincidences, in which an uncorrelated neutron happens to fall within the coincidence window; these events form a spatially random background.

For detected neutrons, the measured scintillation signal does not uniquely identify the specific reaction history (e.g., elastic or inelastic scattering, or other non-elastic channels such as (n, p) or $(n, 2n)$); it only indicates that the neutron has interacted prior to detection. The second class of detected radiation consists of prompt γ -rays produced primarily by inelastic neutron interactions. Images are reconstructed separately for neutrons and γ -rays detected during the same acquisition.

For each coincident event, the following steps are performed:

1. The alpha particle’s interaction position on the YAP scintillator is determined from the resistive readout signals. This position defines the initial direction vector of the coincident 14.1 MeV neutron.
2. The time difference (Δt) between detection of the associated α particle (t_0) and the signal in the scintillator (t_{scint}) represents ToF from the tagged emission to the detected event. For neutron events, Δt is the transit time of a tagged source neutron that has scattered in the sample (e.g., elastically or via other interactions) before reaching the scintillator. For γ -ray events, Δt corresponds to the time between tagged neutron emission and subsequent prompt γ -ray detection.
3. Assuming the neutron interaction occurs along its initial trajectory defined by the position of the associated alpha particle, the lateral coordinates are determined by the position-sensitive alpha detector, while the interaction depth (Z) can be inferred from the neutron ToF. In this study, we focus primarily on two-dimensional (2D) imaging based on lateral positioning; depth reconstruction will be addressed in future work optimizing CFD parameters, which helps achieving sufficient timing resolution for accurate depth determination.
4. The event is projected back along the initial neutron trajectory onto a plane representing the alpha detector’s field of view. Each coincident event contributes to the 2D image where the pixel coordinates correspond to the alpha detection position (and thus the neutron direction).
5. We produced Δt (ToF) histograms for CLYC and EJ-309 measurements (see Figs. 6(a) and 6(b)) to select a temporal range where cylinders are located to minimize background which includes other objects in the room, walls and the ground and isolate the signals from the samples in time.
6. We then discriminated neutron and γ -ray events based on PSD ratio.

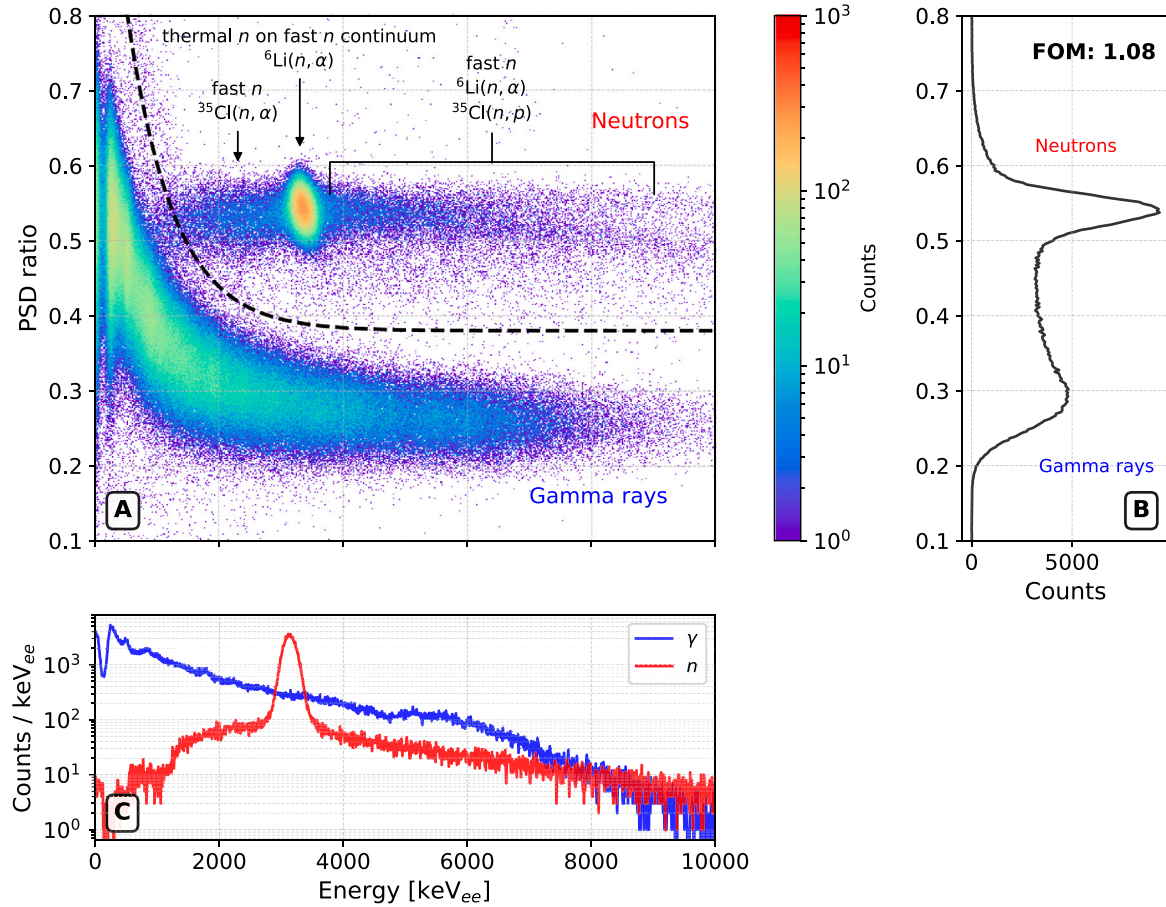


Fig. 4. Pulse shape discrimination (PSD) for the CLYC detector from the measurement performed using the samples shown in Fig. 2. (A) 2D histogram showing PSD ratio versus energy (keV_{ee}), clearly separating γ -rays (lower band), fast neutrons (middle band), and thermal neutrons (intense peak at $\sim 3.2 \text{ MeV}_{ee}$). (B) Projection of the PSD ratio showing the separation between gamma and neutron populations and the calculated FOM. (C) Pulse height spectra shown separately for γ -ray and neutron events as a function of calibrated gamma-equivalent energy in keV_{ee} .

Two factors contribute to the width of the experimental Δt (ToF) distributions from the CLYC and EJ-309 measurements shown in Fig. 6. First, the overall span of the distribution is set by the PIXIE-16 validation window, which is much wider than the 80 ns coincidence gate. Because any α -neutron pair occurring within this larger validation interval is accepted, the Δt histograms naturally extend well beyond 80 ns and include random coincidences. Second, the sharpness of the sample-related peaks within this window is determined by the detector timing resolution. In the CLYC measurement, non-optimized CFD settings and the inherently slower scintillation response broaden the prompt peak associated with the sample within 25–75 ns in Fig. 6(a)), whereas the EJ-309 detector produces narrower peaks within 130–150 ns as seen in Fig. 6(b)) where the distinct peaks in that Δt range are due to varying contributions from different nuclei in the samples. While the long Δt tails arise from acquisition-window logic, the peak broadening that limits time-based spatial resolution is due to detector and CFD timing performance.

Radiation source images are reconstructed in the coordinate frame of the α detector, yielding an angular projection of the sample volume as seen from the neutron generator's emission point. Generating images specific to different radiation types relies crucially on the PSD analysis. For the CLYC detector, events are classified according to their position in the PSD versus energy plot (Fig. 4A): Image based on the thermal neutron peak is generated using events within an elliptical region around the prominent ${}^6\text{Li}(n, \alpha){}^3\text{H}$ capture peak at approximately 3.2 MeV_{ee} ; fast neutron image utilizes events from the broader neutron band excluding the thermal peak, and γ -ray image is formed from

events within the γ -ray band (see Figs. 7). In the case of the EJ-309 detector, which effectively detects only fast neutrons and γ -rays, events are separated into distinct fast neutron and γ -ray images by applying a cut to the PSD distribution as shown in Fig. 5A.

By accumulating counts in the corresponding pixels of the α detector plane for each radiation type, we generate separate images that map the spatial origin of detected thermal neutrons, fast neutrons, and γ -rays originating from the cylinders as presented in Section 6.

5.3. Simulated data analysis

For the analysis of the GEANT4 simulation output, we focused on extracting physical observables that are directly comparable to the experimental measurements. The goal was to characterize the neutron scattering dynamics within the samples and to interpret the origin of the detected signals. For each simulated neutron, the toolkit provides detailed information on the particle trajectory, interaction history, energy deposition, and time of arrival at the detector.

During post-processing, we first filtered the simulation output to identify all epithermal and fast neutrons that reached the active detector volume (the $2'' \times 2''$ CLYC cylinder in the simulation) by applying an energy threshold at 0.6 eV to separate epithermal and fast neutrons ($E_{\text{arrival}} \geq 0.6 \text{ eV}$) from thermal neutrons ($E_{\text{arrival}} < 0.6 \text{ eV}$). This threshold was selected to distinguish neutrons that retain sufficient energy for fast neutron detection from those that have been thermalized through multiple collisions. The 0.6 eV cutoff corresponds approximately to

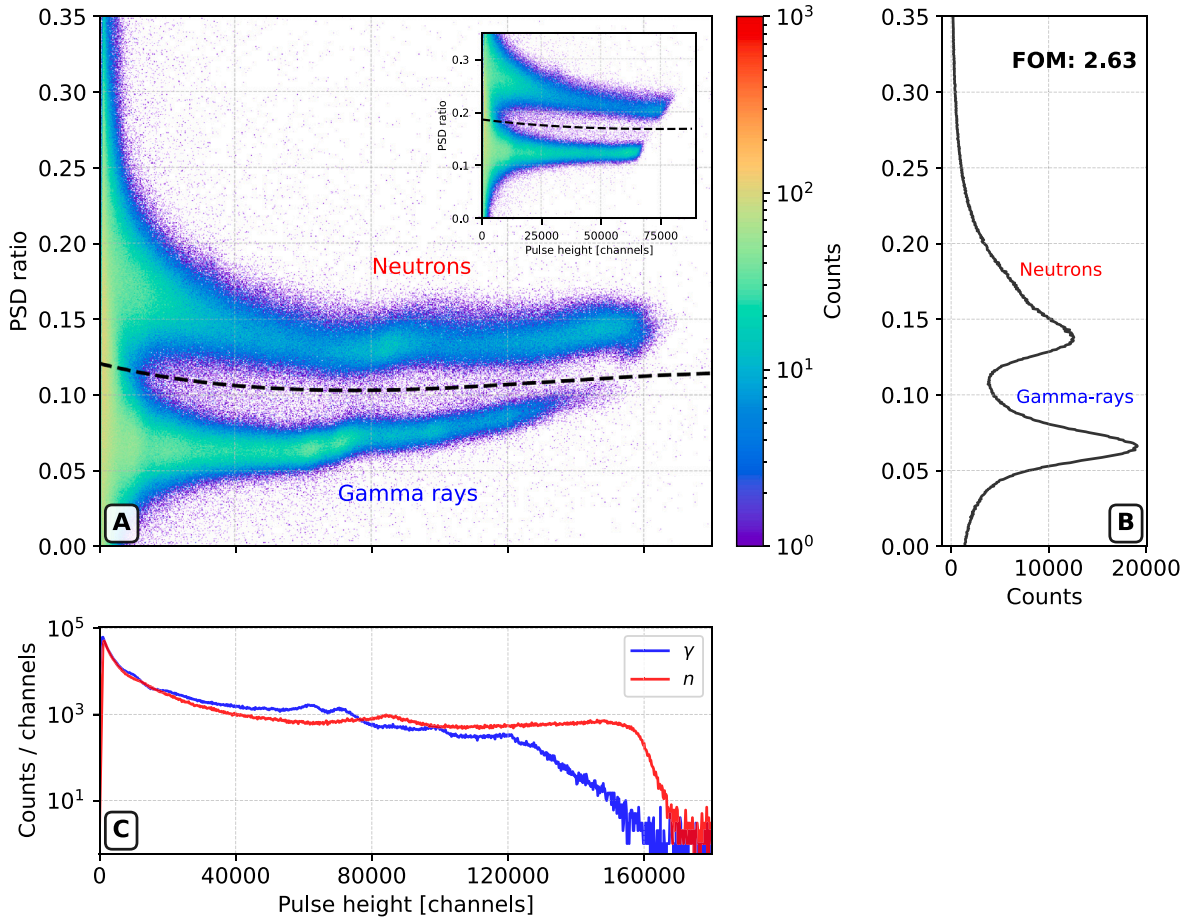


Fig. 5. Pulse shape discrimination (PSD) for the EJ-309 detector. (A) 2D histogram showing PSD ratio versus pulse height, clearly separating γ -rays (lower band) and fast neutrons (upper band). The sub-figure includes an inset that cleaner version of the PSD plot with energy cut off applied where our preamp starts to distort the signal. PSD performance is similar in both cases, however when reconstructing images using fast neutrons and γ -rays, we used the cut off applied version of the PSD data excluding higher energies. (B) Projection of the PSD ratio for a selected energy slice, showing the separation between gamma and neutron populations and the calculated FOM. (C) Pulse height spectra shown separately for γ -ray and neutron events as a function of uncalibrated pulse height.

the cadmium cutoff energy commonly used in planetary neutron spectroscopy to separate thermal and epithermal neutron populations, as used on a modeled equilibrium neutron fluxes for a FAN (ferroan anorthosite) material in [38].

To compare with the experimental API measurements, we applied a temporal range, selecting only those neutrons that arrived at the detector within 80 ns of the initial neutron generation time at the source. This time range was chosen based on where the samples are in time as shown in the Δt spectra in Figs. 6(a) and 6(b). In the experiment the selected 80 ns range also include random coincidence events from the background materials in the room which are not a part of the model. This is why the shape of the experimental Δt plots in Figs. 6 are different than that of the simulated ones shown in Fig. 12. Additionally, the simulated gamma equivalent spectrum for CLYC is compared that of the experimental measurement highlighting the contributions from the background and random coincidences as shown in [39].

For each detected neutron, we traced its history within the sample volumes (Delrin, steel, etc.). We recorded the number of elastic and inelastic scatters, the recoil nucleus (particularly, ^1H , ^{12}C , ^{16}O , and ^{56}Fe) involved in each interaction, time of arrival, and the kinetic energy of the neutron at the detector. This allowed us to differentiate between neutrons that scattered off hydrogen versus those that scattered off other nuclei.

To create simulated images comparable to the experimental results (see Figs. 9(b) and 9(c)), we aggregated the data based on the initial trajectory of the neutrons. For each detected neutron, the (x, y) coordinates of its initial path were binned into a 2D histogram. This process

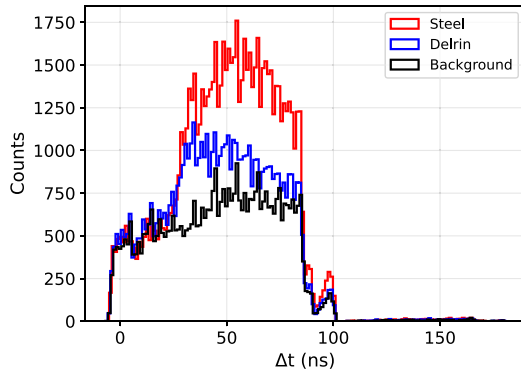
effectively reconstructed an image of the interaction locations within the samples, as viewed from the neutron source, separating signals based on interaction type and recoil nucleus.

To generate the arrival energy and ToF spectra (see Figs. 12, 13(a) and 13(b)), we histogrammed the arrival energy and arrival time for the filtered neutron events. These distributions were further broken down by the final recoil nucleus (^1H , ^{12}C , ^{16}O , and ^{56}Fe) to deconvolve the relative contributions of different elements to the final detected signal. A primary neutron from the source can undergo single or multiple scatter events within the cylinder samples. For the detected events, we considered the final elastic scatter event inside the sample before the neutrons make its way to the detector while keep a tally of the total number of scatter events (including elastic and inelastic interactions) that each detected fast neutron went through along its track.

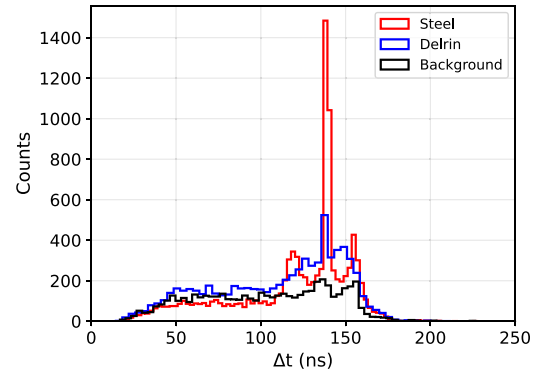
The net scattering angle (φ_{net}) represents the overall angular deviation of a neutron's trajectory from its initial direction to its final detection direction. This angle is important for understanding the relationship between neutron kinematics and material composition. For each detected neutron, the net scatter angle is calculated using the vector dot product:

$$\varphi_{net} = \arccos \left(\frac{\mathbf{d}_{primary} \cdot \mathbf{d}_{detected}}{|\mathbf{d}_{primary}| |\mathbf{d}_{detected}|} \right) \quad (3)$$

where $\mathbf{d}_{primary}$ is the displacement vector for the primary neutron from the source to the initial scatter point inside the sample and $\mathbf{d}_{detected}$ is



(a) CLYC Δt (ToF) histogram. Cylinders are located between 25–75 ns.



(b) EJ-309 Δt (ToF) histogram. Cylinders are located between 125–150 ns.

Fig. 6. Experimental Δt (ToF) histograms of neutron and γ -rays detected by CLYC and EJ-309. The Δt distributions are separately shown for stainless steel (red), Delrin (blue) and background (black) comparing events within unit volume ($2'' \times 3''$ cylinder size). EJ-309 demonstrates a higher resolution to constrain where the samples are in time and the distinct peaks between 125–150 ns in the EJ-309 Δt histogram are due to varying contributions from different nuclei in the sample materials. Background is made of random coincidences originating from neutron interactions with other objects in the room.

the displacement vector from the final scatter point to the detector hit calculated. These displacement vectors are calculated as follows:

$$\mathbf{d}_{\text{primary}} = \mathbf{r}_{\text{scattered}} - \mathbf{r}_{\text{source}}$$

$$\mathbf{d}_{\text{detected}} = \mathbf{r}_{\text{detected}} - \mathbf{r}_{\text{scattered}}$$

$\mathbf{r}_{\text{scattered}}$ is the location of where the last scatter event occurred inside the sample material, $\mathbf{r}_{\text{source}}$ is the location of the neutron generator and $\mathbf{r}_{\text{detected}}$ is the coordinates where the scattered fast neutron first interacts with the detector. For the neutrons to reach the detector positioned at 55° particularly from hydrogen nuclei, they need to undergo multiple scatter events inside the sample materials to have $\varphi_{\text{net}} < 90^\circ$. We use φ_{net} values together with ToF and the number of total scattering events along a neutron's track to study the relation between neutron kinematics and sample composition.

This systematic analysis of the simulated data was an important step for validating the experimental findings and providing a quantitative interpretation of the physical processes that produce the observed contrast in the fast neutron images and contributions from different elements present.

6. Results

In this section, we present the experimental results from the API measurements with CLYC and EJ-309 for imaging materials with large versus low atomic mass number (A) particularly using fast neutrons as well as the simulation results involving CLYC. We discuss the experimental PSD performance, the reconstructed images, and the physical insights gained from simulations regarding neutron interactions.

6.1. Pulse shape discrimination performance

The performance of both CLYC and EJ-309 detectors was evaluated using PSD to separate neutron and γ -ray events. Figs. 4 and 5 show the PSD analysis results for both detectors during measurements with the Delrin and steel cylinders.

For the CLYC detector, three distinct populations are visible in Fig. 4A. The lower band corresponds to γ -ray interactions with faster scintillation decay times, while the middle band represents a continuum from fast neutron interactions that produce longer decay components through recoil nuclei and charged-particle reaction products. The intense peak at $\sim 3.2 \text{ MeV}_{ee}$ arises from thermal neutron capture via the $^6\text{Li}(n, \alpha)t$ reaction. Some γ -neutron overlap appears at lower energies, which is typical for CLYC detectors. The calculated FOM of 1.08 indicates reasonable separation capability.

The EJ-309 detector demonstrates superior PSD performance (Fig. 5). Two populations are observed: the lower γ -ray band and an upper band from fast neutron interactions, with no thermal neutron capture signature as expected for an organic liquid scintillator. The separation between these bands is markedly better than in CLYC, particularly at higher energies, yielding a high FOM of 2.63. This strong PSD capability results from the differing light production mechanisms: γ -rays interact mainly via Compton scattering to produce prompt electron recoil signals, whereas fast neutrons scatter elastically from H nuclei, generating proton recoils with longer decay time components [40,41].

6.2. Experimental imaging results

6.2.1. Fast neutron imaging

Using the PSD analysis to isolate fast neutron events, we reconstructed spatial images of the sample configuration for both detector systems. Figs. 7 and 8 present the experimental imaging results.

The CLYC fast neutron image (Fig. 7(a)) successfully resolves both cylindrical samples, showing clear spatial separation between the Delrin and stainless steel regions, despite the 95% ^6Li -enriched CLYC detector being primarily sensitive to thermal and epithermal neutrons and less so to fast neutrons. While the visual contrast is modest, it demonstrates the system's ability to differentiate materials based on their neutron interaction properties. Quantitative analysis yields fast neutron count densities of $51.3 \pm 10.2 \text{ counts/cm}^3$ in the Delrin region and $49.27 \pm 8.2 \text{ counts/cm}^3$ in the steel region after geometric correction to $r = 20 \text{ cm}$.¹ The difference between the calculated count densities is statistically insignificant, and the CLYC fast neutron image (Fig. 7(a)) shows similar image contrast for both regions. Despite the modest contrast, the spatial separation of the samples is still evident in the image.

The EJ-309 fast neutron image (Fig. 8(a)) shows improved contrast and image quality compared to CLYC, reflecting its larger detection volume, higher intrinsic fast neutron sensitivity, and superior PSD performance. After geometric correction, EJ-309 detects higher fast neutron counts from steel than Delrin ($\approx 1.5\times$). The corrected values are $663.7 \pm 34.1 \text{ counts/cm}^3$ (Delrin) and $997.4 \pm 36.1 \text{ counts/cm}^3$ (steel). The larger contrast in the image is due to Delrin being further from

¹ Since the samples were placed at different distances from the detector, the count densities were corrected to a reference distance of $d = 20 \text{ cm}$ using $C_{20} = C_d \left(\frac{r}{20 \text{ cm}} \right)^n$, where n is the empirically determined distance exponent for the detector geometry. See Appendix for detailed calculations.

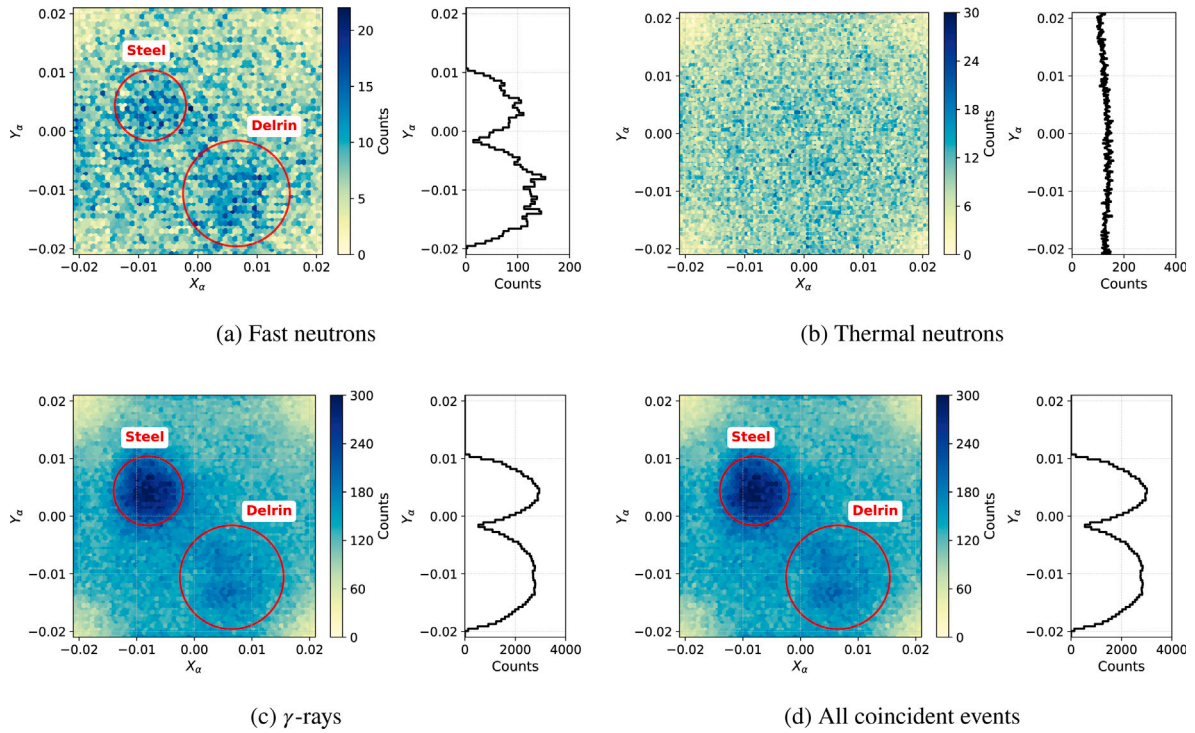


Fig. 7. CLYC detector reconstructed images for diagonal cylinder configuration with (top left) and Delrin (bottom right) samples. (a) Fast neutron events ($E_{\text{arrival}} \geq 0.6$ eV). (b) Thermal neutron events (< 0.6 eV) with limited statistics within the API timing window. (c) γ -ray events showing higher counts from steel due to inelastic scattering. (d) All coincident events combined. Color scales indicate event counts per pixel. Red circles outline the approximate sample locations. Right panels show projection of total count profiles along the vertical axis, demonstrating quantitative contrast between materials.

the detector. This demonstrates clear material discrimination capability for EJ-309, with steel producing about 1.5 times as many detected fast neutron events as Delrin after accounting for geometric effects.

The difference in fast neutron images between CLYC and EJ-309 may reflect EJ-309's enhanced sensitivity to fast neutrons relative to CLYC, as well as the influence of propagated uncertainties from PSD-based event classification. Furthermore, the contrast in fast neutron counts between samples is further examined looking at neutron interaction physics between H-rich and H-deficient materials through simulation analysis in Section 6.3.

6.2.2. Thermal neutron and γ -ray imaging

The CLYC thermal neutron image (Fig. 7(b)) shows no clear resolution of the individual cylinders, as expected. Arriving outside this window, they cannot be spatially correlated with their corresponding alpha particles. The observed thermal neutrons are part of the random coincidences background.

γ -ray images from both detectors (Figs. 7(c) and 8(b)) show higher contrast between the materials. This contrast arises from differences in γ -ray production cross sections and angular distributions, as well as detector specific efficiencies for γ -rays relative to neutrons. However, γ -ray imaging is not the primary focus of this study.

6.3. Simulation insights

Monte Carlo simulations using GEANT4 support the experimental observations, focusing on detected neutrons with $E_{\text{arrival}} \geq 0.6$ eV and detected by CLYC within the first 80 ns, corresponding to the experimental temporal range where the samples are located. The simulations reproduce the experimental trend. To validate the measurements, we modeled a two-cylinder configuration to compare Delrin and steel targets under controlled conditions. Fig. 9(a) shows the simulated image of the two cylinders based on the detected backscattered fast neutrons within the Delrin and stainless steel volumes which is comparable to

Table 2

Elemental microscopic neutron cross sections at ~ 14.1 MeV for elastic (σ_{elastic}), inelastic ($\sigma_{\text{inelastic}}$), and total (σ_{total}) interactions (including other nonelastic interactions) of the most abundant isotopes of the constituent elements used in this study. The values are based on the ENDF/B-VIII.0, ENDF/B-VII.1, and ENDF/B-VII.0 datasets [42].

Element	σ_{elastic} (b)	$\sigma_{\text{inelastic}}$ (b)	σ_{total} (b)	Most abundant isotope
H	0.69	0.00	0.69	^1H (99.98%)
C	0.82	0.42	1.30	^{12}C (98.93%)
O	0.96	0.31	1.60	^{16}O (99.76%)
Fe	1.19	1.22	2.58	^{56}Fe (91.75%)

Elemental microscopic cross sections were calculated using $\sigma = \sum_j P_j \sigma_j$, where σ_j is the microscopic cross section of isotope j and P_j is its natural isotopic abundance (fractional).

the experimental image based on fast neutrons in Fig. 7(a). Figs. 9(b) and 9(c) display only elastically and inelastically scattered neutrons from the samples separately, showing how contributions from H-rich and H-deficient materials vary for both scattering reactions types.

The Delrin sample produced fewer fast neutron events per unit volume, whereas the steel sample appeared more sharply defined in the reconstructed image (see Fig. 9(a)). Both in the images based on elastically and inelastically backscattered neutrons, stainless steel exhibited a higher density of interactions, as expected. Fig. 9(b) shows much less contrast between the materials, similar to the experimental images in Fig. 7(a), whereas in Fig. 9(c), the counts per volume in steel considerably higher than in Delrin due to high inelastic scatter cross section of Fe.

Single-cylinder simulations with different materials placed under the source further illustrate these effects. Fig. 10 presents a comparative analysis of neutron interactions in five materials: Delrin, stainless steel, graphite, HDPE, and water. Fig. 10(a) shows the relative contributions of detected neutrons whose last scatter in the sample was elastic or inelastic before reaching the detector. With the exception of stainless

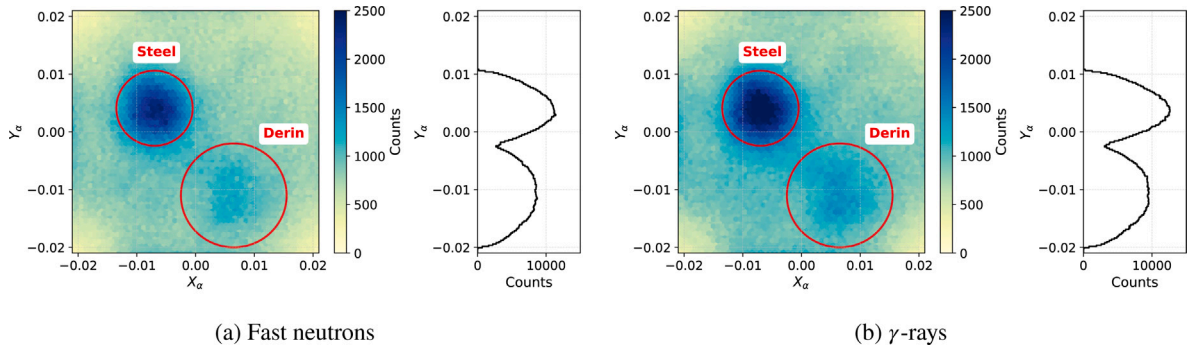


Fig. 8. EJ-309 detector reconstructed images for diagonal cylinder configuration with steel (*top left*) and Delrin (*bottom right*) samples. (a) Fast neutron events showing dramatically improved contrast compared to CLYC, with significantly reduced counts in the Delrin region versus steel region, representing approximately a factor of two difference in detected signal intensity. (b) γ -ray events showing similar spatial contrast between materials due to differences in inelastic scattering cross sections. The enhanced contrast in EJ-309 images can be attributed to the detector's larger detection volume, higher intrinsic fast neutron sensitivity, and superior pulse shape discrimination performance. Color scales indicate event counts per pixel. Red circles outline the approximate sample locations.

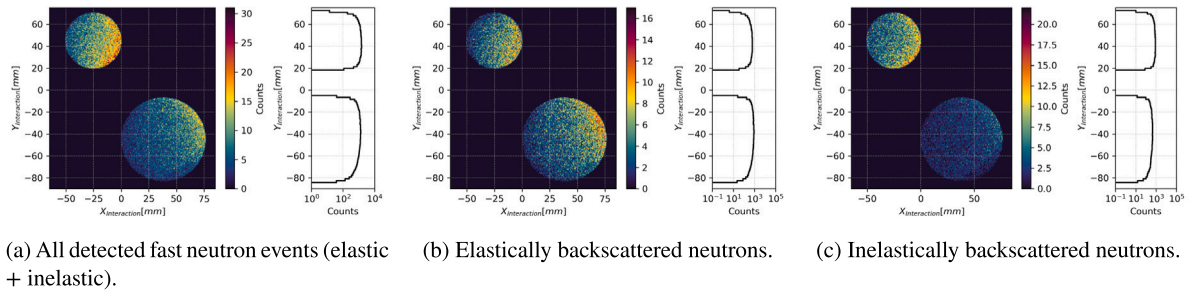


Fig. 9. Simulated maps of detected neutron interaction positions in the sample (heatmap) and the corresponding Y-projection of counts for Delrin and stainless-steel cylinders, for events with $E_{\text{arrival}} > 0.6$ eV detected in CLYC within 80 ns.

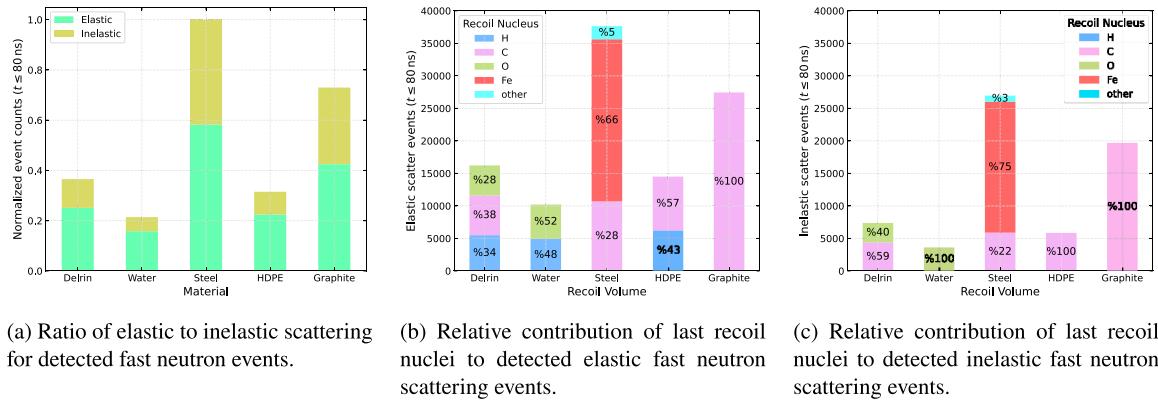


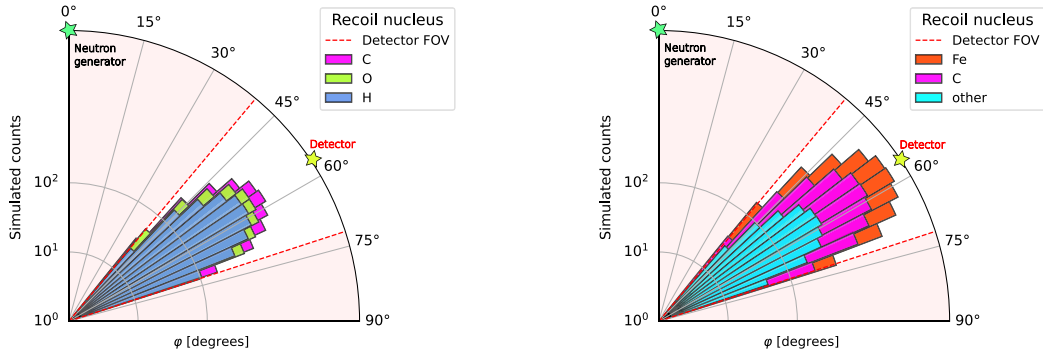
Fig. 10. Comparison of detected neutron interactions across sample materials for fast/epithermal events ($E_{\text{arrival}} \geq 0.6$ keV) within 80 ns.

Table 3

Properties of materials used in the experiments and simulations, including chemical composition, density ρ (g/cm³), and macroscopic cross sections for elastic (Σ_{elastic}), inelastic ($\Sigma_{\text{inelastic}}$), and total (Σ_{total}) neutron interactions at ~ 14.1 MeV. The composition of stainless steel is approximate.

Material	Chemical composition (wt.%)	ρ (g/cm ³)	Σ_{elastic} (cm ⁻¹)	$\Sigma_{\text{inelastic}}$ (cm ⁻¹)	Σ_{total} (cm ⁻¹)
Water	88.81% O, 11.19% H	1.00	0.078	0.010	0.099
Delrin	39.98% C, 6.73% H, 53.29% O	1.41	0.089	0.021	0.121
HDPE	85.60% C, 14.40% H	0.94	0.089	0.017	0.108
Graphite	100% C	1.70	0.070	0.036	0.111
Stainless Steel	75% Fe, 18% Cr, 4% Ni, 2% C, 1% Mn	7.87	0.107	0.106	0.227

Macroscopic cross sections are computed as $\Sigma = \sum_i N_i \sigma_i$, where $N_i = \rho w_i N_A / A_i$ is the atomic number density of element i , using the elemental microscopic cross sections presented in 2.



(a) Distribution of simulated net scattering angles for H, C and O nuclei in Delrin.

(b) Distribution of simulated net scattering angles for Fe, C and other nuclei in stainless steel.

Fig. 11. Simulated neutron scattering angle distributions for elastically scattered neutrons reaching the CLYC detector from different sample materials. (a) Delrin: ^1H (blue), ^{12}C (violet), and ^{16}O (yellowgreen). Detector FOV is indicated by red dashed lines at 55° . (b) Steel: ^{56}Fe (orange), ^{12}C (violet), and other elements (cyan).

steel and graphite, the H-bearing materials (Delrin, HDPE, and water) exhibit a reduced fraction of inelastic last scatter events, consistent with hydrogen having no inelastic scattering cross section at 14.1 MeV.

Figs. 10(b) and 10(c) then display the corresponding contributions for elastically and inelastically scattered neutrons detected by CLYC within the first 80 ns of ToF. For this analysis, we assign each detected neutron to the last interaction in the sample (i.e., the last recoil nucleus/process) because this “exit scatter” is the direct observable that sets the outgoing energy and direction from the sample. These exit parameters, in turn, determine whether the neutron enters the detector’s acceptance and passes the timing/energy cuts. While the full scatter history of each detected neutron (which can include single or multiple nuclear interactions) affects the final outcome, the fast neutron counts are interpreted as being representative of the bulk surface and sub-surface composition. That fast neutron measurements are sensitive to hydrogen is an established truth, supported by a large body of literature from planetary science missions [e.g., 43–46]. However, interpreting these counts with respect to any single element requires careful consideration of the geological context. For example, on Mercury, where hydrogen is scarce, MESSENGER neutron data was used to identify carbon when constrained by other compositional measurements [47]. Similarly, analysis of data from the DAN instrument on the Curiosity rover has attributed increases in neutron counts to Fe suppressions in the subsurface, rather than solely to variations in hydrogen [48]. Notably, in our simulations, the difference in total detected events between steel and the other materials increases, indicating that materials containing lighter elements yield fewer backscattered neutrons counted by CLYC.

Macroscopic cross section values from Table 3 show that in Delrin, $\Sigma_{\text{elastic}} = 0.089 \text{ cm}^{-1}$ (75.5% of Σ_{total}) is dominated by scattering on ^1H , whereas in steel, similar contributions from $\Sigma_{\text{elastic}} = 0.107 \text{ cm}^{-1}$ (46.9% of Σ_{total}) and $\Sigma_{\text{inelastic}} = 0.106 \text{ cm}^{-1}$ (46.6% of Σ_{total}) arising primarily dominated by microscopic cross sections of the most abundant isotope ^{56}Fe . Table 3 also displays Σ for other materials simulated for comparison.

Fig. 10(b) shows that, although ^1H constitutes a smaller mass fraction than other constituent elements (e.g., ^{12}C and/or ^{16}O ; see Table 3), it makes a significant contribution to elastic scattering in Delrin, water, and HDPE due to its large σ_{elastic} . In stainless steel, the relative contribution to both elastically and inelastically backscattered detected neutrons is instead dominated by ^{56}Fe because it forms the bulk of the material ($\sim 75\%$). This dominance persists even though ^{12}C (at $\sim 2\%$) can exhibit a higher σ_{elastic} — and thus a higher Q_{avg} — than ^{56}Fe . For inelastic fast neutron scattering events, ^{56}Fe also dominates as

the last recoil nucleus, consistent with both its substantial $\sigma_{\text{inelastic}}$ at 14.1 MeV and its high abundance in the alloy. Moreover, Fig. 10(c) shows no contribution from ^1H as a last recoil nucleus, consistent with the negligible inelastic scattering cross section of hydrogen at these neutron energies.

There is a bias toward heavier nuclei arising from equal-mass scattering on ^1H , the scattered neutron’s lab angle (φ) ranges from 90° to 180° . A single elastic scatter can in principle send a neutron toward our detector at 56° for heavier elements. The practical reduction in H-tagged fast events is mainly due to the larger mean energy loss per collision and the greater likelihood of multiple scattering, which lengthens the path and ToF so more events fall outside the coincidence selection. These neutrons therefore require multiple scattering, lengthening their ToF and reducing their detection probability within the API coincidence window. Fig. 11 shows the net scatter angle (φ) distributions per last recoil nucleus, calculated using Eq. (3) and the detector geometry, for Delrin and steel, with a breakdown by their major constituent elements. In Fig. 11(a), all scatter events from ^1H as the last recoil nucleus are either single scatter events or preceded by multiple scattering, which lengthens the ToF (as seen in Fig. 12(a)) and reduces the coincidence probability. Fig. 11(b) show that the total counts reaching the detector within 80 ns are higher for steel than for Delrin, with most of the additional contribution originating from interactions with ^{56}Fe .

The corresponding ToF and arrival energy distributions (Figs. 12, 13(a), and 13(b)) further support this interpretation: hydrogen scattering yields higher population of neutrons with lower arrival energies and longer ToF compared to scattering from ^{12}C or ^{56}Fe , reflecting greater energy loss per collision and longer neutron path lengths. These trends are consistent with expectations from microscopic cross sections and nucleus-to-neutron mass ratios.

In summary, Figs. 10–13 demonstrate that ^1H interactions results in neutrons with lower arrival energies and longer ToF distributions than ^{12}C or ^{56}Fe , consistent with greater energy loss per collision and longer neutron path lengths. Heavier nuclei preserve more of the neutron’s initial energy and produce timing signatures more likely to fall within the API coincidence window. In H-rich materials, this timing effect, combined with their high moderation efficiency, explains the reduced fast neutron counts, providing an indirect signature of hydrogen content through the combined influence of microscopic cross sections, macroscopic interaction rates, and API timing constraints.

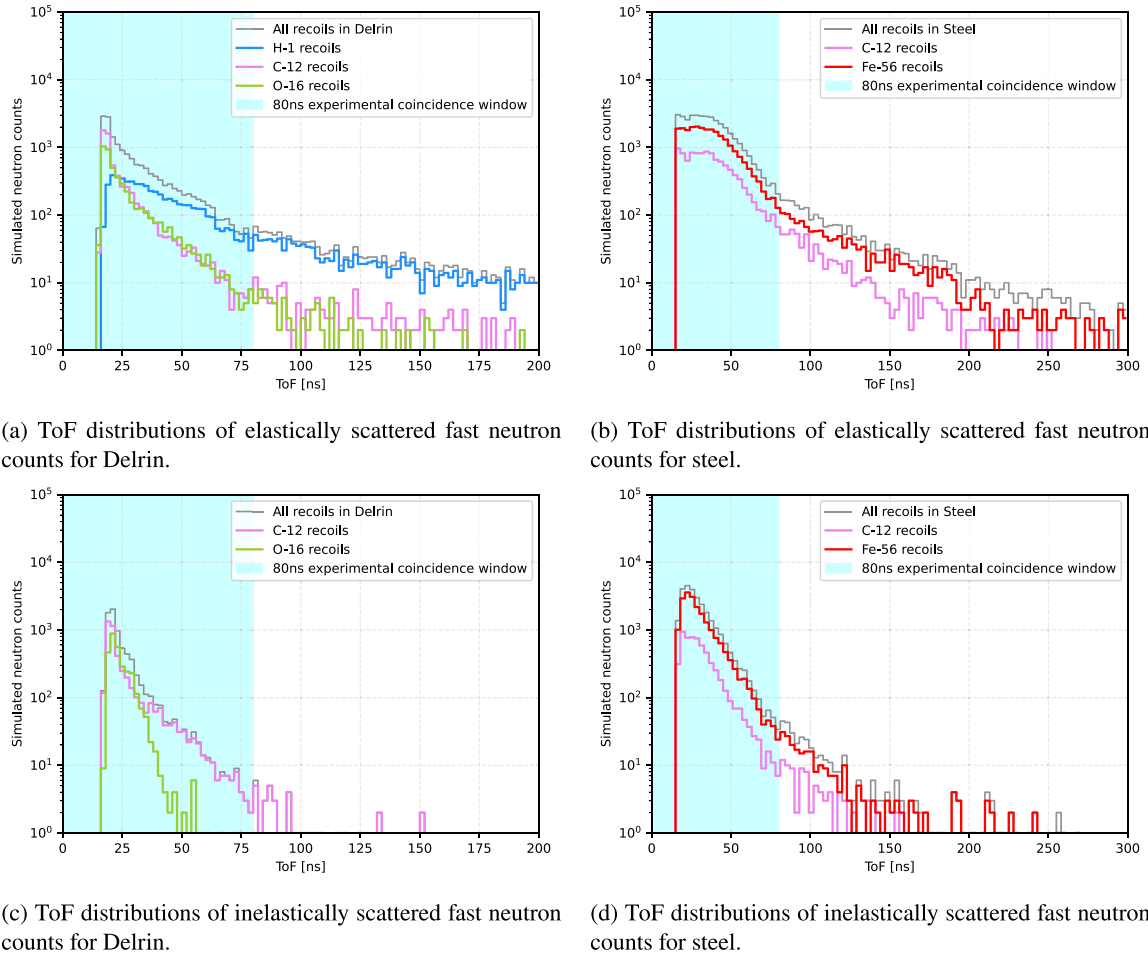


Fig. 12. Simulated ToF distributions for elastically and inelastically backscattered fast neutrons from (left) Delrin and (right) steel detected by CLYC, broken down by recoil nucleus.

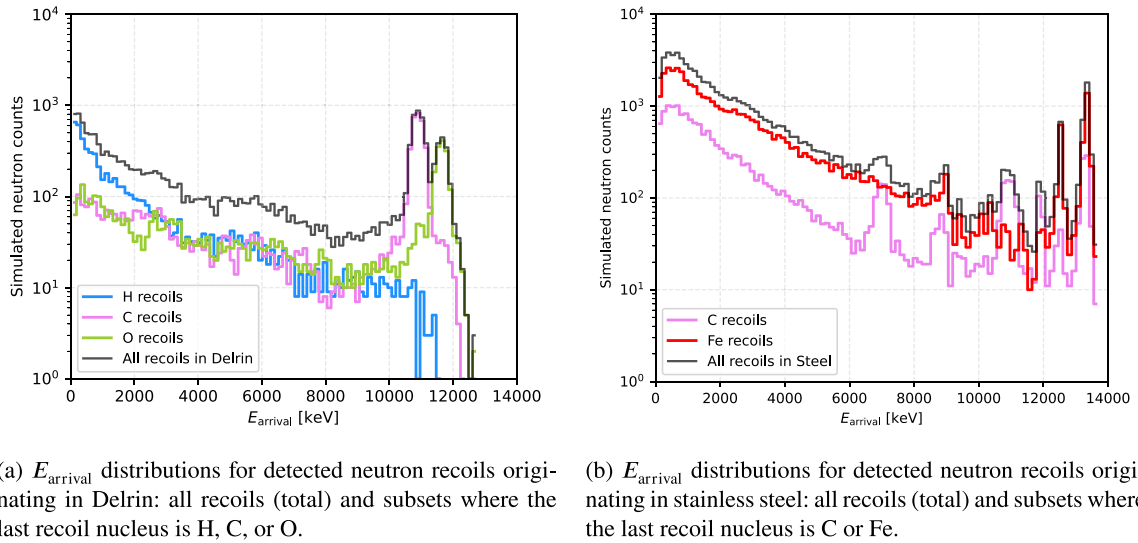


Fig. 13. Simulated arrival-energy distributions for detected fast neutron recoil events (elastic + inelastic) from Delrin and stainless steel cylinders, recorded in CLYC within the coincidence window.

6.4. Physical mechanisms

From a bulk material perspective, the relevant measure for comparing neutron interaction probabilities is the macroscopic cross section

(Σ), which incorporates material density, composition, and the microscopic cross section (σ) of each constituent isotope. Microscopic σ values describe the per-nucleus probability for a given interaction, while Σ determines the total probability per unit path length in the

bulk. This distinction is important when interpreting API imaging contrast, because differences in Σ , which are driven by both elemental composition and density, set the overall scattering rates.

This contrast can be explained directly by the nuclear data in Tables 2 and 3, which quantify both microscopic and macroscopic probabilities for the key isotopes in Delrin and steel. At 14.1 MeV, ^{56}Fe has an elastic cross section of ~ 1.19 barns and a inelastic cross section of ~ 1.22 barns. The inelastic channels remove a discrete amount of energy via nuclear excitation (typically $\sim \text{MeV}$), often leaving the outgoing neutron still in the fast range while changing its direction, thus they can contribute to detected fast neutron coincidences.

In contrast, ^1H in Delrin scatters almost entirely elastically ($\sigma_{\text{elastic}} \sim 0.69$ barns, negligible nonelastic contribution), efficiently moderating neutrons but frequently shifting them outside the fast neutron selection window. ^{12}C and ^{16}O exhibit intermediate behavior, with $\sigma_{\text{inelastic}} \sim 0.42$ and ~ 0.31 barns, respectively—indicating moderate probabilities for inelastic reactions but far fewer channels than for Fe.

At the macroscopic scale, Table 3 shows that Delrin is largely governed by elastic scattering, with $\Sigma_{\text{elastic}} = 0.089 \text{ cm}^{-1}$ corresponding to $\sim 75.5\%$ of Σ_{total} , and dominated by interactions on ^1H . Steel, in contrast, exhibits a much smaller elastic fraction ($\Sigma_{\text{elastic}} = 0.107 \text{ cm}^{-1}$, $\sim 46.7\%$ of Σ_{total}), with the remaining nonelastic contribution dominated by inelastic channels on ^{56}Fe .

Simulated scattering angle distributions (Fig. 11) show that single elastic scattering from ^1H cannot produce laboratory-frame scattering angles large enough to reach the $\sim 57^\circ$ detector geometry in a single interaction. Consequently, H-backscattered neutrons require multiple collisions to be detected, which increases their ToF and often removes them from the fast neutron coincidence window (see Fig. 12(a)). This geometric limitation, combined with hydrogen's exceptional moderation efficiency, explains the reduced fast neutron signal from H-rich materials. In contrast, heavier nuclei such as ^{12}C , ^{16}O , and ^{56}Fe can achieve the required deflection in a single scatter while retaining sufficient energy to be detected within the timing cut (see Fig. 12). Additional simulations with materials like water, HDPE, and graphite reinforce this interpretation: higher H content leads to more efficient moderation and a lower fast neutron signal, whereas materials composed of heavier elements allow for more detectable scattering events. This interplay between scattering kinematics, detector geometry, and timing constraints directly determines which interactions are most likely to produce detectable events and governs the contrast observed in API backscattered fast neutron imaging.

Both elastic and inelastic processes play a major role in shaping the neutron population through multi-step scattering. This is particularly true in steel, where nonelastic reactions account for over one-third of all interactions. While the API system preferentially detects elastically scattered neutrons due to timing constraints, the full interplay of all reaction channels, governed by the macroscopic cross sections, is essential for determining the ultimate detected signal.

6.5. Use in planetary studies

Planetary fast neutron measurements have long established key compositional relationships linking fast neutron production to high $\langle A \rangle$ elements and epithermal and fast neutron suppression to hydrogen abundance [44,49]. Orbital measurements at Vesta and Mercury, for example, have successfully mapped large-scale compositional terranes by relating fast neutron flux variations to changes in average atomic mass and hydrogen concentration [6]. While these studies have significantly advanced our understanding of the global distribution of surface hydration, they are inherently limited by the broad, hemispherical neutron leakage fluxes produced by galactic cosmic rays, which do not provide fine-scale spatial resolution within the instrument's sensing area. Furthermore, passive detection methods measure neutrons continuously within wide energy bands, limiting the ability to constrain variables such as burial depth. API-based fast neutron detection can

address these limitations by providing localized, directionally tagged measurements and time-of-flight information, enabling spatially resolved analyses with depth profile while retaining sensitivity to the same key compositional parameters. Although this study does not investigate depth resolution or hydrogen detection sensitivity, these aspects will be explored in future work.

In the longer term, integrating API-based fast neutron imaging with thermal neutron die-away methods and prompt γ -ray spectroscopy could yield a richly complementary, multi-modal approach to subsurface characterization. Such a combination would extend sensitivity beyond hydrogen to other light elements with distinctive neutron interaction signatures, enhancing applications in planetary mineralogy, volatile evolution, and structural analysis of the shallow subsurface on airless bodies.

7. Conclusion

This proof-of-concept study demonstrates the feasibility of combining API with backscattered fast neutron detection to spatially resolve and discriminate between materials with low and high average atomic mass ($\langle A \rangle$). We experimentally evaluated CLYC and EJ-309 scintillators integrated into an API system using Delrin and stainless steel targets, representing H-rich and H-deficient compositions respectively, to represent contrasting materials.

Our measurements show that API-enabled fast neutron backscatter imaging can clearly differentiate between Delrin and steel. Both detectors, when paired with PSD, produce images with systematically reduced fast neutron counts from the H-rich Delrin. This contrast arises from neutron transport physics: hydrogen efficiently moderates fast neutrons, causing energy loss, larger angular deflections, and multi-step scattering that push many events outside the coincidence window. EJ-309, with its higher fast neutron sensitivity and superior PSD performance, produced more pronounced image contrast than CLYC. However, EJ-309's liquid form factor makes it unsuitable for spaceflight, whereas CLYC with flight heritage [27,50] and multi-modal detection capabilities, remains a viable space-qualified option.

Simulations are essential for interpreting fast neutron images, studying kinematics, and quantifying the challenges of isolating a hydrogen signal from fast neutron data alone. While fast neutron attenuation provides a qualitative signature of hydrogen, quantitatively determining its abundance requires a more comprehensive analysis incorporating thermal neutron flux measurements and γ -ray spectroscopy. Our simulations confirmed that the reduced fast neutron signal from H-rich materials serves as an indirect signature of hydrogen, shaped by the overall neutron transport environment. Interpreting fast neutron image intensity therefore requires careful modeling to deconvolve the contributions from H, C, and other light elements.

Addressing our initial research questions, we conclude that API combined with fast neutron detection is feasible for imaging and distinguishing materials with strong contrasts in hydrogen content and average atomic mass. The spatial resolution is sufficient to resolve objects on the scale of several centimeters, consistent with previous API studies [3,21]. These findings advance active neutron interrogation for planetary science by clarifying the material contrast mechanisms relevant to fast neutron imaging and hold promise for mapping subsurface structures, such as hydrated regolith.

API-based backscattered fast neutron imaging is naturally complementary to existing neutron and γ -ray techniques, adding localized, directional, and time-resolved information to more established flux and spectroscopy measurements. Combining API fast neutron imaging with thermal neutron die-away methods offers a promising approach for probing subsurface layering and quantifying hydration at depth. Similarly, integrating API with active prompt γ -ray analysis — such as the API-LaBr₃ system developed at LBNL [3,21] or the PING instrument [51] — would provide full compositional capabilities by linking element-specific γ -ray signatures with neutron-based hydrogen

detection, creating a genuinely multi-modal GRNS toolkit for planetary exploration.

Future work will focus on quantifying the hydrogen detection sensitivity of this technique and extending it toward 3D profiling of subsurface hydrogen distributions. Furthermore, exploring next-generation scintillators that combine γ -ray, fast neutron, and thermal neutron sensitivity with good PSD and timing properties will be critical. Candidates include EJ-270 plastic scintillators [52] and faster decay elpasolite scintillators (e.g., CLLB, CLLBC) [53], which could deliver improved energy resolution and statistics for quantitative compositional mapping. Finally, expanding simulation tools to model neutron flux attenuation as a function of density and hydration, combining fast neutron, thermal neutron, and γ -ray datasets, will be vital for quantitative hydrogen mapping and for discriminating among different levels of hydration while also characterizing surrounding lithologies.

Overall, this work establishes API-based backscattered fast neutron imaging as a viable technique for planetary surface studies. It can complement existing orbital and landed neutron spectroscopy methods by enabling high-resolution, localized, volumetric geochemical mapping, and by providing a powerful new tool for targeted resource identification in support of *in situ* planetary exploration on the Moon, Mars, and beyond.

CRedit authorship contribution statement

Deniz Ölçek: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mauricio Ayllon Unzueta:** Writing – review & editing, Validation, Software, Resources, Methodology, Funding acquisition, Conceptualization. **Craig Hardgrove:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Arun Persaud:** Writing – review & editing, Supervision, Software, Resources, Methodology, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT-4 (OpenAI) in order to improve the readability and language of the manuscript. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Deniz Ölçek reports a relationship with University of Oslo that includes: employment and travel reimbursement. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Geometric correction of neutron counts

To compare neutron counts detected from samples placed at different distances from the detector, we applied a geometric efficiency correction based on the observed falloff of detected events with increasing source–detector separation.

A GEANT4-based simulation was developed to model the geometric dependence of neutron detection efficiency in the experimental configuration. Neutrons were emitted from a fixed source position (55 cm from the top surface of the Delrin cylinder) with momentum directed in the $-z$ direction towards the cylinder samples with a beam angle of 10° to irradiate them. The neutron energies were sampled from a log-uniform distribution between 0.6 eV and 14.1 MeV in order to mask thermal neutron contributions and focus on epithermal and fast neutron detection. The detector was positioned outside the primary beam path to preferentially register neutrons backscattered from the sample. Its height (z) and lateral offsets (x) from the target were similar to those used in the laboratory measurements, ensuring direct correspondence between simulated and experimental geometries.

$$r = \sqrt{x^2 + z^2}.$$

For each detector position, the total number of detected neutron events was recorded within the energy range of interest and plotted as a function of r . The data were well fit by a power-law model:

$$C(r) = A \cdot r^{-n} \quad (4)$$

where $C(r)$ is the number of detected neutrons at distance r , and n is the empirical falloff exponent determined from simulation.

The best-fit values are $n_{\text{CLYC}} = 1.427$ (2"×2" CLYC detector) and $n_{\text{EJ-309}} = 1.189$ (5"×5" EJ-309 detector). The difference reflects the larger EJ-309 detection volume, which subtends a greater solid angle at a given distance and is less affected by projection effects in the lateral scan geometry. Although a purely geometric decrease would follow an inverse-square law ($n = 2$), the fitted exponent is smaller. This deviation reflects that the correction accounts not only for the change in solid angle with distance but also for distance and orientation dependent variations in the detector's intrinsic efficiency. Additionally, due to the simulated neutron spectrum being deliberately weighted toward epithermal and fast energies, these n values are spectrum-specific and may differ if a significant thermal component is present.

To enable fair comparison of detected neutron counts from different sample positions, we apply the following geometric correction:

$$C_{\text{corr}}(r') = C(r) \cdot \left(\frac{r}{r'}\right)^n \quad (5)$$

where $C(r)$ is the measured count at distance r , r' is the reference distance, and $C_{\text{corr}}(r')$ is the count normalized to that reference. The appropriate n value is used for each detector type.

Assuming Poisson statistics for neutron detection, the standard uncertainty is given by:

$$\sigma(C) = \sqrt{C}$$

which leads to the corrected uncertainty:

$$\sigma_{\text{corr}}(r') = \left(\frac{r}{r'}\right)^n \cdot \sqrt{C(r)} \quad (6)$$

This correction procedure enables meaningful comparisons between neutron count densities observed from samples at different distances, while accounting for geometry-driven efficiency changes and the specific response geometry of each detector.

Data availability

Data will be made available on request.

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