

Simultaneous very small angle and small-angle neutron scattering measurements enabled by flat-panel-type photomultiplier detectors at SANS-J, JRR-3

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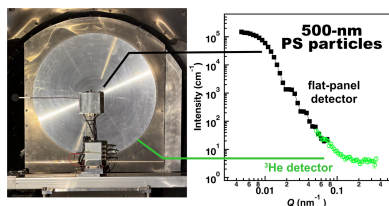
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We have replaced the conventional high-spatial-resolution photomultiplier-based neutron detector (PS-PMT; R3239, Hamamatsu), which has been widely used for very small angle neutron scattering (VSANS), with four flat-panel-type high-spatial-resolution photomultiplier detectors (FPDs; H12700A, Hamamatsu) arranged in a square array on the small-angle neutron scattering instrument SANS-J at the JRR-3 research reactor. The FPD system provides seamless detection of scattered neutrons over an effective area of $80 \times 80 \text{ mm}^2$, which is larger than that of the PS-PMT. Owing to the optimized design of the scintillator, optical diffuser and light shielding, the FPD exhibits improved detection efficiency, spatial resolution and signal-to-background ratio compared with the conventional PS-PMT. Furthermore, by exploiting the negligible dead area surrounding the neutron-sensitive region of the FPD, simultaneous and continuous VSANS and SANS measurements without gaps in Q were achieved. By combining the FPD with a downstream ^3He main detector, a wide scattering-vector-magnitude range from approximately 10^{-3} to 0.3 nm^{-1} can be covered in a single measurement.

1. Introduction

Following the development of neutron lenses (Choi *et al.*, 2000; Oku *et al.*, 2007) and high-spatial-resolution position-sensitive photomultiplier tubes (PS-PMTs; Hirota *et al.*, 2005; Iwase *et al.*, 2012), many small-angle neutron scattering (SANS) instruments have extended the accessible scattering-vector range to values of Q well below 0.01 nm^{-1} (Oku *et al.*, 2007; Iwase *et al.*, 2007; Iwase *et al.*, 2011; Radulescu *et al.*, 2012; Radulescu *et al.*, 2016; Radulescu, 2025; Pipich & Fu, 2015; Wood *et al.*, 2018; Barker *et al.*, 2022; Zuo *et al.*, 2024). At SANS-J, the SANS instrument installed at the Japan Research Reactor JRR-3, a PS-PMT positioned 10 m downstream of the sample enables measurements at scattering angles $\theta > 0.01^\circ$ ($Q > 0.002 \text{ nm}^{-1}$). In this configuration, very small angle neutron scattering (VSANS) signals are separated from the non-scattered direct beam, which is tightly focused onto the PS-PMT using MgF_2 neutron lenses (Kumada *et al.*, 2023).

However, VSANS measurements using the PS-PMT suffer from three major limitations. First, the PS-PMT (R3239; Hamamatsu, Japan) has been discontinued and is no longer commercially available, necessitating the development of a replacement to ensure long-term operational reliability. Second, the acquisition time required for VSANS measurements is significantly longer than that for conventional SANS measurements. Whereas the incident neutron beam passes through an upstream slit with a square opening of $A_u = 20 \text{ mm}$



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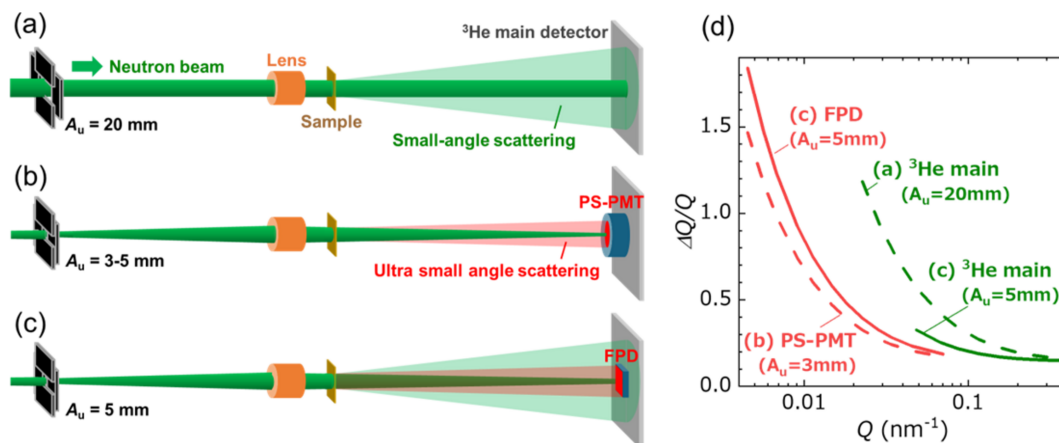


Figure 1

Configurations for (a) SANS and (b) VSANS measurements with the PS-PMT, and (c) the newly developed configuration for simultaneous VSANS and SANS measurements with the FPD, together with (d) the calculated $\Delta Q/Q$ as a function of Q calculated using the resolution functions (Hammouda & Mildner, 2007).

for conventional SANS measurements, the aperture must be reduced to 3–5 mm in VSANS measurements to tightly focus the beam onto the PS-PMT, at the expense of beam intensity [Figs. 1(a) and 1(b)]. Third, the neutron-sensitive area of the PS-PMT available for SANS measurements is limited to approximately 74 mm in diameter (Iwase *et al.*, 2011), which is insufficient for seamless coverage over a wide Q range. Although the beam center has been offset toward the edge of the sensitive area, the PS-PMT can measure scattering only up to $Q \approx 0.06 \text{ nm}^{-1}$.

To overcome these limitations, we replaced the PS-PMT with four flat-panel-type multi-anode photomultiplier tube detectors, hereafter referred to as the FPD (Satoh, 2018). The FPD system outperforms the existing PS-PMT system at SANS-J not only in neutron detection area but also in spatial resolution, sensitivity and signal-to-background ratio (see below). Moreover, the neutron-sensitive area of the FPD is nearly equal to its projection area, and the detector operates directly inside the vacuum tube, whereas the PS-PMT was sealed in a 180 mm-diameter air chamber within the vacuum tube. As a result, the projection area of the FPD onto the downstream ^3He main detector (Noda *et al.*, 2016) is much smaller than that of the PS-PMT with its air chamber. By exploiting the small projection area of the FPD, we achieved simultaneous VSANS measurements with the FPD and SANS measurement with the ^3He main detector over a Q range from $\sim 10^{-3}$ to 0.3 nm^{-1} [Fig. 1(c)]. Such simultaneous measurements reduce the total measurement time and enable the investigation of nano- and micro-scale structures in dynamically evolving samples without temporal offsets between different Q regions. A similar approach has been implemented at the VSANS instrument at the National Institute of Standards and Technology (NIST) (Barker *et al.*, 2022), where horizontally and vertically arrayed multiple ^3He detectors are arranged to form a central square opening that allows VSANS events to reach a high-spatial-resolution CCD-based scintillation detector positioned downstream. In contrast, our system provides a simpler experimental configuration, as

simultaneous measurements can be performed without any opening in the ^3He main detector by placing the FPD in front of it.

In this paper, we describe the performance of the FPD detector system, including the scintillator and readout electronics, and discuss the feasibility and performance of simultaneous VSANS and SANS measurements based on representative experimental results.

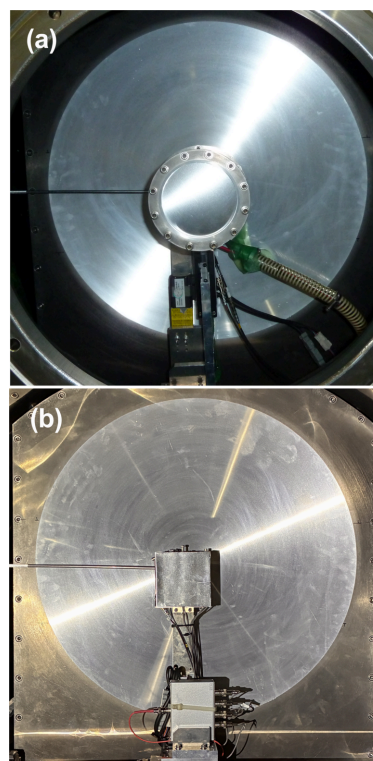


Figure 2

Photographs of (a) the previously used PS-PMT in an air chamber and (b) the FPD placed immediately upstream of the main detector.

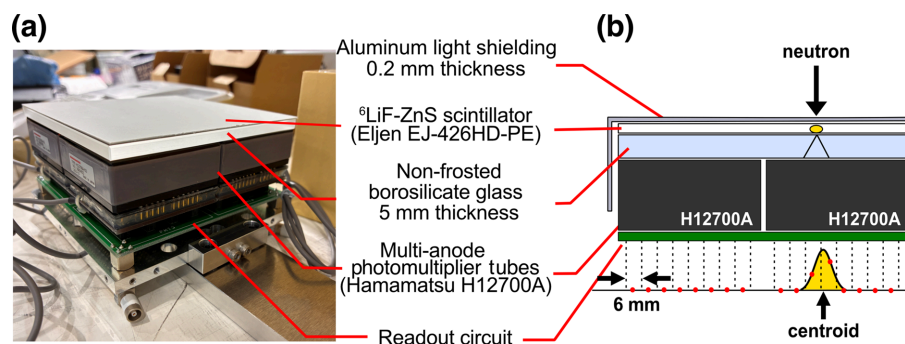


Figure 3
(a) Internal configuration of the FPD unit. (b) Schematic illustration of the sub-pixel neutron position determination mechanism.

2. Experiment

Fig. 2 shows photographs of (a) the previously used PS-PMT in an air chamber and (b) the newly installed FPD unit immediately upstream of the main detector in a vacuum flight tube. The FPD is smaller than the PS-PMT. This is because the PS-PMT is housed in a 180 mm-diameter atmospheric chamber to prevent discharge, whereas the FPD operates in vacuum.

Fig. 3 shows the internal configuration of the FPD unit. It consists of a 0.2 mm-thick aluminium light shield, a 0.5 mm-thick $^6\text{LiF-ZnS}$ scintillator composite (EJ-426HD-PE; Eljen, USA), a 5 mm-thick non-frosted borosilicate glass plate, four flat-panel-type multi-anode photomultiplier tube assemblies (H12700A; Hamamatsu, Japan) arranged in a square array and a resistive charge-division readout circuit. The scintillation light generated by neutron-induced nuclear reactions was spread in the glass plate within the critical angle for total internal reflection (43°) and detected by the multi-anodes of the H12700A with a 6 mm pitch. Here, the borosilicate glass plate instead of quartz was used behind the scintillator to absorb transmitted neutrons, which backscatter and scintillate light over a wide area of the scintillator. The detected signals were processed by the resistive charge-division circuit, amplified and digitized using the NEUNET readout system (Sato *et al.*, 2004; Sato *et al.*, 2009). The centroid position was calculated from the current ratio of the signals at the two ends.

3. Results and discussion

Fig. 4 shows the FPD image obtained under a uniformly distributed neutron field. Gapless images were obtained with the four H12700A units, because the neutron detection area ($48.5 \times 48.5 \text{ mm}^2$) is almost equal to the projection area ($51.75 \times 51.75 \text{ mm}^2$) of each H12700A. A cross-shaped dip accompanied by neighboring peaks is observed at the boundaries between adjacent H12700A units. Signals outside the region defined by $17 \leq X \leq 96 \text{ mm}$ and $13 \leq Y \leq 90 \text{ mm}$ were excluded from the subsequent data analysis.

Fig. 5 shows a neutron transmission image of a cadmium mask with 1 mm-diameter holes arranged at 4 mm intervals on the FPD. The peaks are approximately equally spaced; however, the spacing becomes smaller near the edges and

larger at the boundaries between adjacent H12700A units. The uneven count distribution, variations in peak spacing and positional deviations observed at the boundaries in Figs. 4 and 5 are probably caused by counting loss and a slight shift of the signal centroid derived from the anode arrays across the boundary gaps relative to the scintillation light distribution on the H12700As. The count rate at each pixel was normalized by that in Fig. 4 to correct variations in sensitivity. On the other hand, the positional deviation ΔX , corresponding to the difference between the observed peak position X_{peak} and the hole position of the mask X_{hole} , was ignored in the SANS measurements. When the beam is centered on one of the four H12700As at $X = X_0$, the ratio $\Delta X / (X - X_0)$, corresponding to the Q shift induced by the positional deviation of the FPD, is at most 0.06. Because this value is much smaller than the typical neutron wavelength resolution in SANS, $\Delta\lambda/\lambda = 0.15$, one of the major factors determining the Q resolution, the ΔX of the FPD has a negligible impact on SANS measurements.

Fig. 6 shows a neutron transmission image obtained through an L-shaped cadmium mask rotated by 180° on the FPD and its horizontal line profiles at $Y = 20\text{--}40$ and $68\text{--}89 \text{ mm}$. The two mask edges are positioned at the center of one H12700A and at the boundary between adjacent H12700As, respectively. The edge responses in the line profiles $h(X)$, representing the

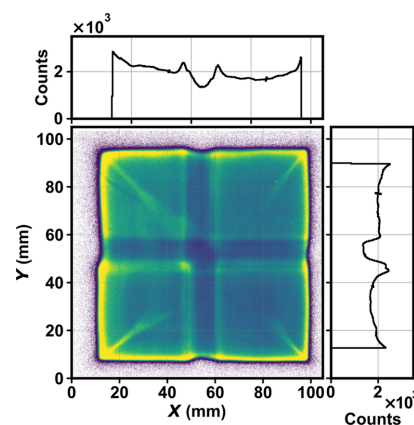


Figure 4
FPD image for a uniformly distributed neutron field. The right and top plots show the vertical and horizontal line profiles. The total acquisition time was 39600 s.

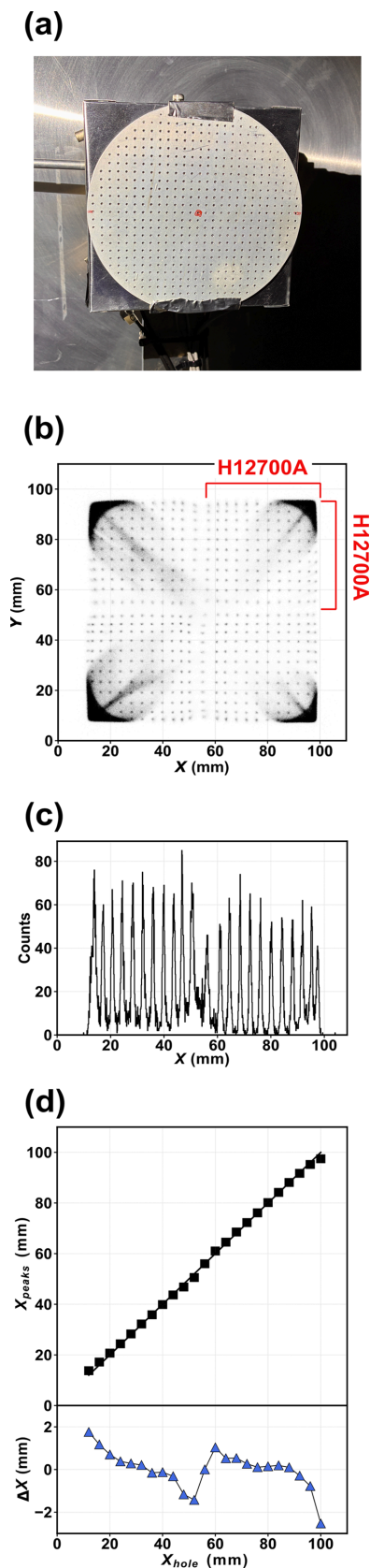


Figure 5
(a) Cadmium mask attached to the FPD. (b) Neutron transmission image through the mask. (c) Line profile along the X direction at $Y = 48\text{--}51$ mm. (d) Plots of X_{peak} versus X_{hole} and ΔX versus X_{hole} . The total acquisition time was 7200 s.

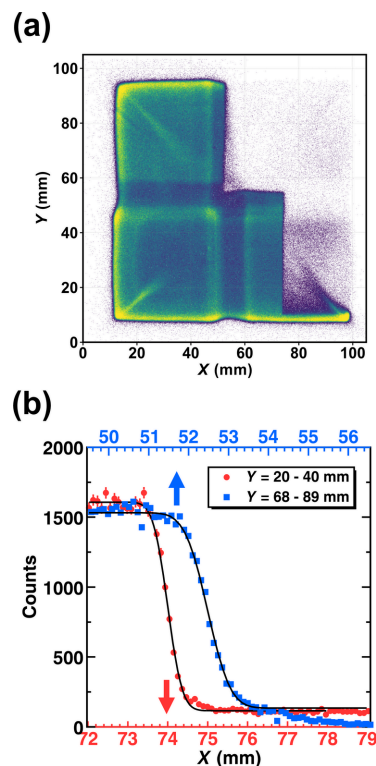


Figure 6
(a) The cadmium-masked FPD image. (b) The X -direction line profiles and the fits by equation (1).

neutron counts as a function of X , were fitted with an error function,

$$h(X) = h_{\text{low}} + \frac{h_{\text{high}} - h_{\text{low}}}{2} \left[1 + \operatorname{erf} \left(\frac{X - X_{\text{edge}}}{\sqrt{2}\sigma} \right) \right]. \quad (1)$$

Here, h_{low} and h_{high} are the lower and upper count levels, X_{edge} is the fitted position of the mask edge, and σ is the standard deviation of the Gaussian spatial response, which is 0.28 mm at the center and 0.45 mm at the boundary. The former value is smaller than that of the PS-PMT of 0.45 mm (Iwase *et al.*, 2011), whereas the latter value is comparable.

Fig. 7(a) shows the total counting rate over the entire FPD detector for the neutron beam transmitted through a high-density polyethylene (PE) attenuator. The neutron beam with $A_u = 5$ and 20 mm was tightly focused (Hiroi *et al.*, 2026) near the FPD, located 1.5 m downstream of the sample position, in order to investigate the saturation behavior of the FPD counting rate as a function of neutron beam intensity. For $A_u = 20$ mm, the count rate increased exponentially as the PE thickness decreased; however, it showed saturation behavior above approximately 40000 counts per second for PE thicknesses below 2 mm. In contrast, for $A_u = 5$ mm, the counting rate followed an exponential dependence down to zero PE thickness. The counting dead time estimated from the saturation behavior was $6.01 \pm 0.01 \mu\text{s}$, which is close to the scintillation decay time of the scintillator of $6.9 \mu\text{s}$ (Sykora *et al.*, 2018). These results indicate that the maximum counting rate was limited by the scintillation decay time.

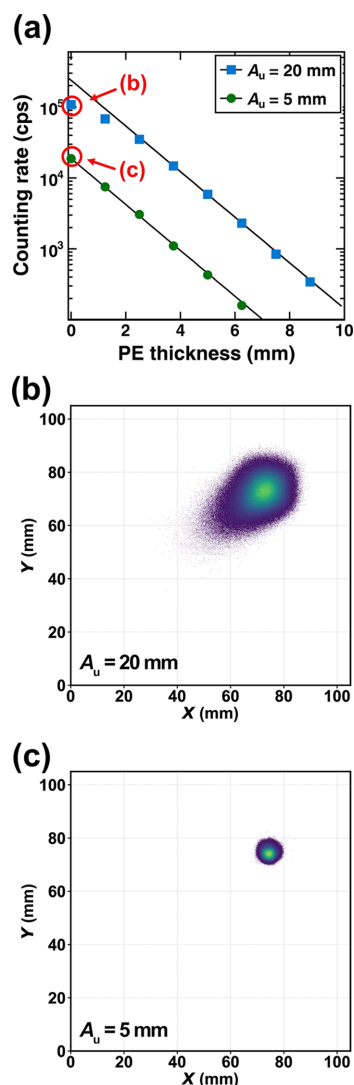


Figure 7

(a) Count rate over the entire detector as a function of the PE thickness for the tight focusing neutron beam. Each data point was acquired for 20 s. (b, c) FPD images of the unattenuated neutron beam (zero PE thickness).

Figs. 7(b) and 7(c) show FPD images of the unattenuated neutron beam. For the beam with $A_u = 20$ mm, not only count loss but also a streak extending toward the center of the detector unit was observed. In contrast, for the beam with $A_u = 5$ mm, neither count loss nor streak appeared. Thus, with $A_u = 5$ mm, the FPD simultaneously measures the very small angle scattering signal and the transmitted beam intensity, which is used to determine the sample transmission.

From this point onward, we compare the data obtained with the FPD and the PS-PMT using intensity versus Q plots. Note that the following data were obtained by placing 1 cm-side right-angled isosceles cadmium masks at the four corners of the FPD to suppress streaks extending from the corners toward the center, as observed in Figs. 4–6.

Fig. 8 compares the direct-beam profiles of the focusing beams without a sample, normalized to the intensity at $Q \rightarrow 0$ nm⁻¹, so that differences at higher Q mainly reflect detector-

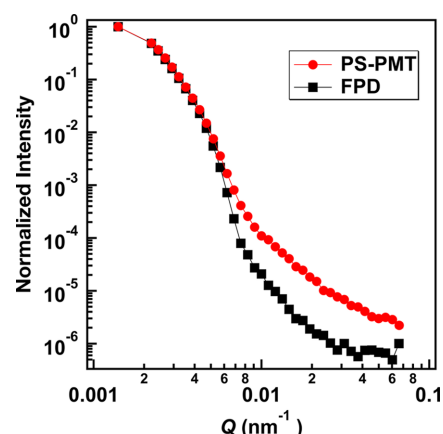


Figure 8

Intensity versus Q plots of the focusing beam measured with the PS-PMT (circles) and the FPD (squares) using an upstream slit aperture (A_u) of 2 mm. The intensity at $Q \rightarrow 0$ nm⁻¹ was normalized to unity. The acquisition time for each measurement was 3600 s.

related background. Although the normalized intensities measured with both the PS-PMT and FPD sharply decreased with increasing Q up to $Q = 6 \times 10^{-3}$ nm⁻¹, they showed shallower slopes at higher Q values. The normalized intensity of the shallow-slope component is higher for the PS-PMT than for the FPD, indicating that this component mainly originates from detector-related background scattering rather than from the beam profile itself.

The normalized intensity of the shallow-slope component for the FPD was reduced by a factor of up to ten compared with that for the PS-PMT, suggesting that the background contribution observed with the FPD was substantially lower than that with the PS-PMT. It has been reported that scattering from the MgF₂ lens contributes to the sloping background observed at $Q > 6 \times 10^{-3}$ nm⁻¹ in the focusing configuration (Barker *et al.*, 2008; Barker & Mildner, 2015; Glinka *et al.*, 2015; Kumada *et al.*, 2024). If the lens scattering contribution were eliminated, the superiority of the FPD in terms of detector-related background could become even more evident than indicated by the observed intensity ratio of the shallow-slope component. The reason for this remarkably low detector-related background remains unclear.

Fig. 9 shows the scattering intensity versus Q plot of polystyrene nanoparticles having a nominal diameter of 508 nm with a standard deviation of 8.5 nm (3500A, Thermo Fisher, USA) dispersed in H₂O at 1 wt% in a 1 mm-thick quartz cell, measured with the PS-PMT and the FPD using $A_u = 2$ mm. The background signal was subtracted to extract the scattering intensity. While hardly a single fringe can be identified with the PS-PMT, four fringe oscillations are observed in the scattering curve measured with the FPD. These performance improvements of the FPD can be attributed to two factors: the enhanced scintillation efficiency achieved using a thicker scintillator, and the lower background level of the FPD system, as shown in Fig. 8.

In addition to its high technical performance, the compact size of the FPD is another major advantage for simultaneous

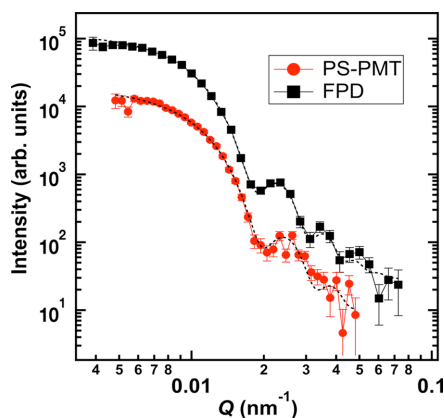


Figure 9

Intensity versus Q plot of 508 nm-diameter polystyrene nanoparticles measured with the focusing beam ($A_u = 2$ mm) using the PS-PMT for 1800 s and the FPD for 2000 s. The intensities were scaled by the incident neutron counts to evaluate the improvement in the signal-to-noise ratio resulting from the higher counting rate of the FPD. The dashed lines represent the theoretical curves smeared by the instrumental resolution.

measurements. Fig. 10 shows the results of simultaneous VSANS and SANS measurements of polystyrene nanoparticles using the main ^3He detector and the FPD in the focusing configuration with $A_u = 5$ mm. The Q ranges covered by the FPD and the ^3He detector overlapped in the range of 0.05 and 0.07 nm^{-1} . In addition, the two detectors exhibited comparable values of $\Delta Q/Q$ within this overlapping region, as shown in Fig. 1(d). These features enabled the two scattering curves to be merged smoothly, thereby achieving gapless simultaneous measurements over a Q range from 0.0045 to 0.35 nm^{-1} .

In previously reported setups for simultaneous VSANS and SANS measurements (Barker *et al.*, 2022), the ^3He main detector for SANS consists of multiple one-dimensional ^3He detector units arranged vertically and horizontally to form a central aperture for VSANS measurements using a down-

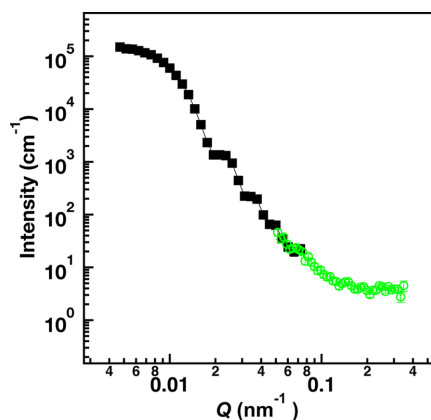


Figure 10

Intensity versus Q plots of the 508 nm-diameter polystyrene nanoparticles measured simultaneously with the FPD (filled squares) and the ^3He main detector (open circles) in the focusing configuration shown in Fig. 1(c) using an upstream slit aperture (A_u) of 5 mm for 21600 s. The intensities obtained with both detectors were calibrated on an absolute scale using the calculated scattering intensity of the polystyrene nanoparticles.

stream high-spatial-resolution CCD-based scintillation detector. In contrast, our setup achieves simultaneous measurements simply by placing the compact FPD in front of a conventional main detector consisting of a single ^3He detector array unit, thereby significantly simplifying the detector configuration.

The simultaneous measurement scheme offers two principal benefits. First, it reduces the number of detector reconfigurations required per sample, thereby improving measurement throughput. As described above, the detector configuration for the simultaneous VSANS and SANS measurements allows concurrent acquisition of the scattering beam and transmission. Second, the method enables time-resolved *in situ* measurements of nanoscale structural evolution. The simultaneous VSANS/SANS measurements provide continuous structural information over real-space length scales ranging from approximately 20 nm to 1 μm in a single measurement. This capability is expected to facilitate *in situ* studies of material aggregation, disintegration and microphase transition under external fields (Miyamoto *et al.*, 2007; Motokawa *et al.*, 2007; Motokawa *et al.*, 2016; Iwase *et al.*, 2009; Nishijima *et al.*, 2016; Hirata *et al.*, 2025) without concerns about time loss associated with changes in detector configuration.

4. Conclusion

The FPD enables seamless detection of scattered neutrons over an effective area of approximately $80 \times 80 \text{ mm}^2$, which is larger than that of the PS-PMT. In combination with optimization of the scintillator, optical diffuser and light-shielding structure, the FPD exhibits superior performance compared with the PS-PMT in terms of detection efficiency, spatial resolution and signal-to-background ratio. Furthermore, by exploiting the negligible neutron-insensitive regions surrounding the detection area, simultaneous VSANS and SANS measurements were achieved in the Q range from the order of 10^{-3} to 0.3 nm^{-1} using the FPD together with the downstream ^3He main detector. This capability is expected to enable high-throughput measurements and to facilitate time-resolved studies.

The FPD is also planned to be installed at a newly constructed SANS instrument located adjacent to SANS-J at JRR-3. Similar to the VSANS instrument at NIST (Barker *et al.*, 2022) and the Bio-SANS instrument at the High Flux Isotope Reactor at Oak Ridge National Laboratory (Heller *et al.*, 2014), the new instrument will employ multiple ^3He detector banks positioned at different sample-to-detector distances to enable simultaneous measurements over the high-, medium- and small-angle scattering regions. By further incorporating the FPD into this detector configuration, truly simultaneous measurements spanning high-angle, medium-angle, small-angle and very small angle scattering are expected to be realized, covering an extended range of scattering-vector values from approximately 0.002 to 6 nm^{-1} .

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Conflict of interest

We have no conflict of interest.

Data availability

The data supporting the results can be accessed upon request.

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