

Article

Neutron Source Localization Using Plate-Shaped Fast Neutron Detectors

Mitsuo Koizumi ^{1,*}, Kota Hironaka ¹, Tohn Takahashi ¹, Hirokuni Yamanishi ²
and Genichiro Wakabayashi ²

¹ Integrated Support Center for Nuclear Nonproliferation, Security and Human Resource Development (ISCN), Japan Atomic Energy Agency (JAEA), Shirakata-Shirane 2-4, Tokai-Mura, Naka 319-1195, Ibaraki, Japan; hironaka.kota@jaea.go.jp (K.H.); takahashi.ton@jaea.go.jp (T.T.)

² Atomic Energy Research Institute, Kindai University, Kowakae 3-4-1, Higashiosaka 577-8502, Osaka, Japan; yamanishi@kindai.ac.jp (H.Y.); genichiro@kindai.ac.jp (G.W.)

* Correspondence: koizumi.mitsuo@jaea.go.jp

Abstract

To ensure nuclear security at major public events, portable detectors are essential for surveying wide areas and verifying the absence of nuclear and radioactive materials. Fast neutron detectors enable surveys for localizing neutron-emitting sources and nuclear materials over wide areas. A neutron detector with pulse-shape-discrimination plastic scintillators sensitive to fast neutrons is used herein, thereby suppressing responses to scattered neutrons and reducing gamma-ray background. By adopting a plate-shaped scintillator, the detector exhibits high characteristic directionality. From the measured count-rate distribution along the survey path, both the source distance and point of closest approach can be inferred from peaks and widths of the distribution. However, for more rapid and reliable neutron source localization, empirical functions capable of reproducing the measured count-rate distribution are highly desirable. This paper proposes simple empirical functions and demonstrates that reliable source positions can be determined through chi-squared fitting.

Keywords: plastic scintillator; pulse shape discrimination (PSD); directional fast neutron detector; angular dependence; neutron source survey

1. Introduction

Nuclear security is a critical concern worldwide due to the expanding use of nuclear energy and widespread application of radioisotopes [1,2]. In particular, the potential threat of terrorism involving nuclear and radioactive materials (NRMs) has driven efforts to strengthen nuclear security measures [1–4]. Gamma-ray detectors play a main role in the detection, measurement and survey of NRMs. Gamma-ray signatures are characterized by photons from radioactive materials with a wide range of energies and intensities emitted. However, the signature can be attenuated by shielding and obscured by radiation from naturally occurring radioactive materials (NORMs), as well as commercially available medical and industrial radioisotopes. Unlike gamma-rays, neutrons can penetrate gamma-ray shielding materials and provide unique signatures of nuclear materials and neutron sources. In particular, weapon-grade nuclear materials are of the greatest concern from a nuclear security perspective [4]. Interference of ambient neutron background flux is as low as approximately 100 n/s m², predominantly originating from cosmic rays [4,5].



Academic Editor: Richard Kouzes

Received: 9 July 2026

Revised: 7 August 2026

Accepted: 18 August 2026

Published: 24 August 2026

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To prevent the illicit transportation of NRMs, radiation portal monitors installed at border crossings, ports, and other access points are equipped with both gamma-ray and neutron detectors [6]. Portable radiation detectors are also used for on-site inspections to detect NRMs and verify public safety at venues and events. A variety of detector systems have been developed for these purposes [1–4]. Meanwhile, the shortage of ^3He gas has become a major concern for the deployment of ^3He detectors, which have been widely used as highly efficient, gamma-ray-insensitive thermal neutron detectors [7].

Conventional thermal neutron detectors measure signals generated by neutron-induced nuclear reactions. To achieve high detection efficiency, these detectors typically require a moderator to slow down fast neutrons emitted from neutron sources (NSs). However, the use of moderators increases the overall weight and size of the detectors and results in the loss of essential information about the incident neutrons, such as their energy, arrival time, and incident direction. Directional NS survey methods using thermal neutron detectors have been proposed based on the use of collimators and neutron shields to determine the direction of arrival of thermal neutrons [8,9]. A moderator-based method has been developed in which fast neutrons are moderated to produce angular dependence in the count rates of thermal neutron detectors located on opposite sides of a moderator [8–10].

Compact and portable fast neutron detectors would be suited for practical NS surveys. In particular, plastic scintillators are sensitive to fast neutrons, insensitive to thermal neutrons, mechanically robust, and cost-effective. The sensitivity to gamma rays of the plastic scintillators, which interfere with neutron measurements, can be mitigated by employing pulse shape discrimination (PSD). This enables discrimination between neutron-induced signals and gamma-ray-induced signals [11–17]. Although liquid scintillators generally provide superior neutron–gamma-ray discrimination performance, their use is often avoided because of concerns regarding flammability and toxicity.

We have developed directional portable fast neutron detectors for NS surveys based on PSD plastic scintillators [18,19]. The use of plate-shaped detectors for NS localization has been proposed using measurements of count-rate distributions acquired along a survey path [19]. Owing to the directional sensitivity of the detector, a characteristic count-rate distribution is obtained along the survey path, containing information on the source distance and the point of closest approach, from which the location of the NS can be inferred. In a previous study, we demonstrated the potential of directional detectors for NS localization based on the peak positions and widths of the measured count-rate distribution. However, the evaluation can be affected by statistical fluctuations. Furthermore, the count-rate distribution cannot be readily represented by analytical functions and are generally obtained through numerical simulation. Therefore, empirical equations capable of reproducing measured count-rate distributions are highly desirable for rapid and reliable NS localization using chi-squared fitting.

In this paper, empirical functions are employed to reproduce the measured count-rate distributions. By fitting these functions to the measured data using the chi-squared method, both the source distance and the point of closest approach can be estimated, thereby enabling NS localization.

2. Experimental Setup

The developed detector is a square PSD plastic scintillator (250 mm $\times$ 250 mm $\times$ 25 mm, EJ-276, Eljen technology, Sweetwater, TX, USA [11,12]) equipped with four photomultiplier tubes (H11934-100-010, Hamamatsu Photonics, Hamamatsu, Japan) mounted on 25 mm $\times$ 25 mm corner cuts of a plate [19]. Signals from the photomultiplier tubes were digitized at 14 bits and 500 MS/s using a DT5730 digitizer (CAEN, Viareggio, LU, Italy). The triggered pulse waveforms were numerically integrated over long and short time

windows to obtain charges Q_L and Q_S , respectively. Event information, including trigger timing, was recorded in list mode and analyzed offline. A PSD parameter defined as $PSD = (Q_L - Q_S)/Q_L$ was used to separate neutron and gamma-ray events, with Q_L and Q_S being the sums of the four detector outputs. Discrimination performance was evaluated by a figure of merit ranging from 0.4 to 0.5 [19], being lower than those reported in [15–18]. Nevertheless, the PSD plastic scintillators provided advantages in neutron measurements owing to the mitigation of gamma-ray background signals.

Measurements were performed using a PuBe (α, n) NS (1.4×10^6 n/s), where the dose rates at 1 m from the source were approximately 55 $\mu\text{Sv/h}$ for neutrons and 4.0 $\mu\text{Sv/h}$ for gamma rays. Figure 1 illustrates the configuration of a detector moving along the X axis, with x_0 denoting the point of closest approach to the source and r_0 denoting the distance from the NS. The detector orientation angle relative to the X axis is denoted by θ_{det} .

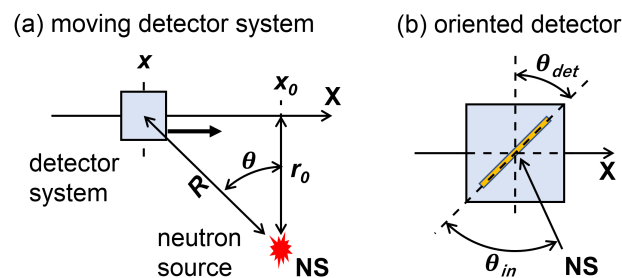


Figure 1. Geometry of a moving detector. (a) The detector moving along the X-axis at distance r_0 from the neutron source (NS), with detector position x , point of closest approach x_0 , and angle θ between x and x_0 at the NS. (b) Angles θ_{det} and $\theta_{in} (= \theta - \theta_{det})$ indicate the detector's orientation on the moving system and radiation incident angle, respectively.

3. Empirical Functions for Detector Response of Neutron

The experimentally measured neutron and gamma-ray count rates per detector with orientation angle θ_{det} at $x = x_0$ are shown in Figure 2. The counting rate decreases markedly as the angle falls below 30° and reaches the minimum at 0° , where the source is aligned with the plane of the detector major axes, thus demonstrating the detector's pronounced directional sensitivity. This distribution could not be reproduced using simple trigonometric functions, because the count rate depends not only on the solid angle but also on the incident angle [18,19]. Simulations can be used to evaluate the count rates; however, they require a certain amount of computational effort. In contrast, the measured distributions exhibit saturation-like behavior, indicating that simple empirical functions may be used to approximate them. The observed angular dependence is suitably reproduced by the following empirical function:

$$f(\theta_{det}) = a_0 + a_1 \times (1 - \exp(-\theta_{det}/a_2)), \quad (1)$$

where a_0 , a_1 , and a_2 are fitting parameters. Details of the fitting results, including the fitting parameters and relative residuals, are presented in Appendix B.1.

If the source-to-detector distance is short, the spatial distributions of neutron flux and incident angles across the detector's surface may influence the detector's response function. In the present study, source-to-detector distances greater than 1 m are considered. Under these conditions, the effects of such spatial distributions are assumed to be negligible, and the shape of the detector response function can be treated as independent of the source distance.

A numerical analysis is performed using the empirical function. Count rate $Y(x)$ (1/s) is calculated as a function of detector position x and detector orientation θ_{det} using Equation (1):

$$Y(x) = Nf(\theta_{in})/R^2, \quad (2)$$

where N is a normalization factor corresponding to the neutron emission rate, θ_{in} is the radiation incident angle on the detector given by $\theta_{in} = \theta - \theta_{det}$, and R is the distance between the source and detector:

$$R = \sqrt{r_0^2 + (x - x_0)^2}. \quad (3)$$

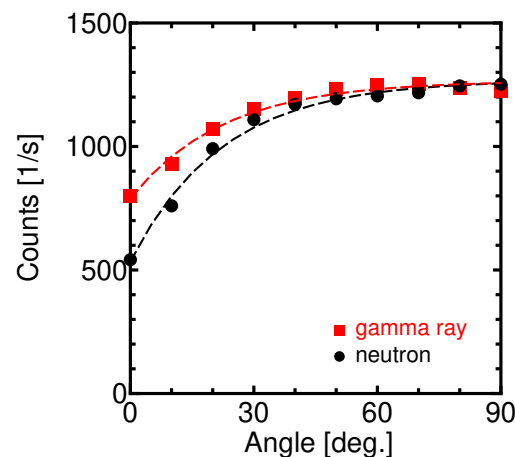


Figure 2. Experimental neutron and gamma-ray count rates according to detector orientation angle at $x = x_0$ with $r_0 = 1$ m. The plotted data are identical to those shown in Figure 3 of [19]. Neutron and gamma-ray events are shown by black circles and red squares, respectively. Each measurement was performed for 600 s using a PuBe (α , n) source (1.4×10^6 n/s). Statistical uncertainties are smaller than the symbol size. The dashed curves represent fitted the empirical function (Equation (1)) $f(\theta_{det}) = a_0 + a_1 \times (1 - \exp(-\theta_{det}/a_2))$, where a_0 , a_1 , and a_2 are fitting parameters. The data used in these plots are provided in Supplementary Dataset S2.

The count rates at each detector position x are evaluated using Equation (2) for an NS of 10^6 n/s at $x_0 = 0$ m with $r_0 = 1$ m. Detector orientation θ_{det} is evaluated at 0° , 90° , and $\pm 45^\circ$. The results are shown as black solid lines in Figure 3.

For the detector at $\theta_{det} = 90^\circ$, the black line of Figure 3a shows a broad peak with a full width at half maximum (FWHM) of approximately 1.9 m, corresponding to $2r_0$. In contrast, for the detector at $\theta_{det} = 0^\circ$, Figure 3b shows a sharp dip at $x = 0$ m flanked by two bumps separated by approximately 0.8 m, clearly indicating the point of closest approach, x_0 . For intermediate orientations θ_{det} of $\pm 45^\circ$, Figure 3c,d show broad peaks similar to the peak of the parallel detector in Figure 3a. A small inflection appeared near $x = \pm 1$ m for $\theta_{det} = \pm 45^\circ$. This corresponds to the position where the detector plane aligned with the NS, i.e., where $\theta_{in} = 0^\circ$. At this position, the solid angle decreases significantly, leading to a reduction in the count rate, as shown in Figure 2. The peak position slightly shifts opposite to this deviation, and the FWHM of approximately 1.7 m corresponds to approximately 85% of $2r_0$.

The source position can be inferred from the count-rate distributions through parameters such as the FWHM and peak positions. However, these quantities are often influenced by statistical fluctuations and the environment. To robustly estimate the source–detector geometry, we apply simple analytical functions corresponding to different detector orientations as follows. A description of the derivation of these functions is given in Appendix A.

$$g_1(x) = A \frac{r}{R^3}, \quad (\theta_{det} = 90^\circ), \quad (4)$$

$$g_2(x) = A \frac{1+w\sqrt{(x-x_0)^2/R}}{R^2}, \quad (\theta_{det} = 0^\circ), \quad (5)$$

$$g_3(x) = A \frac{1+w\sqrt{((x-x_0)+r)^2/R}}{R^2}, \quad (\theta_{det} = -45^\circ), \quad (6)$$

$$g_4(x) = A \frac{1+w\sqrt{((x-x_0)-r)^2/R}}{R^2}, \quad (\theta_{det} = +45^\circ), \quad (7)$$

Here, A and w are fitting parameters, and $R (= \sqrt{(x-x_0)^2 + r^2})$ is the source–detector distance, where r is the corrected distance between the source and detector path.

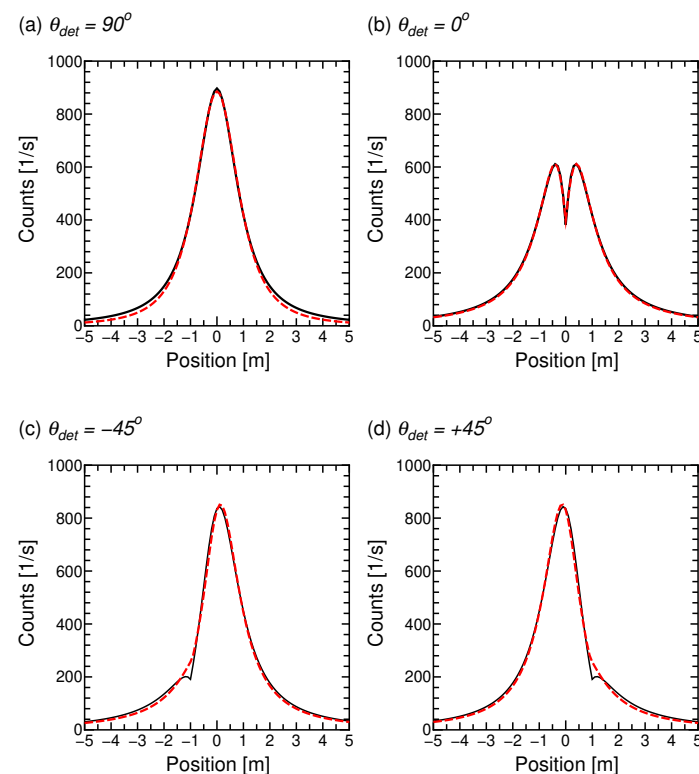


Figure 3. Count rates of the moving detector according to position x for a NS of 10^6 n/s at $x_0 = 0$ m with $r_0 = 1$ m. Results are shown for detector orientations of (a) $\theta_{det} = 90^\circ$, (b) $\theta_{det} = 0^\circ$, (c) $\theta_{det} = -45^\circ$, and (d) $\theta_{det} = +45^\circ$. The black curves represent the calculated results using Equation (2), and the red curves show the fitting results obtained using empirical Equations (4)–(7). The data used to in these plots are provided in Supplementary Dataset S3.

The red dashed lines in Figure 3 represent fitting over peak region $-1.5 < x < 1.5$. Details of the fitting results, including the fitting parameters and relative residuals, are presented in Appendix B.2. The calculated count-rate distributions were reproduced using the empirical functions. However, the fitting parameter r differs slightly from the actual distance between the source and the detector path, r_0 . This discrepancy arises from the limitations of the simple empirical functions. Therefore, correction factor B was introduced to compensate for the discrepancy such that $r = B r_0$. The resulting values of B are listed in Table 1. Since the discrepancy depends on the empirical function employed, the value of B varies with the detector orientation, θ_{det} . Overall, the fitted curves suitably reproduce the distribution with negligible discrepancies for practical NS surveys.

Table 1. Evaluated parameter B of Equations (4)–(7) determined by chi-squared fitting.

Detector Orientation	Parameter B
0°	1.246 (6)
90°	0.829 (6)
$\pm 45^\circ$	0.93 (2)

The sum of count-rate distributions obtained from different detector orientations (θ_{det}) indicates the presence of a source, and the subtraction of the count-rate distributions indicates its orientation. Figure 4a shows the summed and subtracted count rates for detectors at θ_{det} of 90° and 0° . The summed count rates exhibit a small dip, indicating the point of closest approach with an FWHM approximately 10% broader than $2r_0$. The subtracted count rates show a sharp peak at $x = 0$ m. At the tails of the peak over $|x| > 1$ m, the subtracted count rates become negative because the solid angle of the detector at θ_{det} of 90° exceeds that of the detector at θ_{det} of 0° when $x > r_0$. Excluding these negative regions, the FWHM of the peak is approximately 25% of $2r_0$, while the peak count reduces to approximately 60% of the maximum.

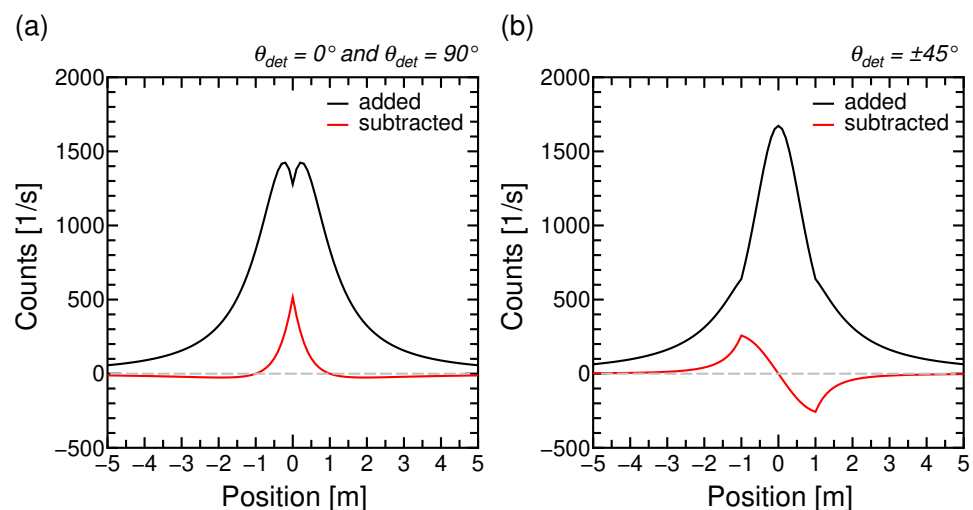


Figure 4. Summed (black lines) and subtracted (red lines) count rates calculated using Equation (2) for paired detectors with orientation angles of (a) $\theta_{det} = 0^\circ$ and 90° , as well as (b) $\theta_{det} = \pm 45^\circ$. Grey dashed lines indicate the zero-count-rate level. The data used in these plots are provided in Supplementary Dataset S4.

Figure 4b shows summed and subtracted distributions for detectors at θ_{det} of $\pm 45^\circ$. The summed count rates exhibit a sharp peak with an FWHM of approximately 60% of $2r_0$. Small deviations are clearly visible on both sides at x of ± 1 m. The subtracted count rate exhibit positive and negative peaks at x of ± 1 m, with a zero crossing at $x = 0$ m, directly revealing the source geometry in terms of both r_0 and x_0 . A peak inversion indicates the source direction. If the source is located horizontally opposite to the survey path, the subtracted distribution is reversed.

4. NS Localization by Fitting

Consecutive measurements with directional detectors along a survey path allow effective localization of radiation sources. Applying chi-squared fitting with empirical functions enables quantitative source localization, simplifies analysis, reduces statistical fluctuations, and provides reliable estimates.

Figure 5 shows experimental neutron counts according to detector position x for a source placed at a horizontal distance of 1 m and $x_0 = 0$ m. Source location r_0 and x_0

were evaluated using chi-squared fitting with Equations (4) and (5) and the orientation-specific parameters, B , listed in Table 1. Details of the fitting results, including the fitting parameters and relative residuals, are presented in Appendix B.3. The resulting fitted curves are shown as dashed lines in Figure 5, with the parameters listed in Table 2. They successfully reproduced the experimental distributions.

Table 2. Evaluated parameters by chi-squared fitting. The detectors' orientations used for fitting are listed in the left most column.

Detector	H = 0 m		H = 0.7 m	
	r_0 [m]	x_0 [m]	r_0 [m]	x_0 [m]
0°	1.00 (2)	−0.005 (6)	1.24 (2)	−0.028 (3)
90°	1.08 (2)	0.02 (1)	1.34 (2)	0.02 (1)
0° and 90°	1.06 (2)	0.002 (7)	1.32 (3)	−0.019 (8)

To generalize localization, source height H should be considered. As shown in Figure 6, the source location can be represented in cylindrical coordinates (r , ϕ , and x). The count-rate patterns are strongly affected by the azimuthal angle ϕ of the source and the detector's orientation angle, θ_{det} . For instance, a detector at θ_{det} of -45° exhibits a deviation at $x = r_0$ when the source is at ϕ of 0° (Figure 3c). As ϕ increases or decreases, the deviation shifts toward $x = 0$. The deviation transforms into a dip at $x = x_0 \approx 0$ when the source is above or below the detector's path ($\phi \approx \pm 90^\circ$), similar to Figure 3b. For a source at ϕ of $\pm 180^\circ$ (i.e., opposite side), the deviation moves to $x_0 = -r_0$ (Figure 3d). These complex variations arise from the axial asymmetry of the detector relative to its moving path, except for the detectors oriented at θ_{det} of 0° and 90° .

Detectors with an orientation θ_{det} of 0° exhibit fourfold rotational symmetry along the moving path, thus being approximately axially symmetric except at the corners of the square plate that have cuts for photomultiplier tubes. Hence, the similar deviation at the point of closest approach appears for sources at any azimuthal angle ϕ , as illustrated in Figures 5a and 5b for a source height of 0.0 ($\phi = 0^\circ$) and 0.7 m ($\phi = 35^\circ$), respectively.

Detectors with an orientation θ_{det} of 90° exhibit twofold rotational symmetry, with the main detector surface parallel to the moving path. Consequently, the source does not cross the plane along the detector major axes, resulting in a broad count-rate distribution. The peak count at $x = x_0$ varies with azimuthal angle ϕ , reaching its maximum at a ϕ of 0° and $\pm 180^\circ$ and its minimum at a ϕ of $\pm 90^\circ$, with substantial reductions at ϕ of 60 – 120° and -120 – -60° , following the angular dependence shown in Figure 2. However, the decline in the detector count rate at a θ_{det} of 90° is only approximately 50% from the source position for ϕ ranging from 0° to $\pm 90^\circ$.

Figure 5b shows the count responses of detectors at a θ_{det} of 0° and 90° for an NS at a height of 0.7 m and horizontal distance of 1 m (i.e., $\phi = 35^\circ$). The FWHM of the count-rate distribution for the 90° detector is approximately 3 m, which is broader than that expected for a distance of 2.44 m. This is probably due to the response (i.e., efficiency) of the detector along the moving path being varied by the radiation incident direction determined by the azimuthal angle, ϕ , of the source, as well as detector position x and orientation θ_{det} .

The fitted parameters listed in Table 2 reproduce the experimental conditions within 10% discrepancies. When using only the data from the 0° detector, the fitted values differ by less than 3%. These deviations are sufficiently small for practical applications, such as survey and localization of a source in large open venues.

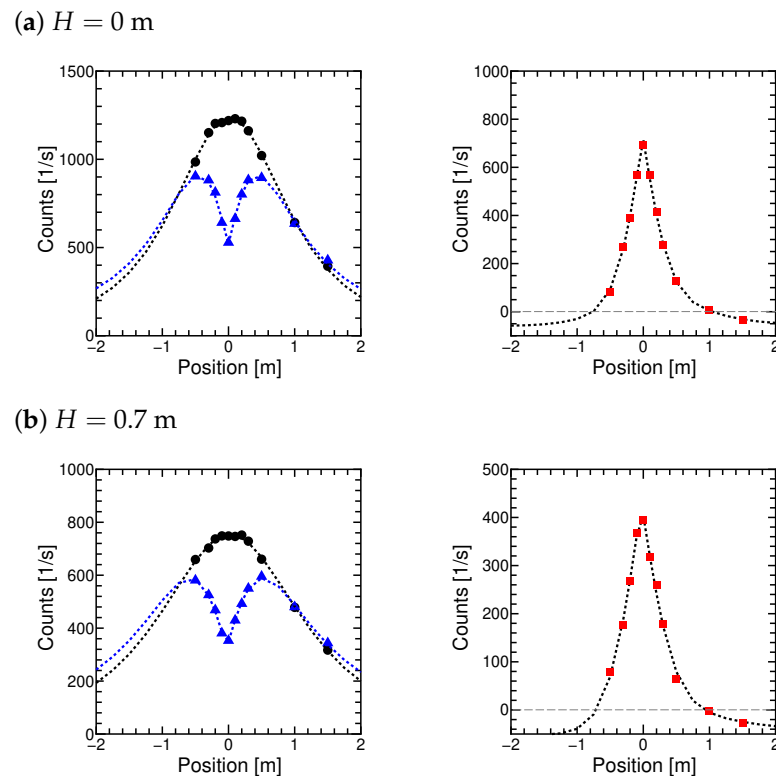


Figure 5. Experimentally measured count rates according to detector position x retrieved from Figure 8 of [19]. The NS was placed 1 m horizontally from the survey path and at heights of (a) 0.0 and (b) 0.7 m. In the first column, black circles and blue triangles indicate detector orientation angle (θ_{det}) values of 90° and 0° , respectively. The second column shows the difference between the two detectors as red squares. Each measurement was performed for 5 min per data point. The statistical uncertainties are smaller than the symbol's size. Dashed lines represent the fitting results using Equations (4) and (5). Horizontal grey dashed lines of the right panels indicate the zero-count-rate level. The data used in these plots are provided in Supplementary Dataset S5.

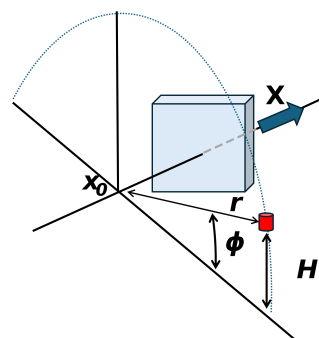


Figure 6. Geometry of source in cylindrical coordinates (r , ϕ , and x), where H is the source height. A detector with orientation angle θ_{det} moves from left to right along the X -axis, and x_0 represents the point of closest approach.

5. NS Survey Using Moving Detector

To evaluate the sensitivity of the detectors at θ_{det} of 90° and 0° to an NS, we simulated expected count-rate distributions along the survey path. The simulation was performed using Equation (2), integrating the count within position bins, x , using parameters, B , listed in Table 1 for a PuBe (α , n) source (1.4×10^6 n/s) at a height H of 0 m.

For a realistic evaluation, background contributions should be considered in the count. Gamma-ray and neutron backgrounds increase the baseline of the count-rate distribution. In our study, the gamma-ray count rate for the NS measurement with a detector orientation

of $\theta_{det} = 90^\circ$ was approximately 1300 cps, corresponding to a dose rate of $4.0 = \mu\text{Sv/h}$. Under these measurement conditions and assuming a neutron–gamma discrimination figure of merit (FOM) of 0.5, approximately 12% of neutron and gamma-ray events are misclassified as each other [20]. Assuming a natural gamma-ray background dose rate of $0.3 \mu\text{Sv/h}$, the gamma-ray contribution to the neutron count rate is estimated to be approximately 10 cps based on the aforementioned results.

Gamma rays emitted from naturally occurring radioactive materials (NORMs) may distort the count-rate distribution by producing additional peaks. However, similar distributions will also be observed in the gamma-ray count-rate distribution measured with a higher statistic. Their impact can be reduced by increasing the analysis threshold at the expense of reduced neutron-counting statistics.

Neutron background is primarily generated by cosmic rays. The flux of background high-energy neutrons in the energy range from 1 MeV to 100 MeV can be estimated to be approximately $5 \times 10^{-3} \text{ n/s cm}^2$ by integrating a conventional neutron energy spectrum, $n(E) = 0.001E^{-1} \text{ 1/(s cm}^2 \text{ GeV)}$ [5]. For comparisons, the neutron flux from an NS with an emission rate of $1.4 \times 10^6 \text{ n/s}$ at distance of 10 m is estimated to be approximately 0.1 n/s cm^2 . In this case, the count rate is higher than the cosmic-ray-induced neutron background.

Neutrons emitted from a source are scattered by surrounding materials such as concrete, soil, and other structures. These neutrons undergo multiple scattering, lose energy, and may eventually be captured. Some scattered neutrons can still reach the detector and influence the measured neutron count-rate distribution. However, their contribution is expected to be limited because fast neutron detectors are primarily sensitive to unmoderated neutrons. Consequently, neutrons that may have lost a substantial fraction of their energy through scattering are less likely to contribute significantly to the measured count-rate distribution. Nevertheless, the impact of scattered neutrons should be evaluated in future studies under realistic conditions.

For simplicity, the effects of background neutrons, gamma rays, and neutrons scattered by surrounding materials on the count-rate distributions were neglected in this simulation.

The starting points for measurements were randomized to resemble realistic measurements because the source position is generally unknown, and the detector system was assumed to move at 0.5 m/s , corresponding to a relatively slow walking speed.

Figure 7 shows the simulated counts along the survey path. Abscissa x/r_0 represents the detector position normalized by source distance r_0 , highlighting the shape of count-rate distributions.

Measurement time T_s governs both the positional resolution of each bin and statistical precision of each data point. A shorter T_s improves the spatial resolution but reduces the counting statistics, while a longer T_s enhances the statistics at the expense of spatial resolution. This trade-off is evident in Figure 7, with Figure 7a,b corresponding to $r_0 = 1 \text{ m}$ and Figure 7c,d corresponding to $r_0 = 10 \text{ m}$.

As source distance r_0 increases, the overall count rate decreases proportionally to $1/r_0^2$, and the distribution along the X axis broadens (compare Figure 7b,c for the same T_s). Figure 7c shows improved positional resolution compared with Figure 7b but with reduced statistical precision. This loss can be mitigated by summing adjacent data points, but this comes at the cost of losing spatial resolution (Figure 7c,d). For a fixed positional resolution in normalized position x/r_0 , the count rate scales as $1/r_0$, as observed by comparing Figure 7a,d.

In realistic measurements, each data point obtained using a moving detector represents the integrated count over a finite spatial interval. This averaging process blurs the count-rate distribution and reduces the accuracy of NS localization. However, the proposed method remains effective when the integration interval is sufficiently small. Furthermore, it

provides a practical and rapid approach to NS localization in situations where approximate source positioning is sufficient.

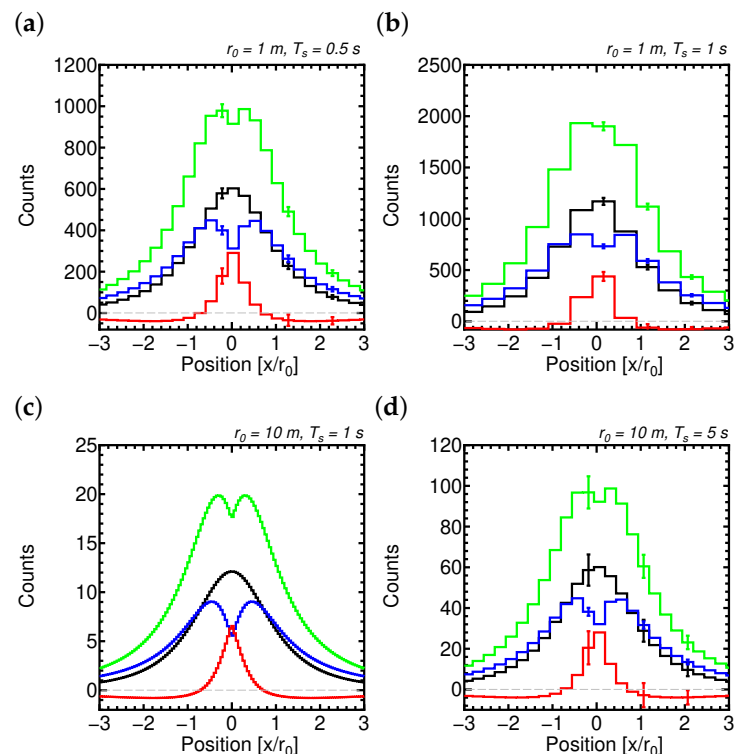


Figure 7. Calculated neutron counts for moving detectors at normalized positions x/r_0 for various distances of source to detector path r_0 and measurement time per bin T_s : (a) $r_0 = 1$ m and $T_s = 0.5$ s; (b) $r_0 = 1$ m and $T_s = 1$ s; (c) $r_0 = 10$ m and $T_s = 1$ s; and (d) $r_0 = 10$ m and $T_s = 5$ s. The black and blue lines represent detectors oriented at θ_{det} of 90° and 0° , respectively, where the green and red lines correspond to the summed and subtracted counts of the two detectors. The horizontal grey dashed lines indicate the zero-count-rate level. The error bars indicate the expected statistical uncertainties at selected points. They are omitted in panel (c) due to their large magnitude (e.g., approximately 30% at the peak of the detector with θ_{det} of 90°). The data used in these plots are provided in Supplementary Dataset S7.

6. Multiple NS Localization

If more than one NS is present, the count-rate distribution becomes more complex, making the localization of multiple NSs difficult. In spectroscopy, the ability to resolve adjacent peaks is characterized by relative resolutions. For example, the performance of gamma-ray spectrometers is commonly evaluated using energy resolution, defined by dE/E , where E and dE denote the peak energy and its FWHM, respectively. A similar concept may be applied to NS localization, where the characteristic width of the count-rate distribution governs the spatial resolving power for separating neighboring NSs. A narrower count-rate distribution provides to a higher spatial resolution for identifying multiple NSs.

Defining the relative resolution as $R = FWHM/r_0$, the relative resolution of a non-directional detector is evaluated to be $R = 2$, since its count-rate distribution exhibits a peak at the point of closest approach with an FWHM of $2 \times r_0$. This can be interpreted to mean that two NSs separated by more than $2r_0$ can be resolved, provided that they have identical emission rate and are located at the same distance r_0 from the detector path. The resolution of the plate detector orientated at $\theta_{det} = 90^\circ$ is also approximately $R = 2$, which is comparable to that of non-directional detectors. In contrast, the detector oriented at $\theta_{det} = 0^\circ$ exhibits a narrow dip in the count-rate distribution at the point of

closest approach. By defining the FWHM as half of the separation between the two peaks appearing on either side of the dip, the relative resolution is estimated to be $R = 0.13$. This represents a substantial improvement in spatial resolution.

Sources located at different distances from the detector path produce more complex count-rate distributions. In such cases, each source contributes a count-rate distribution with a different strength and width, making the localization of multiple NSs more difficult. This difficulty can be mitigated using the difference between count-rate distributions measured with detectors orientations of $\theta_{det} = 0^\circ$ and $\theta_{det} = 90^\circ$. Such subtraction simplifies the count-rate distribution and produces sharp peaks, thereby facilitating the identification and localization of multiple NSs. This improved spatial resolution is a significant advantage of the proposed system for NS surveys, particularly in the presence of multiple sources.

7. Conclusions

For efficient NS surveys in large events, we introduce a fast neutron detector using a plate-shaped PSD plastic scintillator. The developed detector is sensitive to fast neutrons, efficiently suppressing signals from scattered neutrons and discriminating against gamma-ray events. The shape imparts directionality, allowing the detector response to exhibit characteristic count-rate distributions along the survey path that indicate the source location. Empirical functions reproduce the response patterns of detectors with orientations θ_{det} of 0° , 90° , and $\pm 45^\circ$ for an NS at the same height of the detector. The source location can thus be quantitatively determined using chi-squared fitting, enabling simplified data analysis, reducing statistical fluctuations, and providing reliable source localization.

In practical surveys, sources are potentially located at different heights, hindering the detector count response. The detector with an orientation θ_{det} of 0° provides consistent responses across source heights. Conventional empirical functions allow us to determine the source's localization (x_0 and r_0) through chi-squared fitting. Furthermore, the azimuthal angle can be inferred from the count rate associated with the largest signal among the outputs of four photomultiplier tubes (PMTs) at $x = x_0$ [19]. The plate-shaped detector is equipped with four PMTs located at its corners. The output signal amplitude varies depending on the neutron's interaction position within the scintillator. In general, a PMT located closer to the scintillation event records a greater signal. Consequently, the count rates associated with the strongest signal differ among the four PMTs, depending on the detector orientation and the source position. This asymmetry becomes particularly pronounced when the NS is located at the side of the detector. For a detector orientation of $\theta_{det} = 0^\circ$, the azimuthal angle, ϕ , can be determined near the point of closest approach $x = x_0$ with an accuracy better than $\pi/8$. Accordingly, the source can be localized in cylindrical coordinates (r_0 , ϕ , x_0) using a single detector with orientation θ_{det} of 0° .

Detectors with an orientation θ_{det} of 90° exhibit a simple peak response, where only the peak count and its width vary with the source's height. This dependence provides additional information for localizing the source.

The observed count-rate distributions according to the normalized abscissa (i.e., x/r_0) and integrated over a fixed normalized region scale as $1/r_0$, while the instantaneous count rates follow a $1/r_0^2$ relation. Neglecting background contributions, the signal strength indicating the presence of a source as the total counts integrated over a scaled region is proportional to $1/r_0$.

Overall, the proposed directional detector seems to be suitable for integration with systems including unmanned ground vehicles and autonomous mobile robots, and it likely provides an efficient and automated approach for NS survey and gamma-ray source localization at large public events.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/app16178429/s1>, Dataset S2: Raw data used for Figures 2 and A2; Dataset S3: Raw data used for Figures 3 and A3; Dataset S4: Raw data used for Figure 4; Dataset S5: Raw data used for Figures 5 and A4; Dataset S7: Raw data used for Figure 7.

Author Contributions: Conceptualization, M.K.; detector development, T.T. and K.H.; preparation of the experimental field, H.Y. and G.W.; investigation, all authors; data analysis, M.K.; writing—original draft preparation, M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article or the Supplementary Materials.

Acknowledgments: The authors would like to express their sincere gratitude to the research assistant for his experimental and analytical assistance. This research was supported by a subsidy for the “promotion of strengthening nuclear security and the like” from the Ministry of Education, Culture, Sports, Science and Technology, Japan. Part of this study was conducted under the cooperative research program between Kindai University and the Japan Atomic Energy Agency, utilizing the facilities of the Atomic Energy Research Institute of Kindai University. In addition, this work contributes to the Coordinated Research Program, J02015 (Facilitation of Safe and Secure Trade Using Nuclear Detection Technology—Detection of RN and Other Contraband) of the International Atomic Energy Agency.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

NMRs	Nuclear and radioactive materials
NORM	Naturally occurring radioactive material
NS	Neutron source
PSD	Pulse shape discrimination
FWHM	Full width at half maximum

Appendix A. Derivation of Empirical Functions

Figure A1 illustrates a detector oriented at an angle θ_{det} and moving along the X-axis. The distance between the detector and the source at an arbitrary detector position x is given by $R = \sqrt{x^2 + r^2}$, where r denotes the distance of closest approach ($x_0 = 0$). The neutron flux at a distance R from a source can be expressed as $\frac{N}{R^2}$, where N represents the neutron flux at $R = 1$. Assuming a parallel beam at a distance R , the number of neutrons incident on the detector surface can be expressed as $A \frac{\sin(\theta_{det} + \theta)}{R^2}$ or $A \frac{r \cos(-\theta_{det}) + x \sin(\theta_{det})}{R^2}$, where A is a normalization factor corresponding to the neutron flux multiplied by the surface area of the plate detector. For $\theta_{det} = 90^\circ, 0^\circ$, and $\pm 45^\circ$, the above expression can be simplified to $A \frac{r}{R^3}$, $A \frac{\sqrt{x^2}}{R^3}$, and $A \frac{\sqrt{(x \pm r)^2}}{R^3}$, respectively. As shown in Figure 3a of the main text, the count-rate distribution for $\theta_{det} = 90^\circ$ was successfully reproduced using Equation (4). Although the functions for $\theta_{det} = 0^\circ$ and $\pm 45^\circ$ do not fully reproduce the evaluated count-rate distributions, they describe their characteristic features, exhibiting a dip at $x = 0$ and inflections at $x = \pm r$, respectively. In both cases, the count rate becomes zero. Therefore, an additional term corresponding to the response of a non-directional detector ($\propto 1/R^2$) was introduced. This modification results in $A \frac{1 + \omega \sqrt{x^2}/R}{R^2}$ for $\theta_{det} = 0^\circ$ and $A \frac{1 + \omega \sqrt{(x \pm r)^2}/R}{R^2}$ for $\theta_{det} = \pm 45^\circ$, where ω is a fitting parameter. These modified functions successfully

reproduced the measured count-rate distributions, as shown in Figure 3 of the main text. However, the distance parameter r obtained from the chi-squared fitting exhibited a small discrepancy from the actual source distance, r_0 . This discrepancy arises from the limitations of simple empirical functions. To account for this discrepancy, a correction factor B was introduced such that $r = Br_0$. Because the discrepancy depends on the empirical function, the value of B varies with the detector's orientation, θ_{det} .

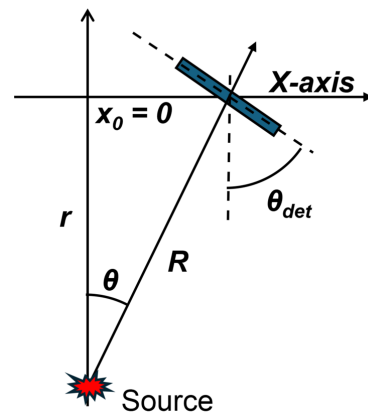


Figure A1. Geometrical relationship between the NS and the detector.

It should be noted that the count-rate distributions represented by Equations (4)–(7) are linearly stretched along the X-axis with an increasing r . This can be seen from the relation $g_n(x) = g_n(rx') = \frac{1}{r^2} g_n(x', r = 1)$, where x' is the detector position x normalized by r ($x' = x/r$), and n denotes the detector orientation characterized by θ_{det} . This means that the shape of the distribution function remains unchanged for different values of r . Therefore, the source distance r_0 can be estimated from the measured count-rate distributions through chi-squared fitting using these functions and the correction factor B .

Appendix B. Details of Fitting

Chi-squared fitting was performed using Gnuplot (Ver.6.0), a portable command-line-driven graphing utility [20]. The errors of the fitted parameter were scaled by the reduced chi-square value such that the estimated errors increase when the reduced chi-square value exceeds unity.

Appendix B.1. Angular Dependence of Count Rate

The fitting was performed using Equation (1). Each data point was weighted according to its statistical uncertainty. The number of data points was 10, the number of free parameters was three, and the numbers of degrees of freedom (ν) was 7. The fitting results are summarized in Table A1, and Figure A2 shows the relative residuals $(y_i - f(x_i))/f(x_i)$. The model function reproduced the data well, except for the data at 10° . However, the discrepancies are only approximately 4%.

Table A1. Results of chi-square fitting for the count-rate distribution shown in Figure 2.

	$\sqrt{\chi^2/\nu}$	a_0	a_1	a_2
Neutron	16.2	534.2 (8)	734 (2)	22.34 (13)
Gamma ray	12.1	789.7 (13)	476.2 (17)	22.7 (2)

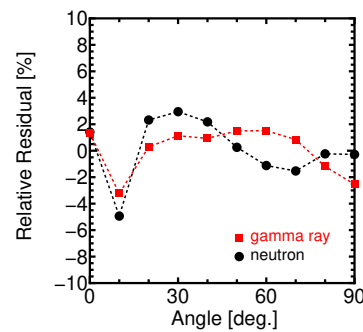


Figure A2. Relative residuals between the experimental data and the fitted function. The data used in these plots are provided in Supplementary Dataset S2.

Appendix B.2. Position Dependence of Count Rate

Fitting was performed in the vicinity of $x = 0$ over the range from $x = -1.5$ m to $x = 1.5$ m. The number of data points was 31, the number of fitting parameters was three, and the number of degrees of freedom was 29 for Equation (4) and 28 for Equations (5)–(7). The fitting results and the fitting residuals are presented in Table A2 and Figure A3, respectively. The residual plots revealed the difficulty of completely reproducing the evaluated count-rate distributions using these simple functions. For $\theta_{det} = 90^\circ$ and $\theta_{det} = 0^\circ$, the relative residuals are less than 10% within the fitting range. Outside this range, the relative residual increases rapidly for functions corresponding to $\theta_{det} = 90^\circ$. However, this increase is partly emphasized because the count rate decreases with an increasing $|x|$. The residual plots for $\theta_{det} = \pm 45^\circ$ show relatively large discrepancies at ± 1 m, indicating the limitations of these simple functions. Nevertheless, these functions reproduce the overall trends of the evaluated count-rate distributions reasonably well, as shown in Figure 3. Using the fitted values of r listed in Table A2, the correction factor B , given in Table 1 in the main text, was determined using the relation $r_0 = r/B(\theta_{det})$, where the actual source distance was $r_0 = 1$ m.

Table A2. Results of chi-square fitting for the count-rate distribution shown in Figure 3.

θ_{det}	$\sqrt{\chi^2/\nu}$	a	r [m]	ω
90°	7.2	1374 (11)	1.246 (6)	–
0°	5.9	275 (6)	0.829 (6)	2.04 (5)
$\pm 45^\circ$	24	468 (17)	0.934 (18)	0.55 (4)

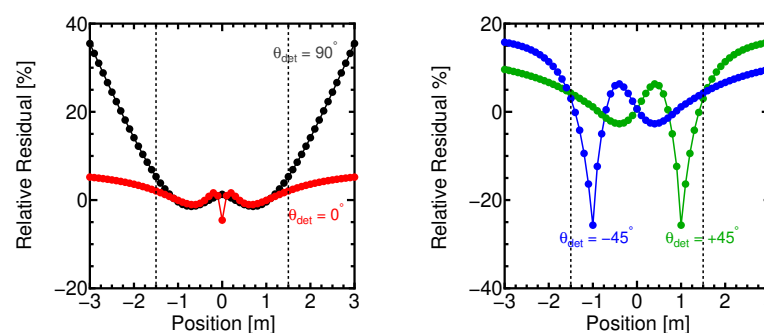


Figure A3. Relative residuals between the evaluated data and the fitted functions, Equations (2) and (4)–(7), for detector orientations of $\theta_{det} = 90^\circ$, $\theta_{det} = 0^\circ$, and $\theta_{det} = \pm 45^\circ$, respectively. The region used for chi-squared fitting is indicated by the dashed lines ($-1.5 \text{ m} \leq x \leq 1.5 \text{ m}$). The data used in these plots are provided in Supplementary Dataset S3.

Appendix B.3. Evaluation of NS Location

Two series of measurements were performed with different detector orientations, $\theta_{det} = 90^\circ$ and 0° , and different neutron source heights, $H = 0.0$ m and 0.7 m. Eleven data points were obtained for each measurement. Chi-square fitting was performed using Equations (4) and (5). The numbers of fitting parameters were four and three, resulting in 7 and 8 degrees of freedom, respectively. The fitting results are given in Table A3. In addition, both measurements were fitted simultaneously using Equations (4) and (5). Common fitting parameters were used for both datasets except for A_1 and A_2 , which correspond to the parameter A in Equations (4) and (5), respectively. Consequently, the fit involved 22 data points, five fitting parameters, and 17 degrees of freedom.

The relative residuals and fitting residuals of the chi-squared fittings are presented in Table A3 and Figure A4, respectively. The relative residuals near the peak were approximately 1%, indicating that the fitting function reproducing the experimental data well.

Table A3. Results of chi-square fitting for the count-rate distribution shown in Figure 5.

H	θ_{det}	$\sqrt{\chi^2/\nu}$	r_0 [m]	x_0 [m]	A_1	A_2	ω	Equations
0 m	90°	15.3	1.11 (2)	0.012 (10)	2231 (74)	—	—	(4)
	0°	7.31	1.04 (2)	−0.005 (6)	—	352 (23)	2.8 (2)	(5)
	0° & 90°	21.0	1.06 (2)	0.002 (7)	2680 (96)	407 (23)	2.5 (2)	(4) & (5)
0.7 m	90°	7.31	1.38 (2)	0.021 (11)	2076 (63)	—	—	(4)
	0°	6.12	1.28 (2)	−0.028 (3)	—	342 (13)	2.84 (9)	(5)
	0° & 90°	13.1	1.32 (3)	−0.020 (8)	2550 (93)	406 (22)	2.6 (2)	(4) & (5)

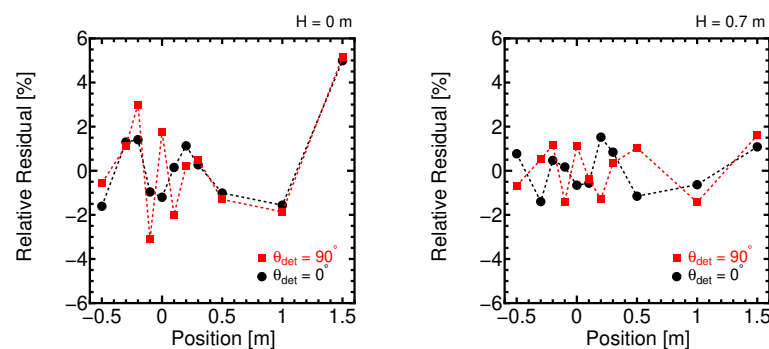


Figure A4. Relative residuals between the experimental data and the fitted functions shown in the left panels of Figure 5. The experimental data were obtained using detectors oriented $\theta_{det} = 0^\circ$ and 90° for the neutron source, which was located at $H = 0.0$ m and 0.7 m. The data used in these plots are provided in Supplementary Dataset S5.

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