Single neutron super-resolution imaging based on neutron capture event detection and reconstruction

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Abstract

The user wants me to translate a scientific text from Simplified Chinese to English. Let me analyze the requirements:

1. **Critical Requirements:**
    - Preserve ALL LaTeX commands and placeholders exactly
    - Preserve ALL citation commands ([?], ??, (??), etc.) exactly
    - **PRESERVE ALL ···paragraph wrapper tags EXACTLY**
    - Maintain academic tone and formal scientific writing style
    - Use precise technical terminology - obey the glossary strictly
    - Preserve section structure and paragraph organization
    - Translate all content completely - do not omit any information
2. **Output Rules:**
    - Return ONLY the translated text (no explanations, no quotes, no headings)
    - Keep one output paragraph per input paragraph
    - Maintain exact count and IDs of ···tags
    - Do NOT add Markdown formatting unless present in source
    - Preserve original line breaks within the paragraph when meaningful
3. **Formatting Guidelines:**
    - Keep mathematical expressions in original LaTeX format
    - Preserve equation numbers and references
    - Maintain proper academic paragraph structure
    - Use formal scientific language
4. **Glossary:**
    - 机器学习 => machine learning
    - 深度学习 => deep learning

Looking at the input text, I notice: - There are no LaTeX commands or mathematical formulas in this text - There are no citation commands - There are no

…tags in the input - The text is about neutron capture event imaging, which is a scientific topic - The text appears to be a single paragraph (though it might be multiple paragraphs in the original document)

Wait, the user instruction says "Translate from Simplified Chinese to English" and provides text that appears to be a single paragraph. But the critical requirements mention preserving …tags. Let me re-read the input carefully.

The input is: "Neutron capture event imaging, as a novel imaging technique, has the potential to substantially enhance theresolution of the existing imaging system. This study provides a measurement method for neutron capture event-distribution and multiple reconstruction methods for super-resolution imaging. This technology can reduce thepoint spread function of the imaging system through single neutron detection and event reconstruction, therebysignificantly improving the imaging resolution. In the experiment, a single neutron detection experiment wasconducted using the highly practical and efficient 6LiF -ZnS scintillation screen, relying on the cold neutronimaging device on the research reactor. In milliseconds of exposure time, a large number of weak light clustersand their distribution inside the scintillation screen were recorded frame by frame, completing single neutrondetection. In the calculation, several reconstruction algorithms were proposed. The location of the neutron cap#2;ture event was calculated by the several processing methods such as noise removal, filtering, spot segmentation,contour analysis, and local positioning. The proposed algorithm achieves higher imaging resolution and fasterreconstruction speed. Combining single neutron detection experiments and reconstruction calculations, singleneutron super-resolution imaging was finally achieved. The results show that the resolution of the 100 μm thick6LiF -ZnS scintillation screen can be improved from 125 microns to 40 microns. It indicates that the proposedsingle-neutron detection and calculation method is an effective technical route, which can significantly improvethe imaging resolution."

This appears to be already in English, not Chinese. Let me check if there' s any Chinese text that I missed. The user message starts with "Neutron capture event imaging…" which is English.

Wait, maybe the user made a mistake and pasted the English text instead of Chinese? Or perhaps this is a test to see if I can handle the case where the input is already in English?

Let me re-read the user' s message more carefully. The user says "Translate from Simplified Chinese to English" but the text provided is in English. This is confusing

Full Text

Preamble

Single Neutron Super-Resolution Imaging Based on Neutron Capture Event Detection and Reconstruction

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Neutron capture event imaging, as a novel imaging technique, has the potential to substantially enhance the resolution of existing imaging systems. This study provides a measurement method for neutron capture event distribution and multiple reconstruction methods for super-resolution imaging. This technology can reduce the point spread function of the imaging system through single neutron detection and event reconstruction, thereby significantly improving imaging resolution. In the experiment, single neutron detection was performed using the highly practical and efficient 6LiF-ZnS scintillation screen, utilizing the cold neutron imaging device on a research reactor. With millisecond-level exposure times, a large number of weak light clusters and their distribution inside the scintillation screen were recorded frame by frame, enabling single neutron detection. In the computational phase, several reconstruction algorithms were proposed. The location of each neutron capture event was calculated through processing methods including noise removal, filtering, spot segmentation, contour analysis, and local positioning. The proposed algorithm achieves higher imaging resolution and faster reconstruction speed. By combining single neutron detection experiments with reconstruction calculations, single neutron super-resolution imaging was finally achieved. The results show that the resolution of the 100 µm thick 6LiF-ZnS scintillation screen can be improved from 125 microns to 40 microns, indicating that the proposed single-neutron detection and calculation method is an effective technical route for significantly improving imaging resolution.

Keywords: Neutron capture reaction, Super-resolution imaging, Weak light detection, Event reconstruction

Introduction

Thanks to the development of neutron sources and advances in neutron detection technology [1-4], neutron imaging can attain exceptional spatial resolution and time resolution, rendering it extensively applicable across numerous fields [5-7]. Nowadays, advanced imaging methods and detection technologies continue to emerge [8-14]. Various neutron scintillation screens, scintillating fibers, CCD/CMOS detectors, neutron imaging plates (NIP), and other key imaging devices have achieved advanced performance [15-20]. It has become very difficult to physically modify imaging instruments to continue improving the resolution of imaging systems. However, with continuous technological development, the demand for higher detection accuracy and more precise detection targets is increasing, urgently requiring neutron imaging technology to move toward higher resolution.

Typically, the neutron imaging detection system mainly consists of a neutron scintillation screen, mirror, lens group, and CCD or CMOS camera [21-25]. Conclusions drawn from modern information optics theory indicate that in a spatially invariant linear system, any imaging device functions as a spatial filter. These devices contribute to point diffusion and blur the image, with the blurring effect of the scintillation screen being particularly critical [26, 27]. Inside the scintillation screen, neutrons react with neutron converters such as 6LiF, after which particle transport and fluorescence transport occur. These transport processes contribute to a strong point spread effect in imaging [28]. The neutron scintillation screen has become the main factor restricting imaging resolution and is a key component for improving the quality of neutron imaging [29].

Research on improving imaging system resolution has become relatively mature [30], covering device characteristics and various imaging methods in hardware [31-34], and various image processing methods in computation [5, 35-37]. Existing research mainly focuses on high-resolution thin screens (50 µm 6LiF-ZnS, or thinner Gd_2O_2S screens [38, 39]), or doped (Gd/B) neutron-sensitive MCPs [40]. In terms of experimental methods, single neutron detection and reconstruction is a novel imaging approach that can obtain high-resolution neutron images through experimental and computational methods without changing the original device, representing a very meaningful technical route.

This work explores a super-resolution imaging method based on single neutron detection and reconstruction that can detect single neutrons and remove blur caused by point diffusion.

Materials and Methods

Theory

In neutron radiography, incident neutrons react with 6LiF in the scintillation screen and excite fluorescence in ZnS. Typically, conventional imaging is achieved by exposing the scintillation screen, integrating the fluorescence distribution $I(t,s)$ over time:

$$I(s) = \int_{\text{Exposure-time}} I(t,s)dt$$

where $I(t)$ represents the image (light intensity distribution), s is the spatial position, and t is the exposure time.

This work achieves single neutron detection by detecting the fluorescence spots generated by neutron reactions one by one. The precise position of the incident neutron is then calculated through a reconstruction algorithm. Using a point with a precise location to replace the fluorescent Airy spot (light clusters) can reduce point diffusion and blurring in imaging. Finally, a large number of light point distributions are added together to form a higher-resolution neutron image.

Theoretically, single neutron detection is equivalent to the time differential of photon distribution $I(t,s)dt$. If these are directly superimposed, the resulting image is equivalent to traditional imaging $\int I(t,s)dt$. If they are superimposed after reconstruction $P(I(t,s)dt)$, super-resolution imaging can be achieved:

$$I_{\mathrm{HR}}(s) = \int_{\text{All-exposure-time}} P[I(t,s)dt]$$

where $I_{\mathrm{HR}}(s)$ represents the high-resolution image, and $P(\cdot)$ represents the reconstruction process.

Although this method can effectively achieve super-resolution imaging, it also places higher demands on detection technology and reconstruction algorithms. Experimentally, to detect a single event, the detection system must obtain a distinguishable weak light signal above intrinsic noise. Computationally, every event in each frame must be extracted and calculated. These large numbers of neutron events consume significant computational resources and time, necessitating improved algorithm efficiency. For weak light sources, the main challenges are experimental detection and positioning calculations, with distinguishing noise from weak light signals being the most critical aspect. Algorithms still need improved discrimination for noise.

Experiment

The most basic task to be accomplished in this experiment is to detect single neutron events. To measure each neutron radiation capture event individually under a continuous neutron beam, the fluorescence produced by the event and its spatial distribution must be measured separately. The spatial distribution of fluorescence is the data basis for both traditional imaging and super-resolution imaging. On one hand, the fluorescence distribution can be directly superimposed during data processing to obtain an image equivalent to conventional integral imaging. On the other hand, the detection results of single neutrons can be processed to achieve super-resolution imaging.

Single neutron detection and reconstruction is the guiding principle of the experiment, as shown in Figure 1 [Figure 1: see original paper]. (I) As shown in Figure 1(a), traditional imaging detects all neutrons within one exposure time, equivalent to time integration. Each Gaussian-like spot overlaps with others, eventually forming a blurred image. (II) As shown in Figure 1(b), single neutron detection aims to detect neutrons one by one, obtaining each individual spot distribution. If reconstruction is not performed, directly overlapping all spots is equivalent to the traditional imaging method. (III) As shown in Figure 1(c), single neutron super-resolution imaging aims to reconstruct the precise position of each neutron event spot by spot. By superimposing the reconstructed points with small-scale distribution (pixel-level), the spatial resolution of imaging can be significantly improved.

The measurements were conducted at the Cold Neutron Radiography Facility (CNRF) located at the C1 beam tube of the China Mianyang Research Reactor (CMRR). The neutrons emitted from the C1 beam tube have a cold neutron spectrum with a characteristic wavelength of 0.26 nm (approximately 0.121 eV). The neutron flux can reach 3.41×10^8 $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and the neutron flux at the sample position can reach 8×10^6 $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [41]. A variety of collimation ratios (tube length and aperture size) are available, and the aperture size used in this work was ϕ 10 cm. The main components of the neutron imaging instrument include a 6LiF–ZnS scintillator screen, mirror, optical lens group, image intensifier, and sCMOS camera. The Cold Neutron Radiography Facility (CNRF) and its imaging system are shown in Figure 2 [Figure 2: see original paper] [42].

The 6LiF–ZnS scintillation screen used at CNRF is also the most widely used and cost-effective neutron scintillation screen. Aluminum with a small cross-section is used as the base material of the scintillator screen, where the scintillator material with a thickness of 100 µm is coated. The scintillator screen is composed of neutron converter material 6LiF, fluorescent material ZnS(Ag), and binder epoxy resin in a mass ratio of 1:2:1.29. The overall density is 2.845 g/cm^3. The typical size of 6LiF and ZnS particles is about 1.5 µm–5 µm. The characteristic wavelength of the fluorescence spectrum is 450 nm, and the fluorescence decay time is 200 ns.

The camera used is the ANDOR iStar-sCMOS, which provides high resolution and high frame rate measurements. The camera can capture 12-bit or 16-bit images with an image array size of 2560$×$2560. The camera can read out images at 50 fps frame rate with full-frame resolution and 16-bit depth. An MCP is installed in the iStar-sCMOS camera as an image intensifier, which can provide a maximum gain of 4096 times, facilitating the detection of weak fluorescence. The MCP has a peak QE of up to 50% and spectral coverage from 120 nm to 1100 nm. The MCP uses P46 phosphor with a light decay time of 200 ns (2 ms for P43), which is the main limitation of the optical inter-frame time (300 ns). Importantly, the optical resolution limit of the MCP (P46 phosphor) produced by Andor is 35 µm.

When collecting images, the field of view size was adjusted to 27 mm$×$27 $mmtocovertheentiresample.Thesamp$ pixels for a higher detection frame rate. The acquisition mode was 12-bit low noise mode. To detect the light spots generated by single neutrons while avoiding stacking of light spots as much as possible, the exposure time of the detector was set to 2 ms. After cooling the camera sensor to 0°C, 190,000 images were collected. After the test was finished, the beam aperture was closed, and 5,000 dark field images were acquired for noise removal.

Reconstruction Method

In theory, each interaction on the scintillation screen material produces a star-shaped spot of light. In the experiment, the light spots produced by each capture reaction are recorded under very short exposure times (millisecond level). In reconstruction, the position of each light spot is calculated and a value is assigned to the corresponding pixel. Reconstructing each nuclear event, every frame, and eventually stacking all frames enables high-resolution imaging. Each reconstruction calculation is for a single event, transforming the imaging technique from a frame-based system to an event-based system.

In the task of single neutron super-resolution imaging, the key steps of the reconstruction algorithm are to: (i) process image noise and extract fluorescence signals; (ii) calculate the location of neutron capture events and reduce the point diffusion effect produced by the imaging device. Ultimately, single neutron detection combined with reconstruction enables super-resolution imaging. The schematic diagram of its principle is shown in Figure 3 [Figure 3: see original paper].

In this work, four advanced algorithms are proposed and reconstruction results are presented. The first is an improved centroid algorithm based on existing methods, and the remaining three are median filter centroid algorithm, median filter extremum algorithm, and Gaussian filter extremum algorithm. A sketch of the calculation process is shown in Figure 4 [Figure 4: see original paper].

Compared with the existing centroid algorithm (Figure 4a), these algorithms have greater advantages in noise discrimination, and the calculated reconstructed images are more credible.

The calculation steps of the centroid algorithm are as follows (Figure 4b): subtracting noise background, spot segmentation, contour morphology analysis, and centroid calculation. In denoising, the image measured in dark field can be used to remove fixed noise, leaving only random noise. In spot segmentation, a threshold is set to eliminate random noise and low SNR light spot signals, after which each spot area is segmented and processed. In contour analysis, the position, area, perimeter, and other morphological features of contours are found and counted, and the relationship between parent and child contours is determined. In centroid calculation, the area and circumference of the contour can be used as conditions to remove low SNR signals and noise. Then the centroid position of the light spot is calculated to obtain a high-resolution image. Compared with the traditional method that directly calculates the spot centroid, this method can remove noise more thoroughly and reconstruct a super-resolution image with higher credibility.

The median filter centroid algorithm is similar to the centroid algorithm (Figure 4c). The difference is that median filtering is added after subtracting the noise background, where the filter kernel covers a radius of 3 pixels. Random noise in the image is close to the signal in gray value and similar to peak-shaped signals in shape, but the noise distribution range is smaller. The function of median filtering is to eliminate random noise similar to the signal. The advantage of median filtering is that it can remove noise with less signal loss. However, its disadvantage is that it changes the signal distribution and flattens the peak of the spot, which may change the centroid position.

The median filter extremum algorithm and Gaussian filter extremum algorithm are faster reconstruction methods (Figure 4d and Figure 4e). The calculation steps of these two algorithms are: subtracting noise background, median/Gaussian filtering, spot segmentation, and local extreme value calculation. Compared with the centroid algorithm, the extremum algorithm has less computation, faster reconstruction speed, and better noise reduction effect.

The addition of median filtering and Gaussian filtering operations can solve two problems. First, for the amount of data from "a large number of images × hundreds of light spots," the faster algorithm obviously has more potential for development. Direct filtering calculation of the entire image is faster than analyzing the morphological characteristics of light spots one by one. Second, in weak light detection such as neutron event imaging, noise elimination is an important task. Although weak noise with low gray values can be removed by thresholding, there are still many noises with large gray values but small areas (compared to signal gray and area) in weak light detection. It is difficult to remove these signal-like noises using the centroid algorithm. However, the operation of filtering and threshold combination can eliminate noise with large gray value but small area, and better distinguish between noise and signal. Compared with median filtering, Gaussian filtering can reduce the gray value of noise to a greater extent and further enhance signal-noise discrimination ability.

Results and Discussion

Experimental Results and Evaluation

When the reactor power was near 10 MW, 1.9×10^5 images and 5×10^3 background images were collected, totaling about 1.3 Tb. One of the original images is shown in Figure 5 [Figure 5: see original paper]. The raw data contains light spots produced by neutron capture events, as well as a large amount of noise. The image noise obtained by the CMOS sensor is mainly divided into random noise and fixed pattern noise.

Fixed pattern noise is mainly caused by reset voltage deviation, which results from factors such as MOS FET threshold voltage deviation in the pixel, gain deviation of the source follower, and gain and bias of the column amplifier. This is a non-transient spatial noise that can be eliminated by multi-frame averaging. The average noise value of 5000 background images can be used to eliminate fixed pattern noise to a certain extent.

There are many sources of random noise, such as power voltage fluctuation, substrate coupling between CMOS sensor and peripheral devices, and reset and readout processes of pixel transistors. It mainly includes shot noise, dark current noise, transfer noise, reset noise, flicker noise (1/f), etc. The spatial distribution of random noise is not fixed, making it difficult to remove directly. It can be distinguished based on gray value and contour features in the reconstruction algorithm, such as using the morphological analysis step in the centroid algorithm (Figure 4b) to analyze area, perimeter, shape, and other characteristics of light spots.

To compare the effects of neutron event imaging, traditional integral imaging results need to be obtained. By subtracting the multi-frame background average from the original image data and then setting a threshold to remove low gray value noise, integral imaging with 2 ms exposure was obtained. After superimposing 1.9×10^5 frames, the traditional integral imaging result is obtained, as shown in Figure 6 [Figure 6: see original paper]. Figure 6 shows that the 125 µm stripes of the resolution grating are clearly visible at a field of view of 2.7 cm$×$2.7 cm, with four easily distinguishable peaks in the grayscale distribution map. For 100 µm stripes, it is difficult for the human eye to distinguish, and the gray distribution does not show ideal four peaks. Therefore, the resolution of the conventional method is considered to be 125 µm, and barely 100 µm.

In the image reconstruction calculation, the centroid algorithm, median filter centroid algorithm, median filter extremum algorithm, and Gaussian filter extremum algorithm were used to calculate the occurrence position of neutron capture events in 1.9×10^5 images, obtaining high-resolution images. The results of the super-resolution experiment are shown in Figure 7 [Figure 7: see original paper]. Analysis shows that the spatial resolution of the super-resolution image is significantly improved, with results summarized in Table 1 .

To more accurately evaluate the super-resolution effect of single neutron imaging, the image can be directly observed subjectively. Objectively, line pair gray analysis and modulation transfer function are used to evaluate the resolution improvement effect.

From the image results, the reconstruction results of the centroid algorithm in Figure 7(a)(b) can achieve a resolution of 50 µm. In gray analysis, 50 µm stripes can be clearly distinguished, while 40 µm stripes cannot be distinguished.

The median filtering centroid algorithm (Figure 7(c)(d)) and median filtering extremum algorithm (Figure 7(e)(f)) have similar effects. Both algorithms can achieve resolutions between 50 µm and 40 µm. In grayscale analysis, 50 µm stripes can be clearly distinguished, and 40 µm stripes can be barely distinguished. The improvement in resolution shows that median filtering can eliminate more random noise. As median filtering changes the signal distribution, it can further reduce the effect of noise on neutron event discrimination. In addition, the extremum algorithm has faster reconstruction speed (5 times faster than the centroid algorithm in this experiment).

According to the reconstruction results in Figure 7(g)(h), the Gaussian filter extremum algorithm can achieve a resolution of 40 µm. The Gaussian filter extremum algorithm obtains the best resolution and fastest reconstruction by virtue of its excellent random noise reduction and its ability to maintain peaks constant.

Modulation Transfer Function (MTF) is an important optical system evaluation indicator that can be used to calculate resolution level. Although observing line pairs is the most direct and reliable method, MTF can still provide additional verification. Computationally, the edge-to-edge method was chosen for calculating the MTF curve. Due to the excellent performance of the Gaussian filter extremum algorithm, its reconstructed image is used as a representative of super-resolution. The MTF curves of the original and super-resolution images were compared, as shown in Figure 8 [Figure 8: see original paper]. The resolution of the images calculated from the curves at 50% and 10% MTF is shown in Table 2 .

At the same MTF, the super-resolution image has higher frequency line pairs, meaning the resolution level is also higher. The resolution obtained at 50% MTF, where the human eye is most sensitive, is 41.7 µm. The resolution obtained by directly observing the grayscale distribution of line pairs is 40 µm. Whether observing line pairs or analyzing MTF to assess resolution, the final results demonstrate that the experimental approach and reconstruction algorithm for single neutron imaging is an effective solution for greatly improving imaging resolution.

Algorithm Feature Mining

To more concretely demonstrate the functions and characteristics of the algorithms, a small area with high signal-to-noise ratio was extracted from the original image for independent calculation, as shown in Figure 9 [Figure 9: see original paper].

The specific calculation steps and processing effects of the centroid algorithm are shown in Figure 10 [Figure 10: see original paper]. (I) Most random noise in Figure 10(a) can be removed by setting threshold segmentation spots. According to Figure 10(b), many noises with higher gray values remain. To minimize loss of neutron signal, the threshold cannot be further increased to remove noise. (II) Contour feature discrimination is a feasible method for further processing. The contour features were calculated using the Suzuki85 boundary tracking algorithm as shown in Figure 10(c). (III) Neutron signals can be filtered out based on contour features. Finally, the distribution of pixel positions where neutron signals are located was reconstructed as in Figure 10(d).

The characteristic of the centroid algorithm is that it can analyze light spots one by one, performing processing based on shape, area, perimeter, and other image moment information. The centroid algorithm has many adjustable parameters, mainly including threshold parameters and spot image moment parameters. However, its disadvantage is that noise elimination is not effective and the computational amount is large.

The Gaussian filter algorithm can improve resolution from 125 µm to 40 µm. To more concretely demonstrate its functions and characteristics, the intermediate calculation results are given in Figure 11 [Figure 11: see original paper]. Through Gaussian filtering, random noise in Figure 11(a) was reduced and smoothed, obtaining the result in Figure 11(b). The distribution area of light spots with low SNR and random noise is generally smaller. Gaussian filtering can greatly reduce their gray scale, enabling better filtering. (II) Therefore, setting a lower threshold after Gaussian filtering can effectively segment out signal spots, as shown in Figure 11(c). (III) Finally, the single-pixel distribution of the neutron signal was reconstructed, as shown in Figure 11(d).

The median filtering extremum algorithm and Gaussian filtering extremum algorithm proposed in this work can process pixel clusters frame by frame rather than one by one. The reconstruction speed of these two methods is faster. Additionally, it is crucial to deal with noise generated by MCP and CMOS in super-resolution imaging. The Gaussian filter extremum algorithm can effectively distinguish signals and noise, reduce signal loss, and does not change the peak position of the light spot. In this experiment, the resolution can be improved from 125 µm to 40 µm, representing a 68% improvement.

Conclusion

This work proved the principle of super-resolution imaging based on neutron capture events. A super-resolution imaging instrument was installed on the cold neutron source of the CMRR. The commonly used 6LiF–ZnS scintillation screen, MCP, and CMOS were used in the hardware. The weak light signal produced by neutron capture events was successfully detected, and super-resolution imaging was achieved using a reconstruction algorithm.

Super-resolution imaging based on neutron capture events requires processing large amounts of image data, so computing time is an important factor. The median filtering extremum algorithm and Gaussian filtering extremum algorithm can process pixel clusters frame by frame rather than one by one. The reconstruction speed of these methods is faster. Additionally, dealing with noise generated by MCP and CMOS is crucial in super-resolution imaging. The Gaussian filter extremum algorithm can effectively distinguish signals from noise, reduce signal loss, and does not change the peak position of the light spot. In this experiment, the resolution was improved from 125 µm to 40 µm, representing a 68% improvement.

This work provides solutions both experimentally and computationally, proving that these solutions have better performance in methodology. If better resolution is pursued, it can be achieved with a smaller field of view, a thinner Gd_2O_2S scintillation screen, and a smaller MCP aperture. Neutron super-resolution imaging can significantly improve spatial resolution, which is attractive for many studies with non-destructive testing requirements. Non-destructive high-resolution testing will also promote more research and applications.

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Note: Figure translations are in progress. See original paper for figures.