10B-doped MCP detector developed for neutron resonance imaging at Back-n white neutron source

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Abstract

Neutron resonance imaging (NRI) has recently emerged as an appealing technique for neutron radiography. Its complexity surpasses that of conventional transmission imaging, as it requires a high demand for both a neutron source and detector. Consequently, the progression of NRI technology has been sluggish since its inception in the 1980s, particularly considering the limited studies analyzing the neutron energy range above keV. The white neutron source (Back-n) at the China Spallation Neutron Source (CSNS) provides favorable beam conditions for the development of the NRI technique over a wide neutron energy range from eV to MeV. Neutron-sensitive microchannel plates (MCP) have emerged as a cutting-edge tool in the field of neutron detection owing to their high temporal and spatial resolutions, high detection efficiency, and low noise. In this study, we report the development of a 10B-doped MCP detector, along with its associated electronics, data processing system, and NRI experiments at the Back-n. Individual heavy elements such as gold, silver, tungsten, and indium can be easily identified in the transmission images by their characteristic resonance peaks in the 1-100 eV energy range; the more difficult medium-weight elements such as iron, copper, and aluminum with resonance peaks in the 1-100 keV energy range can also be identified. In particular, results in the neutron energy range of dozens of keV (Aluminum) are reported here for the first time.

Full Text

Preamble

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Neutron resonance imaging (NRI) has recently emerged as an appealing technique for neutron radiography. Its complexity surpasses that of conventional transmission imaging, as it imposes stringent demands on both the neutron source and detector. Consequently, the progression of NRI technology has been sluggish since its inception in the 1980s, particularly given the limited studies analyzing neutron energies above the keV range. The white neutron source (Back-n) at the China Spallation Neutron Source (CSNS) provides favorable beam conditions for developing the NRI technique across a wide neutron energy range from eV to MeV.

Neutron-sensitive microchannel plates (MCPs) have emerged as a cutting-edge tool in neutron detection owing to their high temporal and spatial resolutions, high detection efficiency, and low noise. In this study, we report the development of a 10B-doped MCP detector, along with its associated electronics, data processing system, and NRI experiments at Back-n. Individual heavy elements such as gold, silver, tungsten, and indium can be easily identified in transmission images by their characteristic resonance peaks in the 1–100 eV energy range; the more challenging medium-weight elements such as iron, copper, and aluminum with resonance peaks in the 1–100 keV energy range can also be identified. In particular, results in the neutron energy range of dozens of keV (aluminum) are reported here for the first time.

Keywords: Neutron resonance imaging; 10B doped MCP detector; White neutron source; Sample nuclide identification

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Introduction

Neutron resonance imaging (NRI) is a nondestructive technique for detecting the nuclide composition and distribution in samples [1–4]. Compared with traditional X-ray and neutron transmission imaging, it offers the advantage of nuclide identification and can provide more comprehensive information regarding the samples. NRI has broad application prospects in materials science, archaeology, the nuclear industry, and other fields [5–9]. This technique analyzes the nuclide composition and distribution in samples by utilizing the characteristic resonances of neutron interactions.

Imaging quality heavily relies on the neutron source and the performance of the neutron detector. Specifically, the detector must achieve high temporal and spatial resolutions, a wide neutron energy response range, and high detection efficiency to obtain energy-counting rate spectra at each spatial pixel. The neutron source must have a broad energy spectrum, high flux, and good temporal resolution. Therefore, the NRI technique presents significant challenges, particularly for medium-energy neutrons ranging from hundreds of eV to hundreds of keV. Current neutron detectors have low detection efficiency in this energy range, which complicates the development of NRI to cover light to heavy elements.

Many neutron detector types, such as scintillator arrays, multi-pole photomultipliers, and position-sensitive gas detectors, are limited by their detection efficiency and spatial resolution, and thus cannot fully meet the requirements of NRI [10–14]. CCD/CMOS cameras with gated time windows have been used in NRI to identify nuclides with resonance peaks in the eV energy range [15–17]. However, their low detection efficiency and poor signal-to-noise ratio hinder attainment of favorable results above the keV range. Neutron-sensitive microchannel plates (nMCPs) have excellent properties including good temporal and spatial resolutions, irradiation resistance, high gain, and low noise. They have been developed for general neutron imaging, including thermal neutron imaging, and are considered suitable for the NRI technique owing to their potential for high neutron detection efficiency [18, 19]. The most commonly used nMCPs are boron- and cadmium-doped detectors. The nMCP matched with Timepix3 electronics has been used in NRI and demonstrated good performance in the ultra-thermal neutron energy region [20–24]. However, it is difficult to identify nuclides with resonances above the keV range. As an analog-digital hybrid chip, the irradiation resistance of Timepix3 is affected by high-flux neutron sources.

A suitable neutron source with good time resolution and high flux covering a large energy range is rarely found. The white neutron source (Back-n) at the China Spallation Neutron Source (CSNS) was built in 2018 and serves as a multi-purpose platform to support nuclear data measurements, detector calibrations, and irradiation-effect tests [25–28]. Back-n exhibits the advantages of a wide energy spectrum (0.5 eV–200 MeV), high flux (2$\times10^{7}$ n/cm^2/s at

55 m from the target with Φ60 mm spot), low background, and good temporal resolution (<1%), which provide favorable beam conditions for exploiting the NRI technique over a wide neutron energy range from eV to MeV [29–32].

This study reports the development of a 10B-doped MCP (called B-MCP hereafter) detector system that includes crossed anode strips, readout electronics, and data processing. Anode strips are suitable for NRI owing to their good performance in terms of irradiation resistance, spatial resolution (100 µm), and counting rate (10 MHz/cm^2). Several NRI demonstration experiments were conducted at Back-n to identify various elements with resonances in different energy regions, ranging from eV to dozens of keV, with performance exceeding that reported in literature.

II. Experimental Setup

The detector system mainly consisted of a B-MCP/MCP stack, crossed anode strips, a front-amplifier module (FAM), a vacuum chamber, readout electronics (including digitization modules (FDMs) and a data aggregation module (DAM)), and a data acquisition computer, as shown in Fig. 1 [Figure 1: see original paper].

The B-MCP/MCP stack, as the core part of the detector, was composed of one B-MCP and two conventional MCPs encapsulated in a ceramic fixture. The B-MCP was developed in cooperation with North Night Vision, and its main parameters are listed in Table 1 . It contained approximately 10 mol% 10B, which was incorporated via glass substrate doping, and the signal gain was approximately one order of magnitude lower than that of the conventional MCP, which is beneficial for neutron detection. A large gain in the B-MCP leads to an excessive amplitude range of neutron signals, which is not conducive to efficient acquisition of neutron events by the electronics. The MCP pores had a bevel angle of approximately 8° and were stacked in a V-shape of two adjacent MCPs to improve secondary electron efficiency and reduce ion feedback. The voltage ratio of the B-MCP and the MCPs was 2:3:3 to further reduce the B-MCP gain, that is, the neutron signal amplitude range.

The crossed strips consisted of diamond pads distributed on the surface layer of the PCB board. The pads were interleaved in both the X- and Y-directions, forming a sensitive area of 65$×65$mm^{2}$ with a total of 256 channels (128 channels in both the X- and Y-directions). The strip pitch in both directions was 0.508 mm with a 0.10 mm gap between adjacent pads. A schematic of this structure is shown in Fig. 2a [Figure 2: see original paper]. The gap between the exit surface of the MCP and the strip layer was 1.1 mm, allowing the electron cloud to "fire" multiple adjacent strips to facilitate localization of the neutron interaction point.

Primary signals were amplified and filtered by the FAMs before further processing, and the FAMs were packaged with the B-MCP stack inside a vacuum chamber to avoid noise. The physical objects of the package are shown in Fig.

2b [Figure 2: see original paper]. The electronics system was developed in collaboration with the University of Science and Technology of China (USTC). Eight FDM boards outside the chamber were responsible for waveform digitization of the amplified signals. The sampling frequency was set to 80 MHz to accommodate a signal pulse width of ~700 ns. The data were aggregated onto a DAM board for storage and offline analysis. The electronics system was triggered by a T0 signal from a proton beam monitor (a fast current transformer FCT on the accelerator) as the start time of the neutron flight, and the threshold was set to 50 fC to filter electronic noise and await the signal trigger. The sampling duration was set to 0.6 µs before and 1.0 µs after the signal trigger, and the waveform on each strip was recorded.

The experimental layout of the B-MCP detector at the Back-n white neutron source is shown in Fig. 3 [Figure 3: see original paper]. Eight FDM boards were assembled in the chamber to optimize space utilization and avoid direct beam irradiation. The surface of the B-MCP was approximately 76 m from the spallation target. The beam spot at the detector was Φ30 mm, which was smaller than the diameter of the B-MCP, allowing the neutron beam to completely pass through the sensitive area of the detector. The neutron flux was approximately 8.5×10^{5} n/cm^2/s, and the energy range was 0.5 eV–200 MeV [34]. The neutron pulse repetition rate was 25 Hz and had a double-bunch structure with an interval of 410 ns and a width of 60 ns for each bunch. This introduced an error of more than 10% in the temporal resolution of neutrons above the MeV range, whereas for neutrons below dozens of keV, this effect was less than 1% and could be ignored in the experiments.

III. Experiment Process and Data Analysis

An empty period of 6 µs after the T0 trigger was set to avoid data blocking in the electronic channels due to complex responses of MCP components to high-energy neutrons. Accordingly, the available energy range extended from 0.5 eV to approximately 0.5 MeV. The amplitude spectra of MCP dark counts and neutron signals were measured by increasing the voltage on the MCPs. Both the amplitudes of dark counts and neutron signals increased, and the two spectra gradually separated as the voltage increased. An appropriate voltage of 2400 V was selected to obtain a good neutron/dark count ratio, as shown in Fig. 4 [Figure 4: see original paper]. Certain large neutron signals were saturated at an ADC channel of approximately 3500 due to limitations in the electronics dynamic range. Conversely, certain small signals were mixed with dark counts and were difficult to separate because neutron signals have a significantly wide amplitude range due to the B-MCP gain. We set a second threshold at an ADC channel of approximately 900 to exclude dark counts and noise. Some small signals whose amplitudes could not be separated from dark counts will inevitably be lost. This reduces the overall detection efficiency but does not affect the trend and details of the neutron spectrum because the amplitude of neutron signals with energies below a few hundred keV is nearly independent of neutron energy.

Multiple adjacent channels are typically fired on the X and Y strips at each neutron event; a typical signal is shown in Fig. 5 [Figure 5: see original paper]. Normally, the signal amplitude in the middle channel is higher than those on both sides, conforming to the electron cloud distribution. Data analysis extracts the time-of-flight and hit positions of each neutron to plot the neutron energy spectrum and beam spot image. The stop time of neutron flight is obtained using the peak of unsaturated channels because the peak position has a stable amplitude; furthermore, unsaturated channels are always present, even in saturated cases. Peak deviations of more than two sampling points (approximately 25 ns) are considered different events within a sampling window, although such situations are significantly rare in the energy region below hundreds of keV. Both gravity and the center of the electron cloud distribution can provide spatial resolution better than 100 µm, which exceeds the width limit of the anode strips. However, this significantly reduces the counts on each pixel and is not conducive to neutron spectrum analysis for resonance imaging. Because the present efficiency of B-MCP is not sufficiently high, we used the central anode strip of the response strips in both the X and Y directions as the hit point, achieving a spatial resolution of 500 µm depending on the pitch of the anode strips.

Fig. 6a [Figure 6: see original paper] presents the neutron energy-count spectrum measured at the Back-n source for 7200 s after deducting dark counts and noise. The kinetic energy of neutrons can be calculated using Eq. (1):

En = (γ − 1)mnc2 (cid:112)1 − (v where v = Lf light/T OF .

The neutron flight length Lf light is 76 m from the neutron target to the surface of the B-MCP. The curve in Fig. 6a shows the response spectrum of the 10B doped in the B-MCP at the Back-n source. Numerous detailed peaks ranging from 0.5 eV to tens of keV arise from the intrinsic microstructure of the Back-n energy spectrum. The resonance peaks of certain nuclides such as 181Ta (~4.2 eV), 95Mo (~45 eV), 55Mn (~340 eV), and 56Fe (~28 keV) in the spallation target are marked. Fig. 6b presents the Back-n beam spot image measured by the B-MCP detector. The half-height, full-width profile of the image was fitted to a diameter of approximately 30 mm, which coincided with the beamline setting. The outer profile of the image corresponds to the size of the B-MCP, that is 56 mm in diameter. The energy spectrum and beam spot of the neutron source can be simultaneously obtained in a single measurement using a B-MCP detector. Moreover, with sufficiently high detection efficiency (or total counts), more detailed analysis can be performed on energy spectra in different spot areas or beam spots at different energy intervals. Here, the neutron energy-count spectrum and beam spot of Back-n are demonstrated to provide a comparison of data for the neutron resonance imaging experiments with samples presented in Sec. IV.

IV. NRI Experiments

The B-MCP detector can provide the position and energy information of each neutron event, allowing flexible data processing in resonance imaging experiments to efficiently obtain more valuable information. In this section, heavy elements including In, Au, Ag, and W with resonances in the eV energy region and medium-mass elements including Cu, Fe, and Al with resonances in the keV energy region were selected to study the resonance imaging performance of the B-MCP detector at the Back-n source. For a sample with unknown composition, there are two approaches for determining the nuclides and their distribution: (1) comparison of neutron energy-count spectra in the full image with and without a sample to determine nuclide components, then selecting neutrons in the resonance region for imaging to obtain the spatial distribution of the corresponding nuclide; (2) observing the sample distribution using total neutron transmission imaging, then analyzing neutron energy-count spectra at sample locations for nuclide composition. A combination of these two methods allows for significantly adequate compositional analysis of samples. In particular, for samples containing a small number of nuclides, the latter approach is more effective.

A. Nuclides with cross-section resonances in the 1–100 eV region

In the eV-energy region, four typical elements including Au, Ag, In, and W were selected, and their dominant cross-sectional resonances [35] with natural abundances are shown in Fig. 7 [Figure 7: see original paper]. These resonances are distributed in the energy range of 1–100 eV, in which the cross-sections of 197Au and 115In are approximately 30,000 barns, and the cross-sections of natAg and natW are approximately 10,000 barns, indicating strong resonance absorption of neutrons in this region. In addition, the B-MCP detector has relatively high detection efficiency in this region due to the larger cross-section of 10B, which is approximately a few hundred barns. Therefore, the identification and imaging of these nuclides in this energy region are relatively straightforward.

Fig. 8a [Figure 8: see original paper] presents the objects of four samples in different shapes with the same thickness of 1.0 mm. These samples were placed at the center of the neutron beam, 70 mm from the B-MCP detector, such that neutrons vertically passed through the sample plane. Using the aforementioned experimental conditions, the measurement was performed for 3 h and the total-transmission imaging of the samples was obtained, as shown in Fig. 8b [Figure 8: see original paper]. Initially, we compared the obtained total neutron energy-count spectra with and without these samples. The results show no apparent difference between these two spectra, and the strong resonance absorptions are invisible (the two identical spectra are the same as those in Fig. 6a), implying that nuclide composition cannot be determined first. The quantity of these samples was relatively small, and the large amount of data in the sample-free region served as a background to extract the resonance peaks of the samples. However, in the total-transmission images, the profiles of the four samples were clearly visible. The image underwent background subtraction and was normalized to comparison data without the samples. The brightness reflects the intensity of neutron absorption, that is, the amount of the sample. It is impossible to identify sample components in the total-transmission image without their shapes because the brightness value is related to both the cross-sections of the nuclides and their areal density on the pixels.

We selected neutron energy-count spectra from the sample areas and normalized them to comparison data to obtain ratio spectra with and without the samples, as shown in Fig. 9 [Figure 9: see original paper]. The peak clusters in the ratio spectra reflect nuclide species, and the intensity of the peaks reflects the areal density of the nuclides, which sufficiently corresponds with the primary and secondary peaks of the four nuclides, namely 115In, 197Au, natW, and natAg. These peaks act as fingerprints to identify the presence of nuclides in the samples. We selected energy regions with these characteristic peaks for full-image neutron resonance imaging. As shown in Fig. 9, the four samples of 115In, 197Au, natW, and natAg can be independently identified using spatial distribution. Each image was normalized and divided by a background image that selected the non-resonance-energy region adjacent to the dominant peak of the nuclide to represent each nuclide separately. This image processing was discussed in a previous article [17]. 115In and natW can be easily identified owing to their distinct and non-overlapping resonances at approximately 1.4–1.5 eV and 18.0–19.5 eV, respectively. However, the dominant peaks of 197Au and natAg overlap at approximately 4.5–5.5 eV, causing them to simultaneously appear during resonance-identification imaging. To distinguish between 197Au and natAg, we selected part of the 197Au peak at approximately 4.8–5.0 eV to exclude natAg, as well as the secondary peaks of natAg at approximately 16.0–16.5 eV. This reduces image statistics, which can be solved by using longer measurement durations. In the absence of coexistence of 197Au and natAg, the imaging effect using dominant peaks was better. Nuclides with cross-sectional resonances in the eV energy regions can be easily identified and imaged using the B-MCP detector at the Back-n source with the advantage of strong resonance peaks.

B. Nuclides with cross-section resonances in the 1–100 keV region

Fig. 10 [Figure 10: see original paper] presents the cross-sections of natCu, natFe, and 27Al over a wide energy range from 100 eV to 500 keV [35]. The resonance peaks were mostly located in this region, and the peak heights were nearly two orders of magnitude lower than those of the heavy elements in Sec. IV A, which complicates nuclide resonance imaging due to reduced imaging contrast. Moreover, the peaks were significantly narrow, which further reduces the cross-sectional integral. Because the widths of resonance peaks in this energy region were comparable to the spacing between the two neutron bunches, the pulse structure introduces approximately 14%–50% of undesired neutrons into the selected resonance ranges [17]. This effect can be resolved with sufficient statistics by using energy-resolved processing, in which the double-bunch structure can still be used to identify these elements by selecting energy-resolved neutrons [36].

Fig. 11a [Figure 11: see original paper] shows Cu, Fe, and Al samples with the same thickness of 10 mm. Fig. 11b shows the neutron transmission image in the full-energy region, in which all constituents are clearly visible. The Cu and Fe samples exhibited high and similar brightness values due to their strong neutron absorption. The Al area is the darkest because its cross-sectional integral over the full-energy region (including nucleus number density) is smaller than those of Fe and Cu, as illustrated in Fig. 10. As expected, individual nuclides could not be identified via total-transmission imaging.

Resonance imaging analyses were performed to identify the samples and their spatial distribution using the same method described in Sec. IV A. The ratio spectra with and without the samples in the sample areas are shown in Fig. 12 [Figure 12: see original paper]. The peak clusters in the ratio spectra reflect nuclide species, which sufficiently correspond with the resonances of the sample nuclides natCu, natFe, and 27Al. We selected energy regions with these characteristic peaks for full-area resonance imaging, as shown in Fig. 12. The three samples of Cu, Fe, and Al could be independently identified with spatial distribution, although not as well as the samples in the eV energy region. This is partly because the intensity and width of these resonances are not large and because the detection efficiency of 10B in the keV region is reduced. In particular, for the Al sample, three wider resonances at approximately 35, 90, and 150 keV were selected instead of the highest resonance. They have a cross-section of only 20 barns, but the signal-to-noise ratio is significantly better than that of a higher but narrow peak. Nuclides with cross-sectional resonances in the keV energy regions can be identified and imaged at the Back-n source with good signal-to-noise ratio of the B-MCP detector. One advantage of the B-MCP detector over other methods such as CMOS/CCD cameras is that it can simultaneously obtain multiple resonances of nuclides for superimposed imaging to improve signal-to-noise ratio and resonant image contrast.

Ideally, B-MCP can provide neutron energy-count spectra at each pixel for more detailed imaging analysis, or the charge distribution of each neutron for higher spatial resolution beyond the strip width. This requires a sufficiently large amount of data with at least one million counts per pixel. Therefore, the detection efficiency of B-MCP is a critical factor for high-quality resonance imaging. A sufficiently large amount of data can also be used to resolve the double-bunch structure of neutron pulses at Back-n, which is beneficial for analysis and imaging of nuclides with resonances above keV. Other aspects of the B-MCP that need consideration include the n/γ efficiency ratio and control of the B-MCP gain, that is, the signal amplitude range. In this study, the images of nuclides with resonances in the keV region demonstrate better results than those obtained by other methods, such as CMOS/CCD cameras, although the detection efficiency of the developed B-MCP is not sufficiently high. This indicates the great potential of the B-MCP detector for achieving good NRI results for most nuclides across a wide energy region from eV to MeV on a suitable white neutron source.

V. Summary and Perspectives

A B-MCP detector system was successfully developed for NRI applications, as well as neutron energy-resolved imaging and spatially resolved neutron spectrum measurements. The MCP stack combining B-MCP and conventional MCPs, readout electronics, and data analysis system have been working sufficiently, and several NRI demonstration experiments were conducted at the Back-n white neutron source. For heavy-element samples such as Au, Ag, In, and W in the 1 eV–100 eV energy region and for medium-element samples such as Cu, Fe, and Al in the 1 eV–100 keV energy region, the experiments achieved good nuclide identification and imaging resolution of 500 µm. In particular, results related to the neutron energy range of dozens of keV were reported for the first time.

To further expand the NRI technique to the neutron energy range of 100 keV to 10 MeV for identifying light elements, the detection efficiency and readout electronics must be improved to handle narrower peaks and significantly high instantaneous data rates. Higher detection efficiency also facilitates analysis of sufficient data to obtain better image resolution using the center of gravity method; for example, approximately 100 µm, which exceeds the width limit of the anode strips. A new version of the B-MCP detector with higher 10B doping and faster electronics is under development.

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