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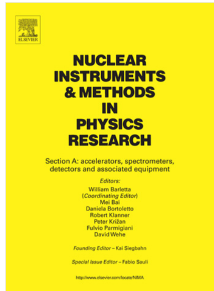

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Measurement of the energy of fast neutrons in the presence of gamma rays using a NaI(Tl) and a plastic scintillator

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A B S T R A C T

In many radiological laboratories, the energies of fast neutrons are very important for radiation diagnostics. In this paper we propose a method based on NaI and plastic scintillation (PS) detectors that measures the fast neutrons. The PS detector is sensitive to both gamma rays and fast neutrons. The NaI(Tl) detector is only sensitive to gamma rays. By subtracting the gamma information from the neutron–gamma mixed energy spectrum, pure neutron radiation information is obtained. Then, applying an unfolding method, the energy distribution of the fast neutron is generated. To verify this method, an experiment measuring the energy of monoenergetic neutrons was performed with the result confirming the effectiveness of this method.

Keywords:

Fast neutron detection; NaI(Tl) scintillation detector; Plastic scintillation detector; Gravel algorithm.

1. Introduction

The measurement of fast-neutron energies is an important procedure in radiation monitoring and diagnostics. With the wide use of neutron detection technology in many fields such as nuclear physics research, nuclear technology applications, and radiation protection, fast-neutron energy is a key physical quantity14[1]. There are two main difficulties associated with this procedure: as the neutron is not electrically charged, the measurement must involve inherently the neutron reaction products; moreover, neutron and gamma rays often coexist, so the influence of gamma rays must be considered[2][3].

In the last decade, neutron detection technology has advanced, although extracting the energy spectrum of neutron radiation remains a challenge.

Common devices used in neutron-energy measurements include Bonner spheres[4] and organic scintillation detectors[5]. Bonner spheres normally include tens of polyethylene spheres of different diameters usually ranging from 2 inches to 12 inches[6][7]. Because of the larger numbers and the size of polyethylene spheres, the Bonner spheres usually takes up a large space and are complicated to use and unsuitable in some small narrow spaces. Organic scintillators usually refer to either liquid or plastic scintillators. Both fast neutrons and gamma rays are detected by organic scintillators. Therefore, pulse-shape discrimination (PSD) of neutron and γ-rays is performed when using organic scintillators for detecting fast neutrons. The PSD needs a special scintillator to achieve the objective. Additionally, being both inflammable and toxic, the liquid scintillator is not able to be used in some workplaces. Recently the PSD has been applied in plastic scintillation detector successfully. However, PSD techniques usually need more complex electronics than multi-channel, which is more susceptible to environmental impact. And in some workplaces such as reactors, where the environment is complex and the ambient temperature is changing, the PSD method may fail.

In this paper, we propose a different method based on a NaI(Tl) scintillation detector and a plastic scintillation (PS) detector to measure the energy spectra of fast neutrons. First, the gamma energy spectrum is measured with the NaI(Tl) scintillation detector. At the same time, the mixed energy deposition spectrum of gamma rays and neutrons is measured using the PS detector. The second step involves calculating the incident gamma-ray spectrum by unfolding the gamma-ray spectrum obtained by the NaI detector and computing the gamma-ray pulse-height spectrum of the PS detector. The next step involves extracting the gamma ray part from the mixed energy deposition spectrum to arrive at the pure neutron deposition spectrum. Lastly, by unfolding the neutron deposition spectrum using the Gravel algorithm, the neutron energy spectrum is produced.

2. Method and materials

2.1. Detection system

The detection system includes a NaI(Tl) detector, a PS detector, and the electronics system. The NaI(Tl) detector (Model CH281, HAMAMATSU Corp, Japan) has a NaI(Tl) scintillator that is cylindrical in shape of dimension Φ50 ×50mm. Similarly, the PS detector (EJ 299-33A, Eljen Technology, Sweetwater, TX) has a cylindrical scintillator of the same size. The electronic systems for these independently-designed detectors include amplifier, ADC, FPGA, and a power management unit. A schematic of the electronics is shown in Fig. 1. To protect the scintillator and circuit, and for ease in transporting, a metal shell was especially designed for the whole detection device (Fig. 2).

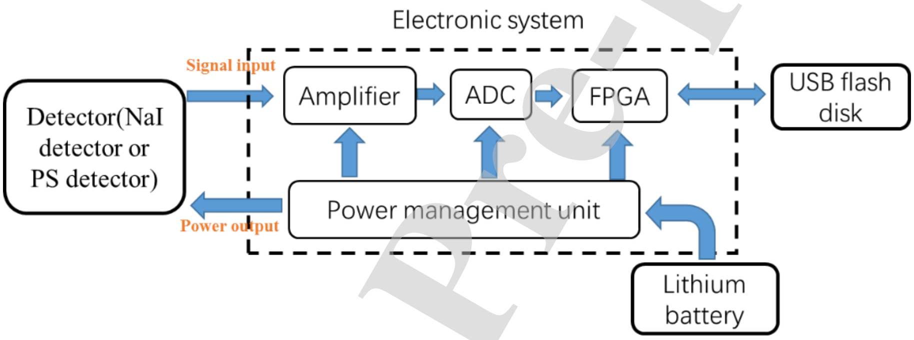

Fig. 1. Electronic block diagram of detection system.

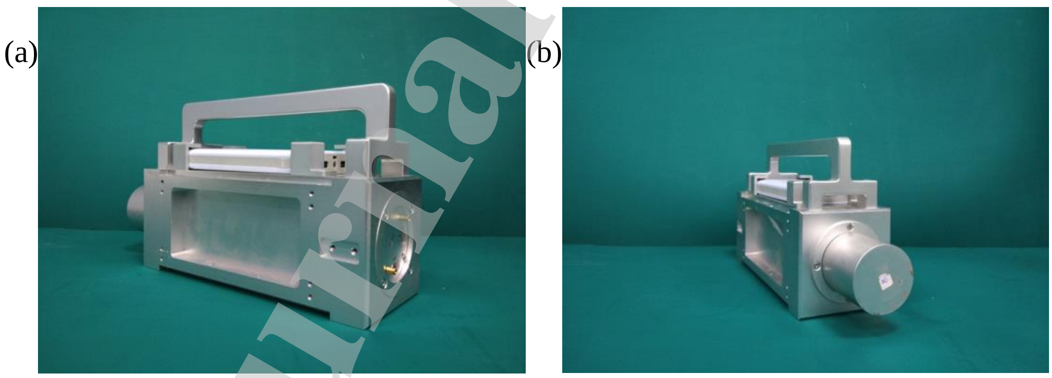

Fig. 2. Actual detection system: (a) PS detection system; (b) NaI(Tl) scintillation detection system.

2.2. Method

In the method (Fig. 3), two types of scintillation detectors, NaI(Tl) and plastic, were used. The NaI(Tl) scintillator has a very small neutron reaction cross, and hence seldom interacts with fast neutrons. The pulse-height spectrum obtained from NaI(Tl) almost only contains gamma-ray information. The plastic scintillator can detect simultaneously fast neutrons and gamma rays.

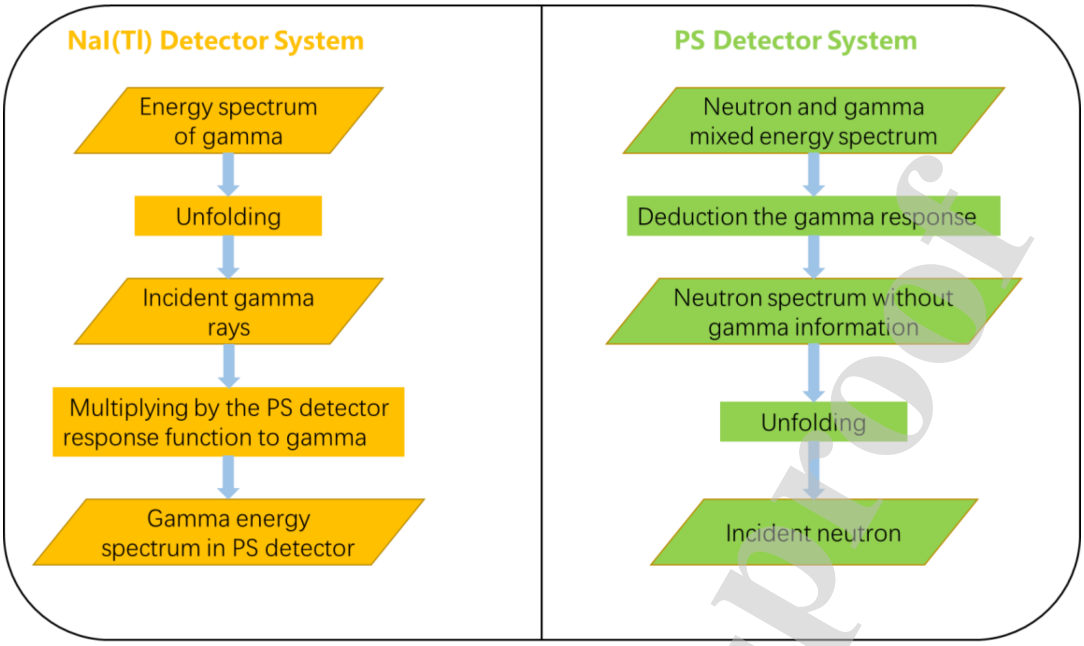

Fig. 3. Flow chart of the method

With the NaI detector being only sensitive to gamma rays, the incident gamma-ray energy is determined by unfolding the pulse-height spectra detected by the NaI(Tl) detector. Then, multiplying the incident gamma energy by the response function of the PS detector to gamma rays yields the energy deposition spectrum of incident gamma rays in the PS detector. Next, the gamma pulse-height spectrum is subtracted from the mixed energy deposition spectrum to obtain the neutron energy deposition spectrum. Finally, unfolding the neutron energy spectrum, the incident neutron energy is obtained.

2.2.1. Unfolding method

The unfolding procedure includes unfolding gamma rays and neutron. Mathematically, both are the same and use the same algorithm. The response of the scintillation detector to gamma rays or neutron is described using the response matrix R. The pulse height spectrum (PHS) of the differential energy spectrum $\Phi_E(E)$ is described by the linear equation [8]

$$N_i = \int R_i(E)\Phi_E(E)dE, \quad (1)$$

where N_i is the number of counts in channel i of the PHS (i=1,…,n, n being the number of channels), and $R_i(E)$ the scintillation detector response of channel i to a particle of energy E. Equation (1) is convenient as N_i reduces to the discrete form ready for computation,

$$N_i = \sum_j R_{ij} \Phi_j, \quad (2)$$

where R_{ij} is the element of the response matrix and Φ_j is the j-th component of the fluence vector (j=1,…,m, and m being the number of bins used in partitioning the energy of the incident gamma rays or neutrons).

The objective in the unfolding procedure is to determine the unknown Φ from the measured N_i and response R. To solve this problem, there are several mathematical methods including least-squares[9], Monte Carlo method[10], maximum entropy method[11], genetic algorithm[12], and artificial neural networks[13][14]. The commonly used and most developed codes for unfolding include SAND-II[15], Gravel[16], and UMG[17].

The Gravel method is an iterative unfolding algorithm, and has been successfully used for unfolding gamma-ray spectra[18]. Recently this method was used to unfold a fast neutron spectrum measured by a scintillation detector[19]. In the present method, the Gravel algorithm is used to unfold both neutron and gamma-ray spectra. In brief, the Gravel algorithm is[19][20]

$$\Phi_j^{K+1} = \Phi_j^K exp\left(\frac{\sum_i W_{ij}^K \ln\left(\frac{N_i}{\sum_{j'} R_{ij'} \Phi_{j'}^K}\right)}{\sum_i W_{ij}^K}\right), \quad (3)$$

where W_{ij}^K is called the weight factor, defined by

$$W_{ij}^K = \frac{R_{ij}\Phi_j^K}{\sum_{j'} R_{ij'}\Phi_{j'}^K} \cdot \frac{N_i^2}{\sigma_i^2}, \quad (4)$$

where σ_i^2 is the estimate of the measurement error, and K is the number of iterations.

2.2.2. Response function

To apply this algorithm to the detection system, the response matrices of the NaI(Tl) detector to incident gamma rays and of the PS detector to incident gamma rays and neutrons must be determined. In this study, the response matrices were calculated using the Geant4 code. In the simulation, two scintillators, one is NaI scintillator, the shape of dimension of which is Φ50 ×50 mm, the other PS scintillator with the same size, were modeled in the Monte Carlo code. The simulation model is shown in Fig. 4.

The outer side of the crystal is wrapped with a layer of aluminum sheet with a thickness of 1 mm to protect the scintillators.

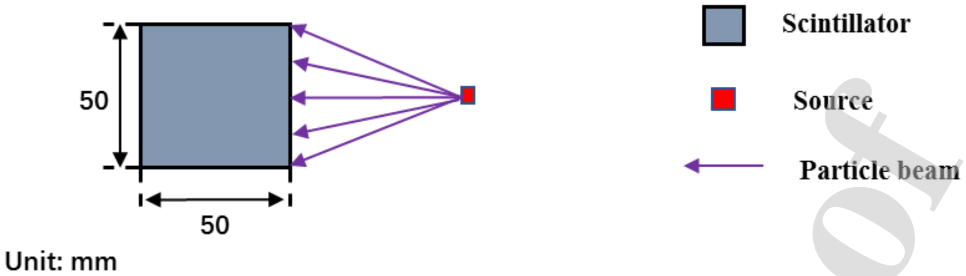

Fig. 4. The simulation model.

In the simulation the radioactive source is located directly in front of the crystal and the emission angle of rays is randomly from 0 degrees to 360 degrees. There is air at room temperature between the detector and the radioactive source. The range of response for the PS detector to neutrons is from 20 keV to 20.48 MeV; the energy spacing chosen was 20 keV. The response function is plotted in Fig. 5. The response functions of the PS and NaI(Tl) detector to gamma rays are shown in Figs. 6 and 7, both having the same energy range from 10 keV to 10.24 MeV, with the energy spacing set at 10 keV.

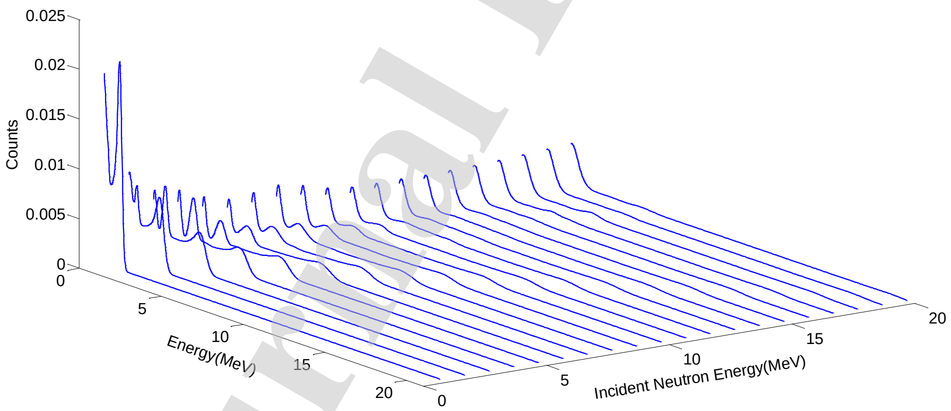

Fig. 5. Response function of the EJ299-33 scintillator to neutrons

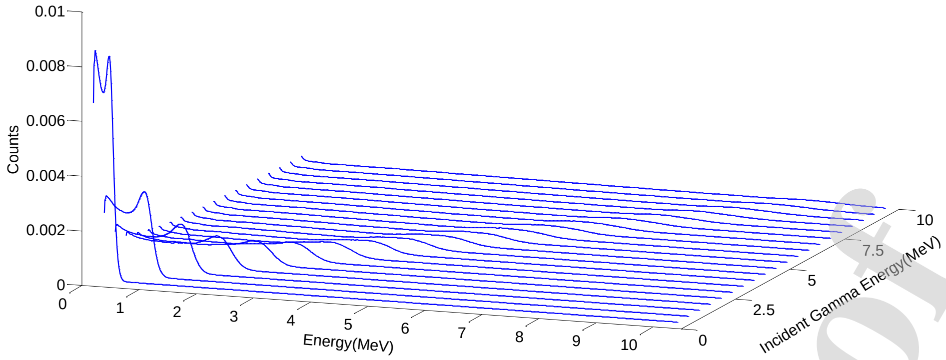

Fig. 6. Response function of the PS detector to gamma rays.

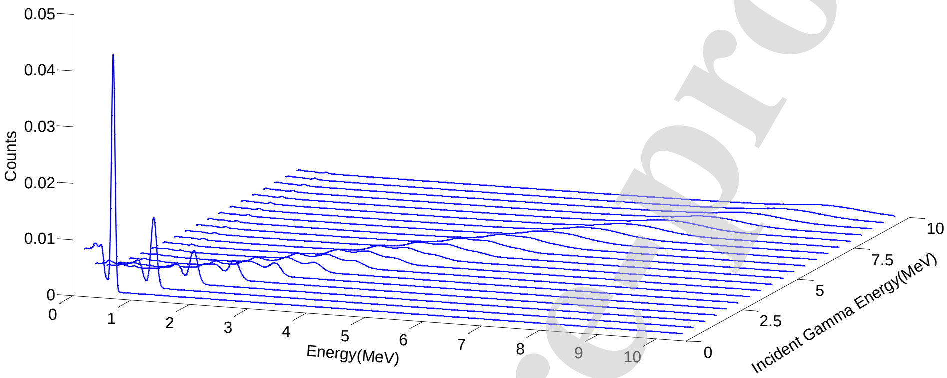

Fig. 7. Response function of the NaI(Tl) detector to gamma rays

3. Experiment and results

Using this method, an experiment to detect the energy spectrum of monoenergetic neutrons was carried out at the Accelerator Laboratory, Institute of Nuclear Science and Technology, Sichuan University. By comparing the experimental results with the theoretical neutron energies, we verified the performance of the method proposed.

3.1. Calibration

Before the experiment, the calibration for the both detector was carried on. The NaI(Tl) scintillation detector, which is used to detect gamma rays, was calibrated directly with a γ radioactive source. In this study, ^{22}Na and ^{137}Cs sources were used for the calibration. The calibration resulted in the correlation

$$E_\gamma = 13.14 \times ch - 113, \qquad (5)$$

where E_γ denotes the energy of the gamma rays, the unit being keV; ch is the number of the channel.

The PS detector is used for detecting gamma rays and neutrons. The constituents of the PS are low atomic number elements such as hydrogen and carbon, so the main reaction type is Compton scattering of gamma rays. The pulse-height spectrum obtained from the PS detector is different from that obtained from an inorganic scintillation detector; indeed, the full energy peak is 'missing'[21]. To calibrate the PS detector, we combined Monte Carlo simulation results and experimental results. Details of the method can be found in Ref. [21]. Similar to Eq. (5), the calibration result establishes the correlation,

$$E_{\gamma} = 1.631 \times ch + 34.1. \quad (6)$$

The PS detector is sensitive to fast neutrons. The most important reaction undertaken by fast neutrons in the plastic scintillator is elastic scattering producing mainly a hydrogen recoil. The maximum energy in the hydrogen recoil is equal to the energy of the incident neutron. With the PS detector calibrated for gamma rays, the energy corresponds to the energy deposition in the electrons of the scintillator. For fast neutrons, it is the recoil hydrogen that loses energy in the scintillator. To calculate the recoiling protons energy, a correlation between electron-equivalent energy and the recoiling protons energy must be determined. The correlation for the type of PS detector used was deduced by Nyibule and Henry[22], specifically,

$$L = -0.15 + 0.25 \times E_{rp} + 0.0096 \times E_{rp}^{2}, \quad (7)$$

where E_{rp} denotes the energy of the recoiling protons, the unit being MeV; L is the light output function, its units being the electron-equivalent MeV, namely, MeVee.

3.2. Experiment and results

Various nuclear reactions emit neutrons including D(d,n), T(d,n), and T(p,n) reaction. In the experiment, we chose the T(d,n) reaction. A deuterium beam was generated at the accelerator and directed onto a tritium target. The target is solid tritium-titanium (T-Ti) target, which has a thickness of 1.833 mg/cm2, and the atom ratio of T to Ti is 1.84. Tantalum foil is behind the tritium-titanium target which could stop the proton beam. At the end of the target, a continuous cooling water flow with a thickness of 4 mm was used to avoid local overheating [23]. In the experimental setup (Fig. 8), the detector and tritium target were in the same horizontal plane, their separation being 1.65 m. Because of the experimental conditions, the deuterium beam was accelerated to 1.5

MeV. The available angles between the beamline and detector were 30°, 60°, and 90° yielding corresponding neutron energies of 17.14 MeV, 16.04 MeV, and 14.64 MeV. The experimental setup (Fig. 9) has the PS detector and NaI(Tl) scintillation detector fixed on a red metal support facing the target. In the experiment the distance between target is about 1.65 m and the distance for the two probes of the detectors is about 10.5 cm, so the largest angle gap for the two detectors is about 1.8°. With the subtle gap the different angles hardly affect the experimental results.

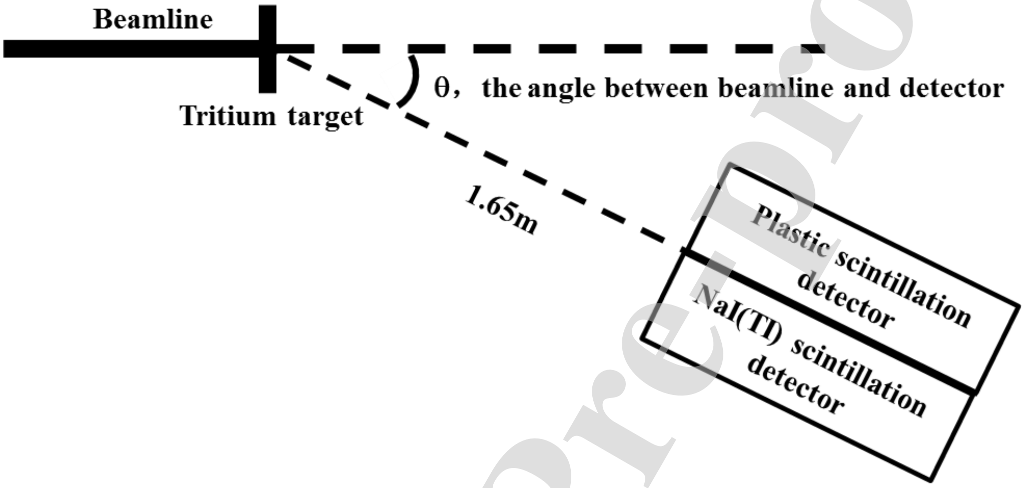

Fig. 8. Schematic of the geometry of the experimental setup.

Fig. 9. Photograph of the experimental setup.

The experimental results (Fig. 10, Fig. 11) include the detection data of the PS and

NaI detectors. The deduction and unfolding results are demonstrated in Fig. 12, Fig. 13 and Fig. 14. Given the incident neutron energies of 14.64 MeV, 16.04 MeV, and 17.14 MeV, the corresponding peaks of the unfolded incident neutron spectra are 15.03 MeV, 16.36 MeV, and 16.67 MeV, respectively.

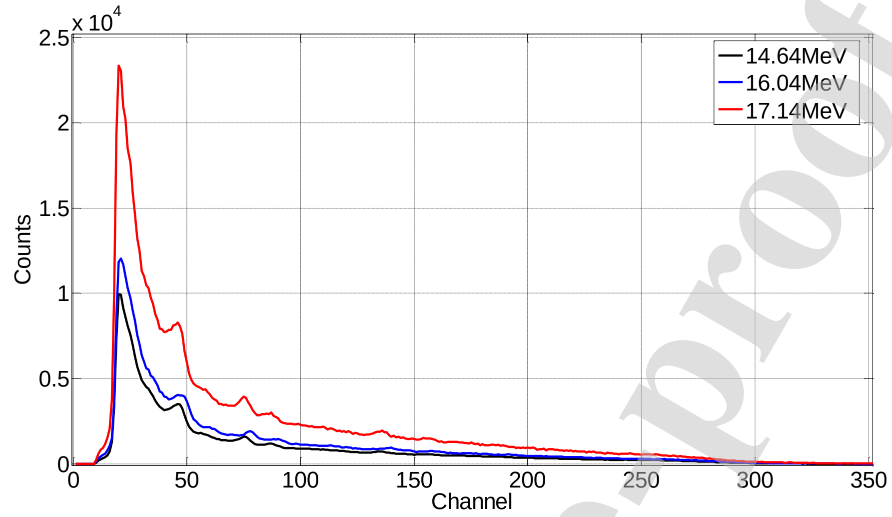

Fig. 10. Pulse-height spectrum detected by NaI detector when the energies of the neutron are 14.64 MeV, 16.04 MeV, and 17.14 MeV.

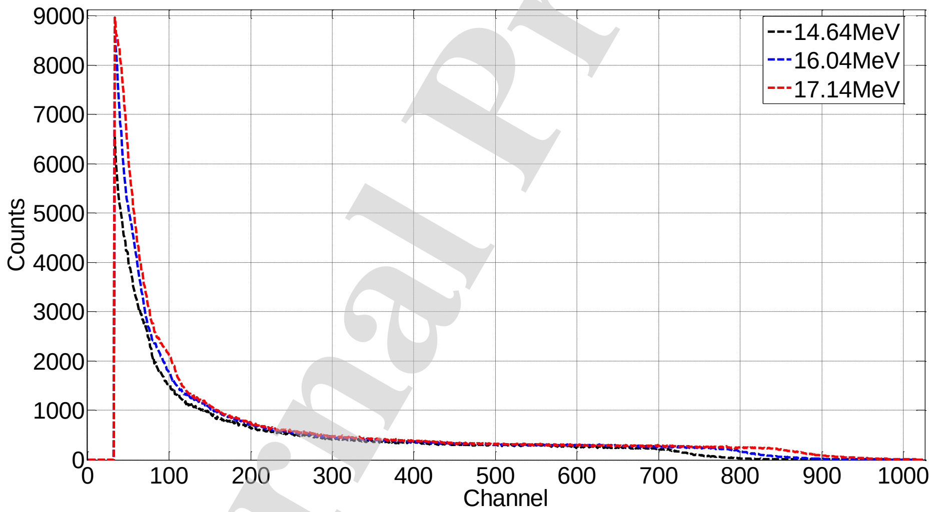

Fig. 11. Pulse-height spectrum detected by PS detector when the energies of the neutron are 14.64 MeV, 16.04 MeV, and 17.14 MeV.

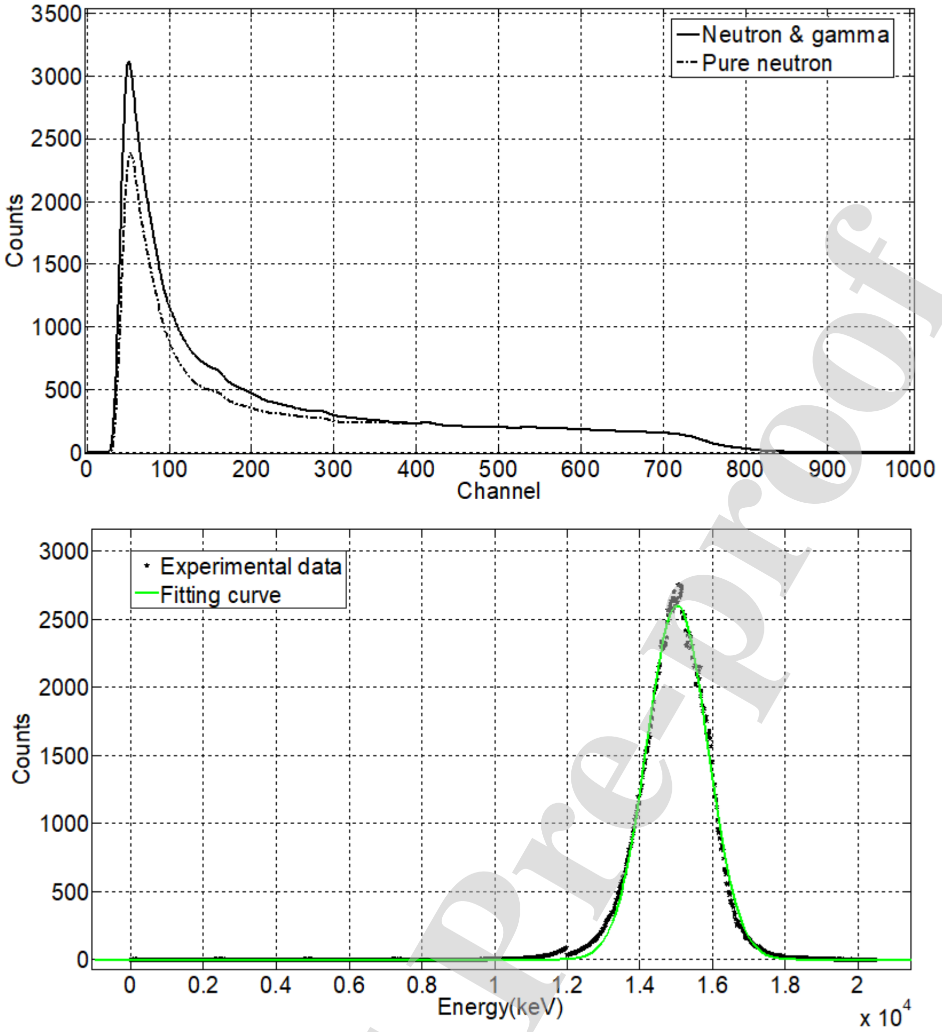

Fig. 12. The results of deduction and the unfolded incident energy spectrum of 14.64 MeV neutron. The upper picture shows the pure neutron spectrum and the gamma-neutron mixed spectrum in PS detector. The picture below shows the calculating neutron energy distribution and the result of fitting data with Gaussian function.

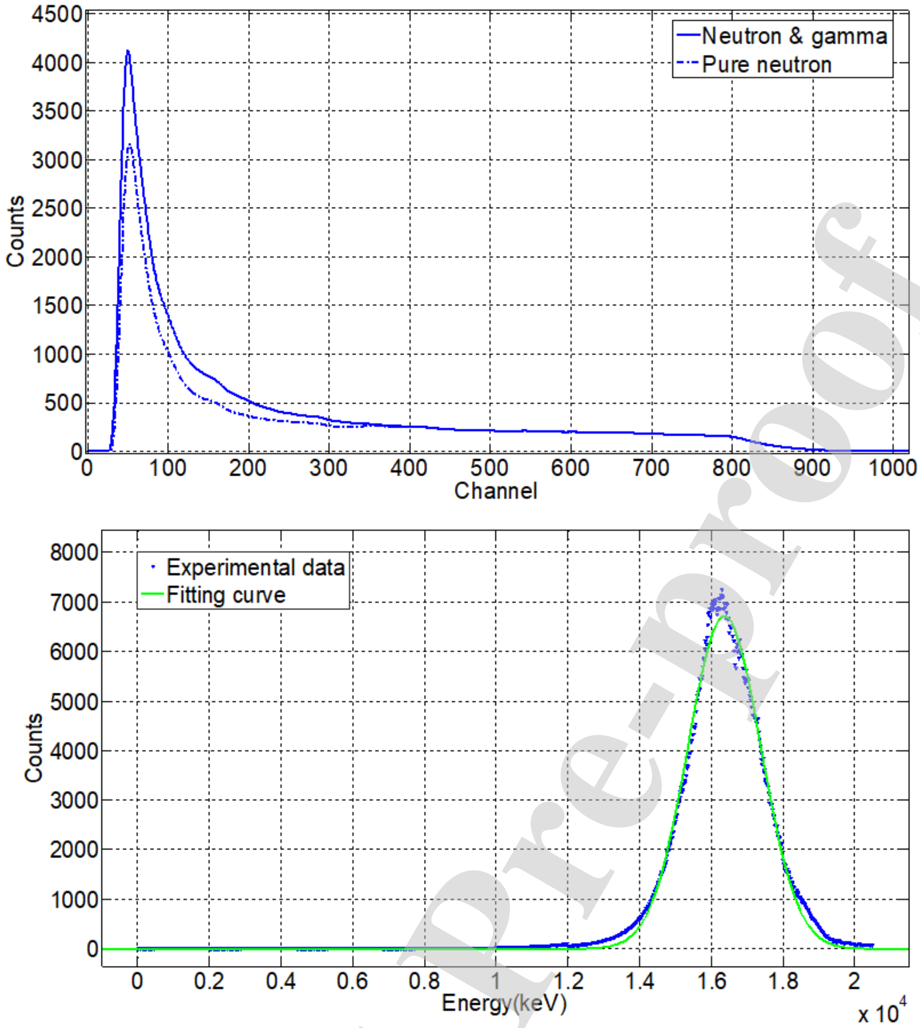

Fig. 13. The results of deduction and the unfolded incident energy spectrum of 16.04 MeV neutron.

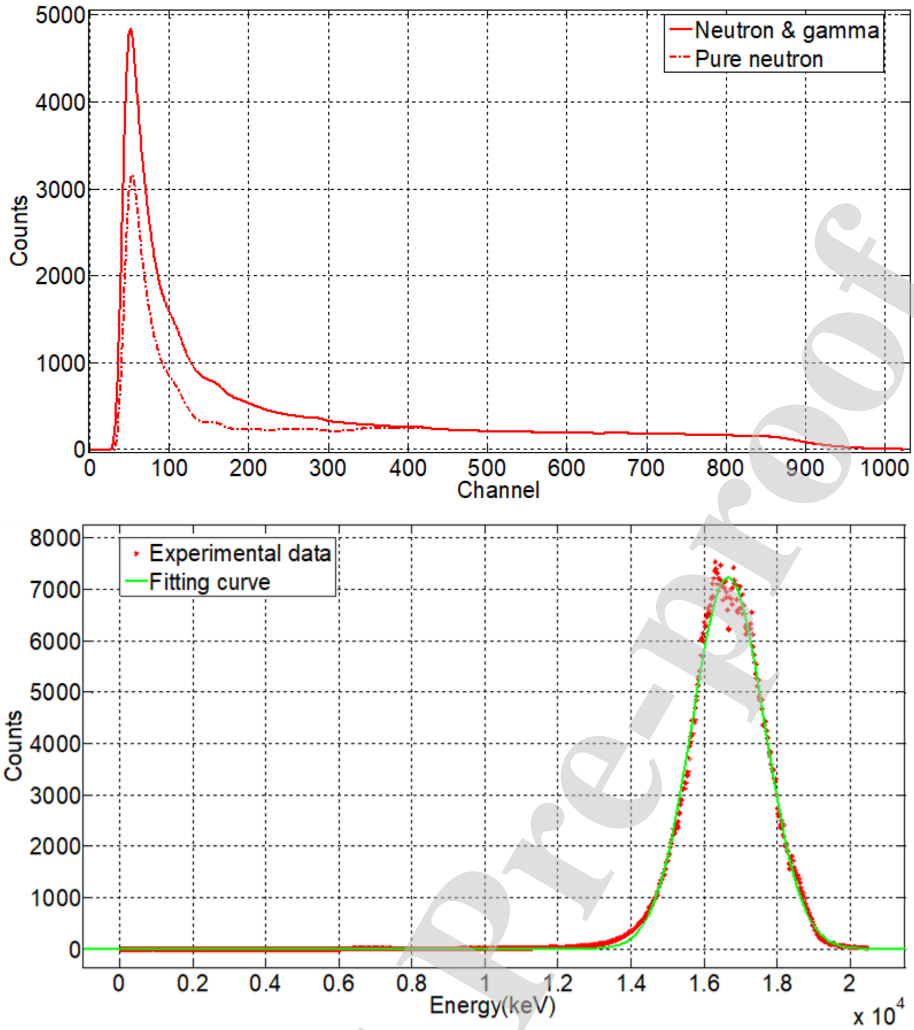

Fig. 14. The results of deduction and the unfolded incident energy spectrum of 17.14 MeV neutron.

These spectra demonstrate that for all three incident mono-energey neutron beams, the neutron energy can be calculated using this spectral method. These incident neutron spectra only include one peak and the peak position is close to the theoretical values. Thus, the experimental results are consistent with theoretical predictions. From the unfolding results it can be also seen that there is an obvious broaden of the neutron energy. First the statistical fluctuation of data is inevitable. Second there are a lot of scattering even during the whole experiment, which adds the straggling of neutron energy. The unfolding algorithm is a kind of iterative algorithms and the computing results has acceptable error. The response function is computed by simulation, which is different with the real response, and this increases the unfolding error. Last the two detector have intrinsic resolution. All the factors mentioned are contributed to the width of the peaks.

4. Conclusion

We proposed a method to obtain the energy spectra of fast neutrons that employed both a PS (plastic scintillation) and a NaI(Tl) scintillation detector. The experimental results show that the method is reliable. There is still a disparity between experimental and theoretical neutron energies. When calibrating these detectors, ^{22}Na and ^{137}Cs were used. The two radioactive sources emit low energy γ rays, below 2 MeV thereby incurring a calibration error in the high energy range. For gamma rays, both detectors have different lower limits, which lead to errors in the deduction procedure at low energies.

Because of limitations in the experimental conditions, only three energy points were used to verify the method, the energy range being 14–17 MeV. Under current experimental conditions, the energy of the available gamma-ray source is below 2 MeV. We plan to verify the method with monoenergetic neutron of different energies that extend the present range of energies and modify the calibration parameters with the gamma-ray source with energies over 2 MeV. Considering the method is feasible to use and the gamma information can be known by the NaI detector, it provides new opportunities in the field of neutron detection.

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Credit author statement

XaioBing Li: Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing.

Zhonghai Wang: Conceptualization, Project administration.

Huanwen Lv: Funding acquisition.

Shuping Wei: Software.

Jiajia Liu: Investigation.

Yudong Wang: Formal analysis.

Xing Fan: Data Curation.

Rong Zhou: Supervision.

Chaowen Yang: Resources.

Declaration of interests

⏏The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: