TEST SI PIN DIODE DETECTORS: A FEASIBILITY STUDY FOR THE NUCLEAR ASTROPHYSICAL EXPERIMENTS PROPOSED USING THE 5SDH-2 TANDEM PELLETRON ACCELERATOR AT HUS

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Abstract. Test experiments for the Silicon PIN diode S3590-09 bare detector which will be used in the first experiments for nuclear astrophysics study using the 5SDH-2 pelletron accelerator at Hanoi university of science is reported. The experiments were performed with alphas from a mixed ^{239,240}Pu-^{241}Am source and proton beams of 1, 1.5, 2.0 and 2.5 MeV from the pelletron as the first feasibility study. The results show that the detector FWHM is less than 0.4% energy of charge particle which satisfies the foreseen requirement for the upcoming experiments

Keywords: Si PIN photodiode.

I. INTRODUCTION

Nuclear astrophysics aims at studying on the origin of chemical elements and the energy emission of stars. This is an interdisciplinary branch of physics concerning various subfields: stellar modeling, nuclear reaction rates, physical cosmology, gamma ray, ... Therefore, this field poses challenges for Vietnamese scientists when the domestic science and technology are at low level comparing to developed countries. It, however, opens research opportunities in suitable aspects in term of both research region and investment. In this field, there are a few studies done by Vietnamese authors, for examples [1, 2, 3, 4, 5, 6, 7, 8, 9] for experimental studies and [10, 11] for theoretical studies. It is noted that the experimental studies were carried out in international laboratories, mostly in Center of Nuclear Study (CNS), the university of Tokyo, Japan in a close collaboration between Vietnamese and Japanese scientists

At the end of 2010, a 5SDH-2 tandem pelletron accelerator was installed at Hanoi University of Science (HUS) and became operational in 2012 [12]. Its maximal acceleration voltage is 1.7 MV, resulting in the accelerating energy from 700 keV to 3.4 MeV for singly charged ions, to 5.1 MeV for doubly charged ions, and up to 6.8 MeV for triply charged ions. As the result, the pelletron is not only suitable for elementary analysis using Proton Induced X-ray Emission (PIXE) and Rutherford Backscattering Spectrometry (RBS)methods [13, 14, 15] but also for nuclear astrophysics study. Up to now, the latter has been not exploited yet.

The astrophysical origin of the proton-rich isotopes of heavy element (from Se to Hg) is not completely understood. For example, the production of some light p-nuclei, such as ^{93,94}Mo and ^{96,98}Ru could not be explained. The favored γ-process in core-collapse supernova cannot produce enough p-nuclei. Thus, there should be other processes responsible for this deficiency. A new νp-process in the nucleon-synthetic process, which is highly sensitive to the physical condition of neutron-driven winds [16], has significantly solved this problem [17, 18]. ^{10}B(α, p)^{13}C reaction is one of the key reactions that bridge from $A < 12$ (the $p-p$ chain region) to $A > 12$ (the CNO region), and responsible for the νp-process at the temperature $T_9 = 1.5-3$ as shown in Fig. 1. This temperature range corresponds to the alpha energy window which can be accelerated by the HUS pelletron.

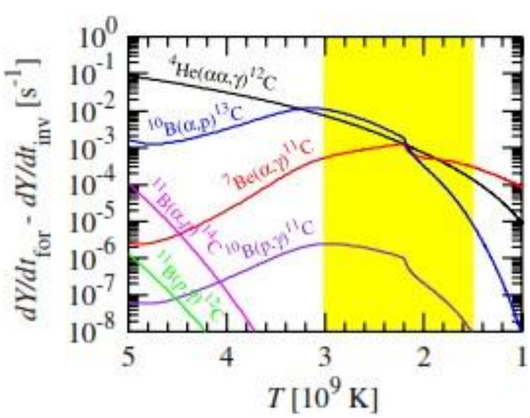

Fig. 1. Nuclear flows ($dY/dt_{\rm for} - dY/dt_{\rm inv}$) for the reaction that bridge from $A < 12$ to $A > 12$ as a function of temperature (T). The yellow band indicates the temperature range relevant to the νp-process ($T_9 = 1.5-3$). This figure is taken from [16].

For the effort to utilize the HUS 5SDH-2 pelletron in nuclear fundamental research via reactions, a research project to study the above astrophysical reaction has been accepted and supported by the Vietnam Ministry of Science and Technology (MOST) as part of the Physics Development

Program Grant No. ĐTĐLCN.25/18 project. This paper presents the testing results for the Si PIN photodiode detectors which will be used in the first experiment to measure the cross sections of $^{10}B(\alpha, p)^{13}C$ reaction with α energies from 0.7-3.4 MeV using the 5SDH-2 pelletron accelerator at Hanoi University of Science. The work is the first feasibility study for the coming experiment.

II. DETECTOR AND EXPERIMENTS

The detectors tested in this study and later on used in the experiment mentioned above were bare chip type of Si PIN photodiode S3590-09 [19]. This detector has an active area of 10 mm x 10 mm, a depletion layer thickness of 0.3 mm and reverse voltage maximum of 100 V. Its photo and dimensional outline are shown in Figure 2.

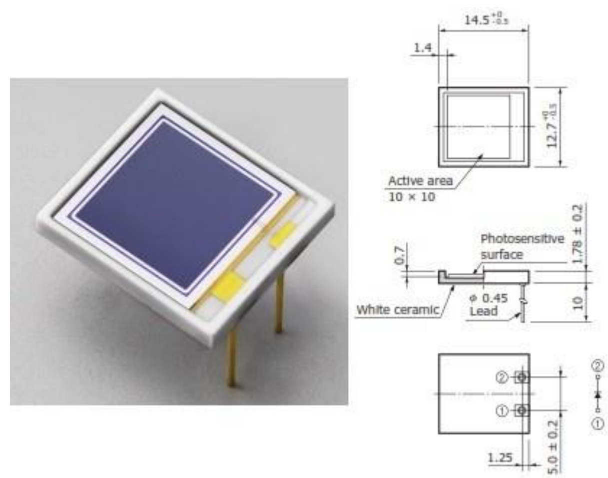

Fig. 2. Photo (left) and dimensional outline (right) of a Silicon PIN diode S3590-09 [19].

The test experiments were carried out with α particles from a Pu-Am mixed source and proton beams from the HUS 5SDH-2 pelletron. The purpose was to test the detector response function to charged particles which will be the main products detected in the experiments, and the detector treatment.

The Pu-Am mixed source contains $^{239,240}Pu$ and ^{241}Pu. These radioactive nuclei emit α particles with energy from 5.2-5.5 MeV. The most intensive energies are tabulated in Table 1.

Figure 3 presents the setup for the test with the α source. The source and the Si PIN photodiode were placed in a scattering chamber. The chamber was pump to 10^{-6} torr vacuum to ensure that almost no energy loss of α particles was caused by the air before they reached the

Table 1. The most intensive energies of α particles emitted by the Pu-Am mixed source.

Nucleus	Energy (MeV)	Percentage (%)
^{239}Pu Ref. [20]	5.105	11.9
	5.143	17.1
	5.156	70.8
^{240}Pu Ref. [21]	5.124	27.2
	5.168	72.7
^{241}Am Ref. [22]	5.388	1.6
	5.443	13.1
	5.486	84.5
	5.544	0.3

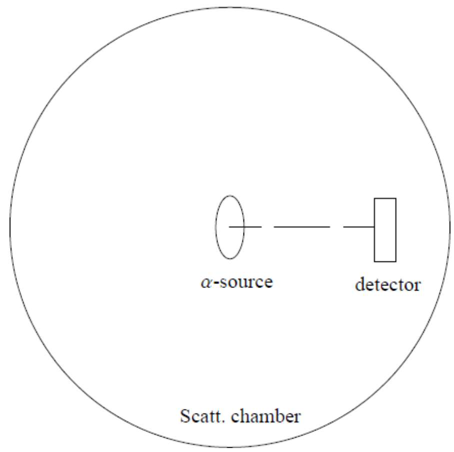

Fig. 3. Experimental setup for the detector test with an alpha source. The scattering chamber was pumped to 10^{-6} torr vacuum.

detector. The chamber and the electronic readout were the same as the test experiments with the proton beams which is discussed below.

The experimental setup of the test experiments with the proton beams from the HUS 5SDH-2 pelletron is presented in Figure 4. The RF ion source (Alphatross-type) was used to produce proton beam. The hydrogen gas extracted from a pressurized bottle was injected to a quartz bottle (not shown) with radio frequency of the applied electrostatic field. Here, the high frequency field ionized the He gas into the plasma state, comprising of positive charged ion and electron. This state was magnified by electromagnetic field from a solenoid. An electrostatic field across the quartz bottle expelled the positive ions into the charge exchange chamber, where they captured

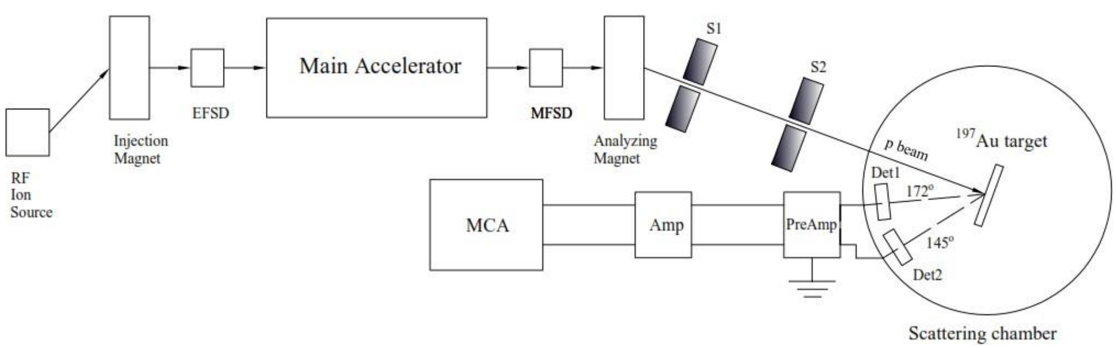

Fig. 4. The HUS 5SDH-2 pelletron scheme and the experimental setup for the test with proton beam. EFSD and MFSD are electrostatic and magnetic focusing and steering devices, respectively. S1 and S2 are slits. Det1 and det2 are tested detectors mounted inside the scattering chamber. The signal was connected to the electronics including preamplifiers (Pre-Amp), amplifiers (Amp) and displayed by a multi-channel analyzer (MCA). Modules are not in the same scale. Details are discussed in the text.

Table 2. The back-scattering proton energies (E_p^{bs}) at 145 and 172 degrees calculated according to the elastic scattering kinematics of p^{197}Au system with different proton beam energies (E_p).

E_p (MeV)	scattering angle (deg.)	E_p^{bs} (MeV)
1.0	145	0.982
	172	0.980
1.5	145	1.473
	172	1.470
2.0	145	1.963
	172	1.960
2.5	145	2.454
	172	2.450

electrons from cesium vapor, converting them into negative charged state. These negative ions were then pre-accelerated by several electrodes in the backend of the RF Ion Source.

The resulting negative ion beam was transported to the main Accelerator by using a dipole Injection Magnet and the Electrostatic Focusing and Steering Devices (EFSD). A nitrogen stripping system located at the high-voltage terminal of the main accelerator was used to convert the beam into positive-charge state, thus the kinetic energy of the proton beam increased twice (tandem mechanism). After the main accelerator, the beam was driven by the Magnetic Focusing and Steering Devices (MFSD), and focused by the Slits (S1, S2) before being led to the Scattering Chamber of 10^{-6} Torr vacuum, where the experimental setup was installed. In this test, four proton energies of 1.0, 1.5, 2.0, and 2.5 MeV were used.

Two detectors (Det1 and Det2) were placed at 145, 172 degrees with respect to the beam direction to detect backscattering protons after beam particles hitting on a 5 mm thick Au-on-glass target. The expected proton energies detected by these detectors were calculated according to the elastic scattering kinematics of p^{197}Au system. These results corresponding to 1, 2, 3 and 4 MeV incident proton beams are shown in Table 2. The detector signals were connected to outside preamplifiers, amplifiers, eventually to the multi-channel analyzer (MCA) via punch-though BNC connectors, see Figure 4.

III. RESULTS AND DISCUSSION

The testing detectors were bare chip as discussed above. So, it was necessary to verify the detector treatment including welding for signal readout and optimizing the reverse voltage, and, finally, to test the detector response function to charged particles.

Firstly, the verification was carried out with the Pu-Am mixed α source. The dependence of the detector Full Width Half Magnitude (FWHM) resolution to 5.48 MeV alphas on the reverse voltage is displayed in Figure 5. It is seen that the FWHM resolution is minimized at 30 V which is in agreement with the result in Ref [23] for the same Si PIN photodiode.

During the experiments, the preamplifiers was grounded to suppress the electronics noises due to ambient electromagnetic interference. The remaining background was from the edge back-scattering particles. To eliminate this edge effect, a 0.5 cm diameter collimator was placed in

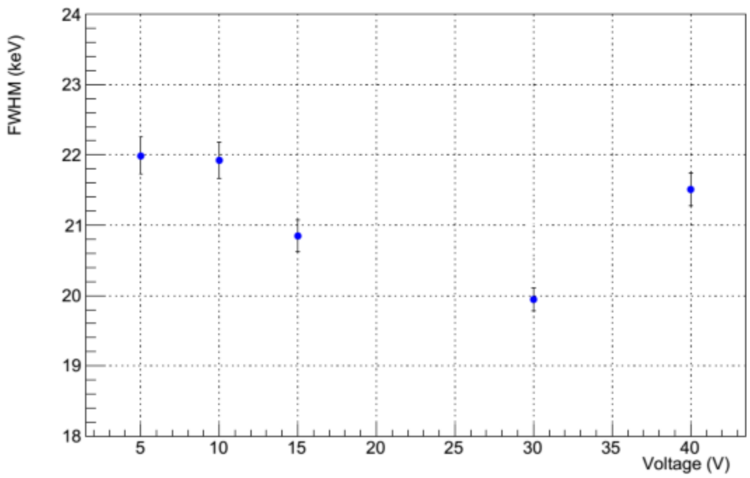

Fig. 5. The dependence of the detector FWHM resolution on the reverse voltage.

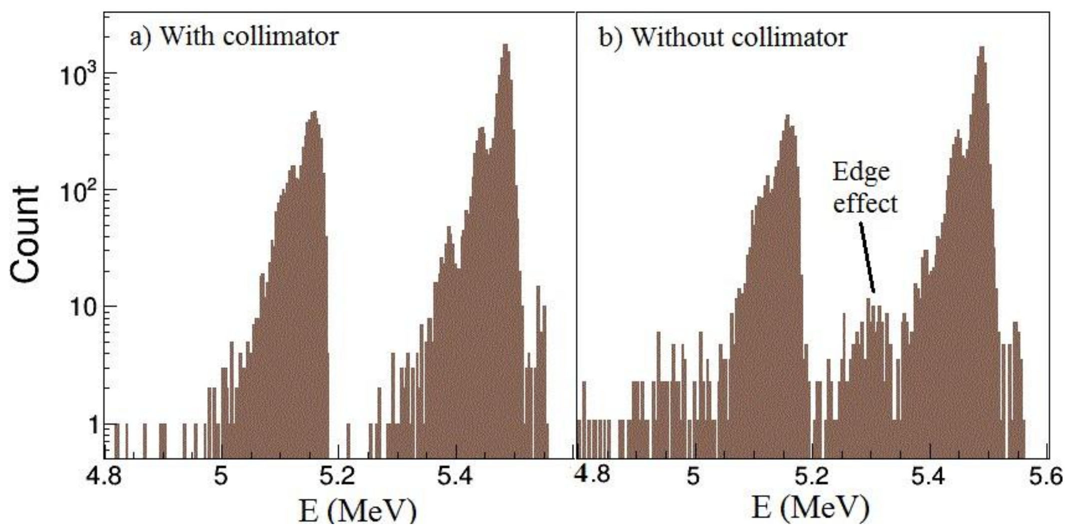

Fig. 6. Alpha energy spectrum with (a) and without (b) collimator.

front of the photodiodes to focus particles to its active area. A comparison between the alpha spectra with and without the collimator is shown in Figure 6. The background in the case with the collimator (panel a) is less than that of the latter case (panel b). As the result, the 30 V reverse voltage and the collimator were used henceforth.

The detector response function to α particles is presented in Figure 7. There are 2 regions in the spectrum for particles emitted by ^{239,240}Pu and ^{241}Am, respectively. According to the branching ratios in Table 1, the energies for the peaks and their origins were assigned as shown in the figure. Because the alpha energies emitted ^{239}Pu and ^{240}Pu are close the peaks were broadened. And

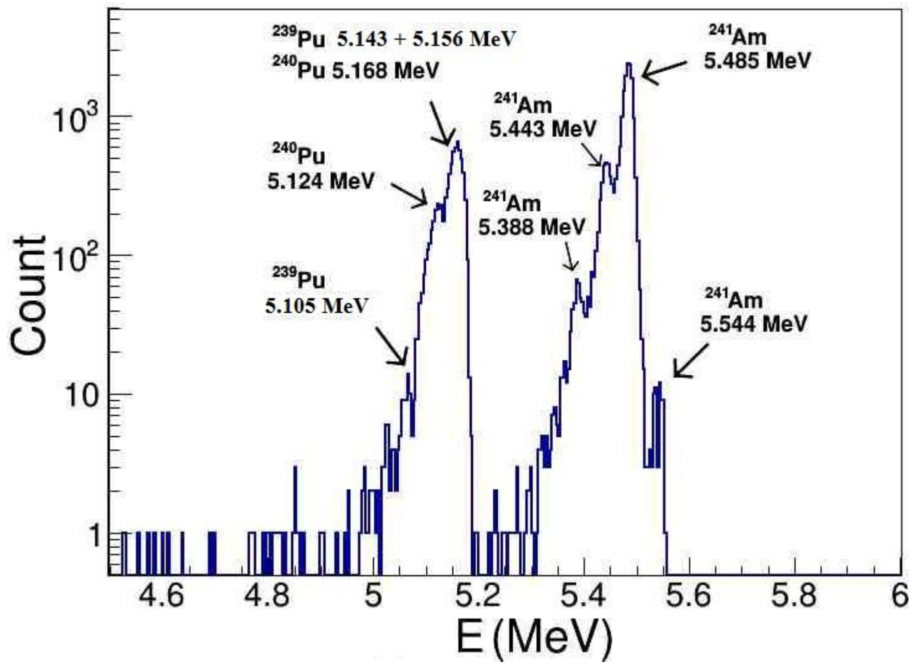

Fig. 7. energy spectrum from Pu-Am mixed source. Details are discussed in the text.

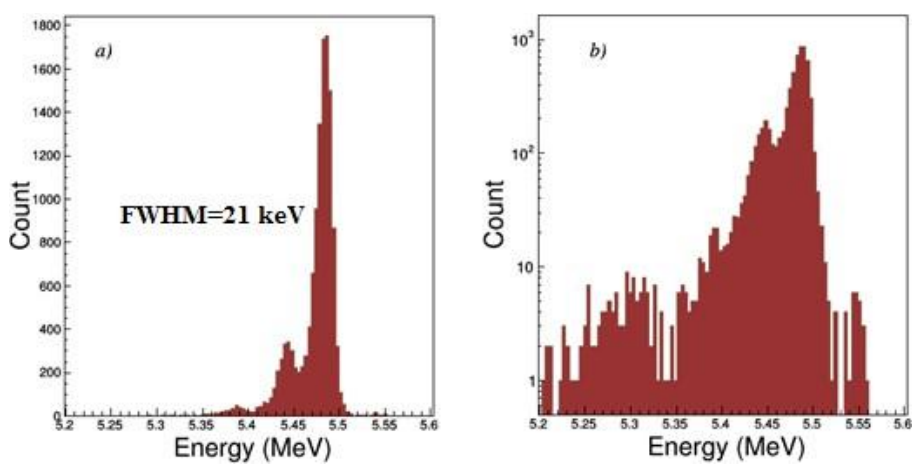

Fig. 8. A zoom in the spectral component of alphas from ^{241}Am as shown in Figure 7 in linear (a) and logarithmic (b) scale.

the current purpose is to test the energy resolution of the detector. The peaks from ^{241}Am, which is well separated from that of ^{239,240}Pu, was investigated.

A zoom in the spectral component of alphas from ^{241}Am is shown in Figure 8. It is seen that 4 peaks corresponding to 5388, 5443, 5486 and 5544 keV were well separated. The FWHM

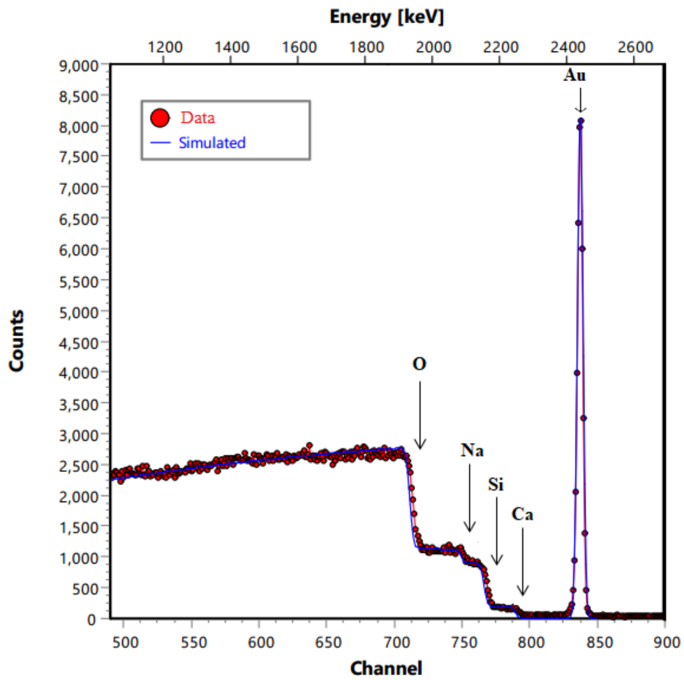

Fig. 9. RBS spectrum of protons at 172 degrees scattered on Au-on-glass target.

of the most intensive peak centered at 5486 keV was found to be 21 keV corresponding to about 0.4% in energy.

The RBS spectrum of protons at 172 degrees induced by 2.5 MeV proton beam on the Au-on-glass target is presented in Figure 9. The target composition was derived by a simulation with SIMRA code [24]. By adjusting the target information, the RBS spectrum was well reproduced as the blue line. The spectral components induce by the interaction of protons with different isotopes were marked correspondingly. The target information is tabulated in Table 3. According to a LISE calculation [25], the energy loss of 2.45 MeV proton is 4.5 keV. Therefore, the 61 nm Au-target thickness was thin in the current experiment. The Au peak in Figure 9 was induced by 2.45 MeV protons elastically scattered from p^{297}Au. The detector resolution is 12.2 keV FWHM corresponding to 0.5% energy.

Table 3. Composition and layer thickness of the Au-on-glass target obtained by SIMRA simulation [24].

Layer	Isotope	percentage	Thickness (nm)
1	Au	100	61
2	O	44	>5000
	Na	17	
	Si	34.5	
	Ca	4.5	

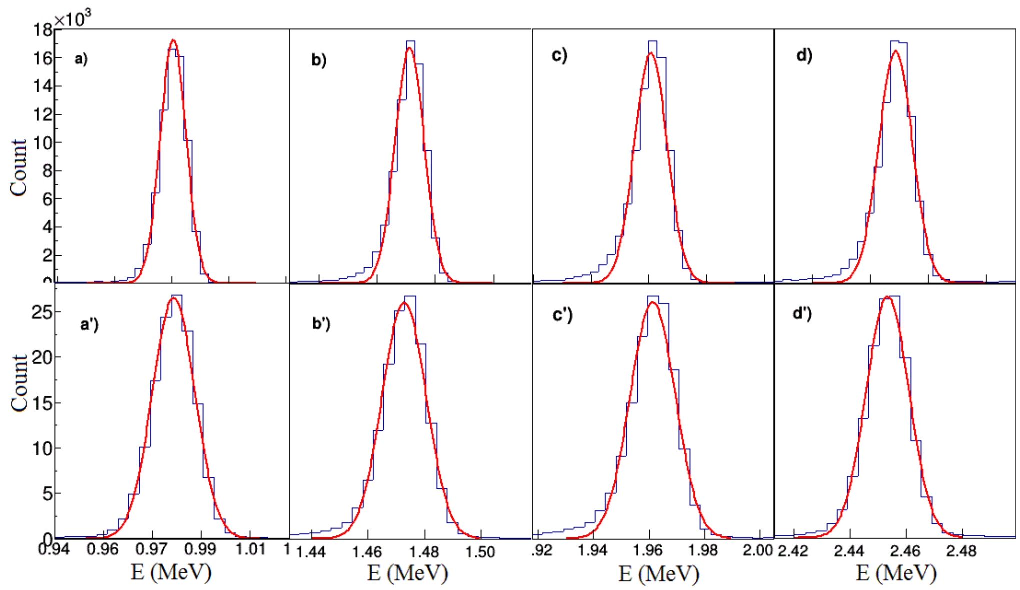

Fig. 10. The zooms in the elastic scattering peaks of the proton RBS spectra with 1, 1.5, 2 and 2.5 MeV proton beams from left to right, respectively. The upper and lower panels are detected by detectors located at 145 and 172 degrees. The spectra were fitted by Gaussian functions.

The zooms in the elastic scattering peaks of the proton RBS spectra with 1, 1.5, 2 and 2.5 MeV proton beams are shown in Figure 10 from left to right, respectively. The upper and lower panels are detected by detectors located at 172 and 145 degrees, respectively. Due to the smaller scattering angles, the spectra in the lower panels show broader peaks comparing to the upper ones.

IV. Conclusion

The Si PIN diode which will be used in the first nuclear astrophysics experiment using the 5SDH-2 pelletron at Hanoi University of Science was tested with alpha particles from a mixed ^{239,240}Pu-^{241}Am α-source and 1, 1.5, and 2.5 MeV proton beams. The detector FWHM was 21 keV for 5486 keV alpha, about 0.4 % energy. The test with proton beam shown that at smaller angle the FWHM was worst than that at large angle because particle traveled thicker target before reaching the detector. The analysis was done with SIMRA simulation to explain proton RBS spectrum. Target thickness and its composition was found. The detector FWHM was 11 keV for 2450 keV proton, about 0.5 % energy. Note that in the simulation the beam spread was also taken into account. In the coming astrophysics ^{10}B(α, p)^{13}C experiments, the aim will be measuring outgoing proton particle. The obtained resolution less than 5 % energy will be expected to fulfill the requirements.

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KIỂM TRA DETECTOR SI PIN DIODE: NGHIÊN CỨU TIỀN KHẢ THI CHO THÍ NGHIỆM VẬT LÝ THIÊN VĂN TRÊN MÁY GIA TỐC TĨNH ĐIỆN KÉP 5SDH-2 TẠI HUS

Tóm tắt nội dung: Báo cáo trình bày các kết quả kiểm tra detector Si PIN diode S3590-09. Đây là loại detector sẽ được sử dụng trong thí nghiệm vật lý thiên văn trên hệ máy gia tốc 5SDH-2 pelletron tại trường Đại học Khoa học Tự nhiên - Đại học Quốc gia Hà Nội. Các thí nghiệm được tiến hành khi đo chùm hạt Alpha phát ra từ nguồn hỗn hợp ^{239,240}Pu-^{241}Am và đo chùm hạt proton với các năng lượng 1, 1.5, 2.0 và 2.5 MeV tán xạ ngược trên mẫu vàng trên kính. Kết quả cho thấy độ phân giải năng lượng của detector nhỏ hơn 0.4% và hoàn toàn đủ điều kiện để tiến hành thí nghiệm trong tương lai.

Từ khóa: **detector Si PIN diode**