Building a VME spectrometer and testing Si PIN diode detector: a feasibility study for the nuclear astrophysical experiments proposed using the 5SDH-2 Tandem Pelletron Accelerator at HUS

Le Xuan Chung[1], B. D. Linh[1], Mai Van Dien[1], Pham Duc Khue[1], Nguyen Duc Ton[1], Bui Thi Hoa[2], Vi Ho Phong[2], Nguyen The Nghia[2], Tran The Anh[2], Phan Viet Cuong[3], and Le Tuan Anh[3]

[1] *Institute for Nuclear* Science *and Technology, VINATOM, P.O.Box 5T-160, Nghia Do, Hanoi, Vietnam*

[2]*Hanoi University of Science, 334 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam*

[3]*Research and Development Center for Radiation Technology, VINATOM, Thu Duc, Ho Chi Minh, Vietnam*

Abstract

This work presents the logical design, connections between NIM and VME electronic modules, and the data acquisition programming to build a complete detector readout system. The test experiments were carried out with commercial silicon PIN diode S3590-09 bare detectors bombarded by charged particles from a ^{241}Am α-source and a proton beam of 2.5 MeV and with a NaI scintillator detector measuring gammas induced by ^{27}Al(p, γ)^{28}Si reaction with proton beam of 1.379 MeV. The test showed that the spectrometer operates steadily. The energy resolutions of the Si diodes were less than 0.5% energy of a charged particle, which satisfies the foreseen requirement for the upcoming experiments.

Key words: VME module, proton beam, Si-PIN diode detector, Pelletron accelerator, data acquisition.

1. Introduction

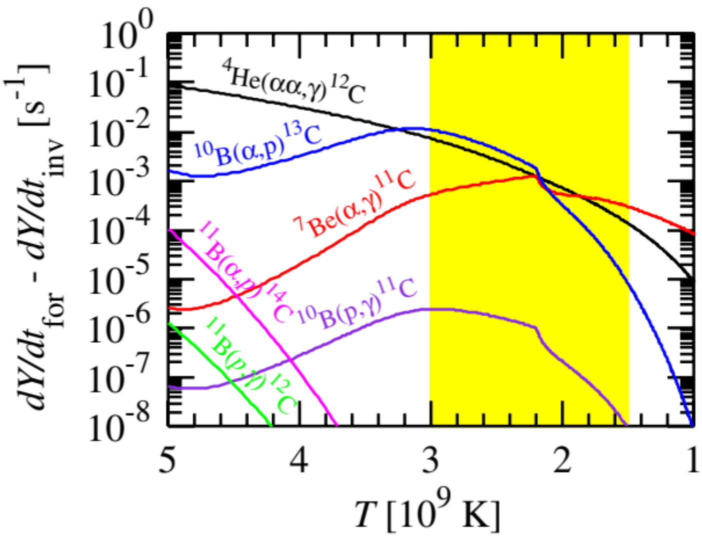

Figure 1. Nuclear flows ($dY/dt_{for}-dY/dt_{inv}$) for the reaction that bridge from A < 12 to A > 12 as a function of temperature (T). The yellow band indicates the temperature range relevant to the γp-process (T_9 = 1.5−3). This figure is taken from [16].

Nuclear astrophysics aims at studying 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, etc. Therefore, this field poses challenges for Vietnamese scientists, while domestic science and technology are at a low level comparing to developed countries'. It, however, opens research opportunities in suitable aspects in terms of both research region and investment. In this field, there are a few studies performed by Vietnamese authors, for example, [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 within international laboratories, mostly with the Center of Nuclear Study (CNS), the University of Tokyo, Japan, in 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 a 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 later has not been exploited yet.

The astrophysical origin of the proton-rich isotopes of a 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, γ)^{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.

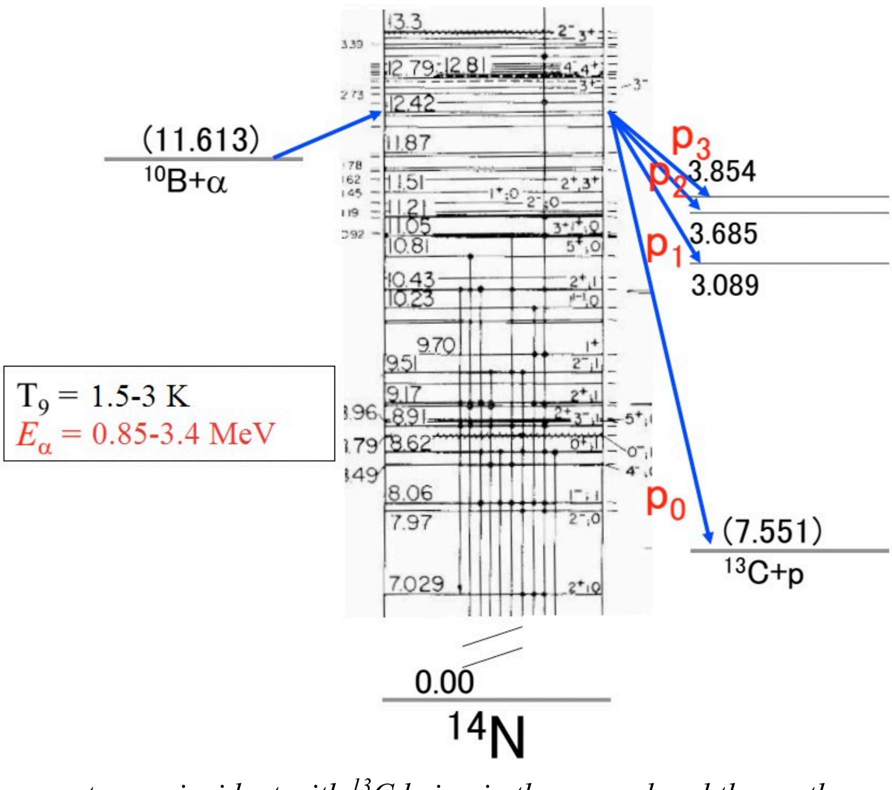

Figure 2. $p_{0\text{-}3}$ protons coincident with ^{13}C being in the ground and three other excited states. Firstly, ^{10}B and α form the ^{14}N compound nucleus. Finally, excited ^{14}N nuclei decay to p_{0_3} and ^{13}C at the ground and excited states, correspondingly. The continuums of ^{14}N and ^{13}C are taken from Ref. [20].

For the effort to utilize the HUS 5SDH-2 Pelletron in fundamental nuclear research via reactions, a research project to study the astrophysical above response 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. The aim of the upcoming experiment is to measure cross-sections of $^{10}B(\alpha,\gamma)^{13}C$ reaction with energies from 0.85-1.4 MeV via the detection of protons from different outgoing channels similar to those reported in [19]. There are 4 proton types, denoted as p_{0-3}, corresponding to the channels where ^{13}C being in the ground or three other excited states, see Fig. 2. According to the kinematical calculation, their energies spread from about 1 MeV to more than 5 MeV depending on the proton emitted angle.

This paper presents the feasibility study for the upcoming experiments, including a complete detector readout system built from NIM and VME electronic modules and the test for the Si PIN diodes used in future experiments.

2. Detector and electronic modules

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 [21]. This detector has an active area of 10 mm x 10 mm, a depletion layer thickness of 0.3 mm, and a reverse voltage maximum of 100 V. Its photo and dimensional outline are shown in Figure 3. In the proposed experiments, p_{0-3} will be detected at six different angles. Therefore, a 6-channel readout system will be needed. For this purpose, 6 A422A Charged Sensitive Preamplifiers, 1 N625 Quad Linear FAN-IN FAN-OUT, 1 N842 8-Channel Constant Fraction Discriminator, 6 N968 Spectroscopy Amplifiers, 1 N405 Triple 4-Fold Logic Unit/Majority with VETO, 1 N93B Dual Timer, 1 V1785NC 8-Channel Dual Range Multievent Peak Sensing ADC, and 1 V2718 VME-PCI Optical Link Bridge were used. Except for the last two modules are VME standard, the others are NIM standard. All these modules are produced by the CAEN company [22].

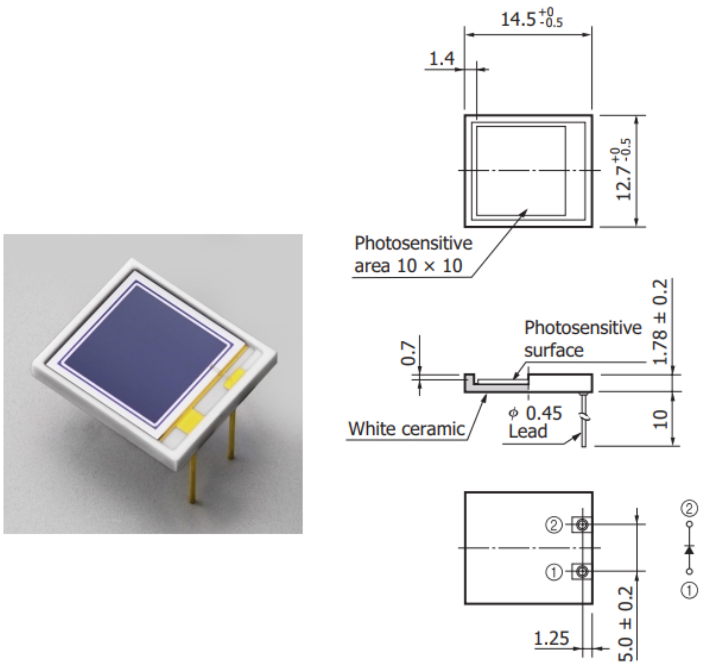

Figure 3. Photo (left) and dimensional outline (right) of a Silicon PIN diode S3590-09 [21].

The electronic scheme of the detector readout system is shown in Fig. 4. The signal from the detector is connected to the A422A preamplifiers. The energy and timing output of the preamplifiers were fed to the N968 amplifier and the N625 FAN-IN FAN-OUT, respectively. After the amplifier, the six energy signals were connected to six ADC channels. The N625 unit converted the polarity of the timing signal from positive to negative because the N842 unit accepted only a negative polarity input. Then, the output signal was connected to the N842 input to set the threshold for the detected signal. Afterward, the six timing signals were fed to the N405 unit to generate an OR output, which was input to the N95B unit to produce a gate to open the ADC. With this connection logic in Fig. 4, the whole detector system was able to measure six channels and to study also coincident signals. Note that the maximal channel of the ADC is 8.

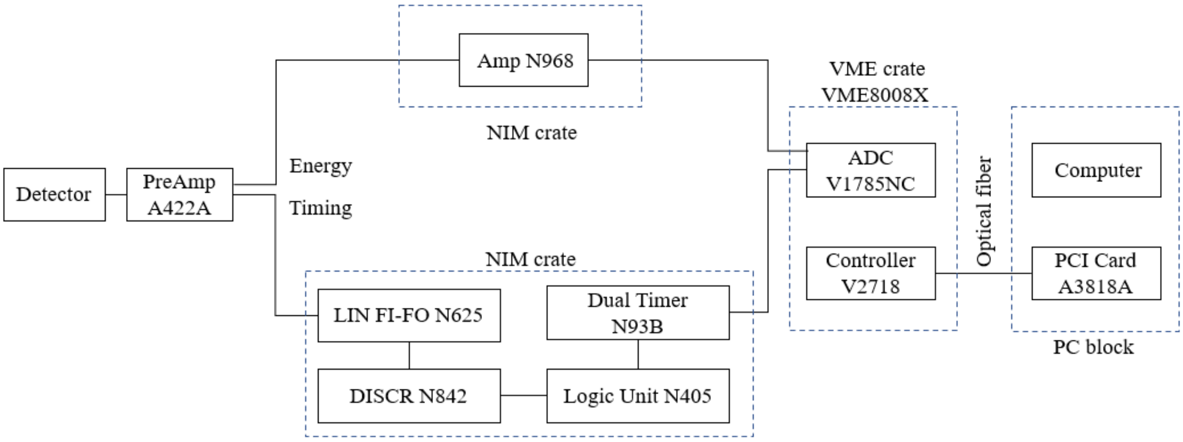

Figure 4. Electronic scheme for a detector readout system. Details are explained in the text.

3. Data acquisition

The data acquisition (DAQ) is needed to communicate the ADC unit with a computer via the crate controller and displays the spectrum detected by detectors on the computer. The V1785 ADC module takes the inputs from detectors and coverts them from analog into a digital value. The converted data, then, is stored in the Multi-Event Buffer (MEB), as shown in Fig. 5. The output data in the buffer is organized in 32-bits words that contain information of geographical address, 12-bit converted value, the number of channels, etc. In our developed DAQ software, the output data are extracted via the read pointer with the help of the CAENVMELib library [24].

Fig. 6 presents the graphical user interface of the developed DAQ software. It contains eight display windows, which permit to show simultaneously eight spectra corresponding to 8 inputs of the V1785 ADC module. The software allows the user to store the interested data in the "Tree" format for latter analysis with ROOT framework [25].

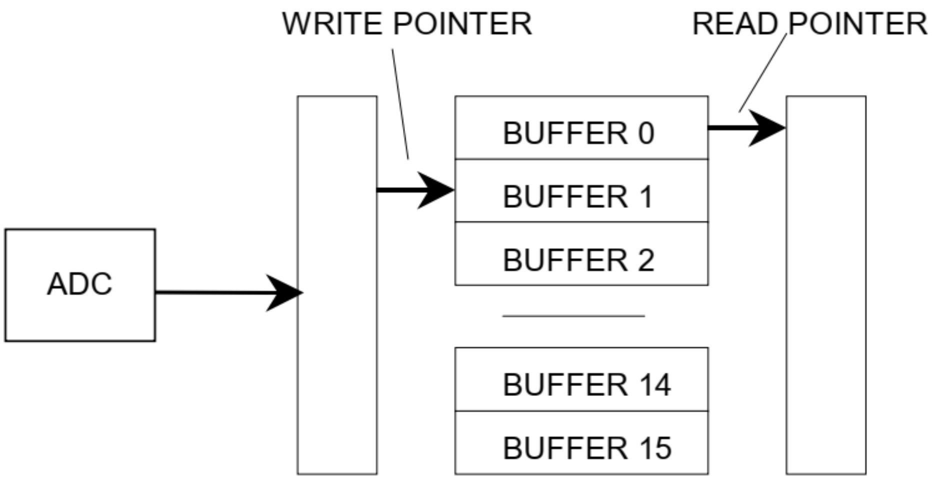

Figure 5. Multi-event buffer [23].

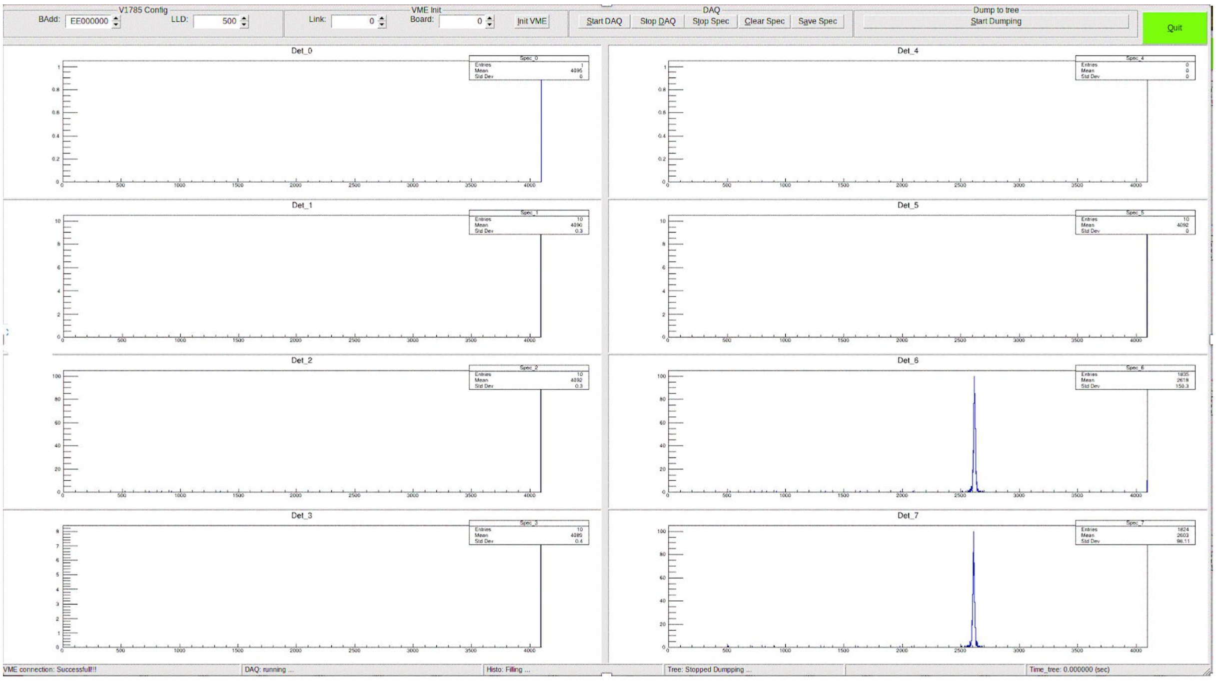

Figure 6. The user interface of DAQ software. Channel 7 and 8 show the testing signal from a pulser.

4. Experiment

Firstly, the test experiment for the Si PIN diodes was carried out with alpha particles from a ^{241}Am α-source. The purpose of this experiment was for both the DAQ and the detector test. The detectors and the DAQ were further tested with Rutherford elastic backscattering protons induced by 2.5 MeV proton beam bombarding on ^{197}Au target and ^{27}Al(p, γ)^{28}Si reaction, respectively. A NaI scintillator detector was used to detect gammas in the later experiment.

The energies of the most intensive alphas from the source are listed in Tab. 1. A Si PIN diode and the ^{241}Am α-source were placed inside a 10^{-6} torr vacuum chamber. As the test for optimal value, a high voltage of 30 V was applied in the Si PIN diode. A collimator of a 6 mm diameter in front of the detector was also used to avoid satellite peaks resulted from the edge effect [26]. The edge effect happens when a particle hits the edge of the wafer, where it loses some energy in the inactive region. As a result, satellite peaks appear at lower energy. The response function of the PIN diode to the alpha particles is displayed in Fig. 7. The two most intensive energy peaks are resolvable. The detector's full with half magnitude (FWHM) is 21 keV for the 5.486 MeV peak, which is equal to 3.59% energy.

Table 1. The most intensive energies of particles emitted from the ^{241}Am α-source and their intensities [29].

E(MeV)	Intensity (%)
5.388	1.6
5.443	13.1
5.486	84.5
5.544	0.3

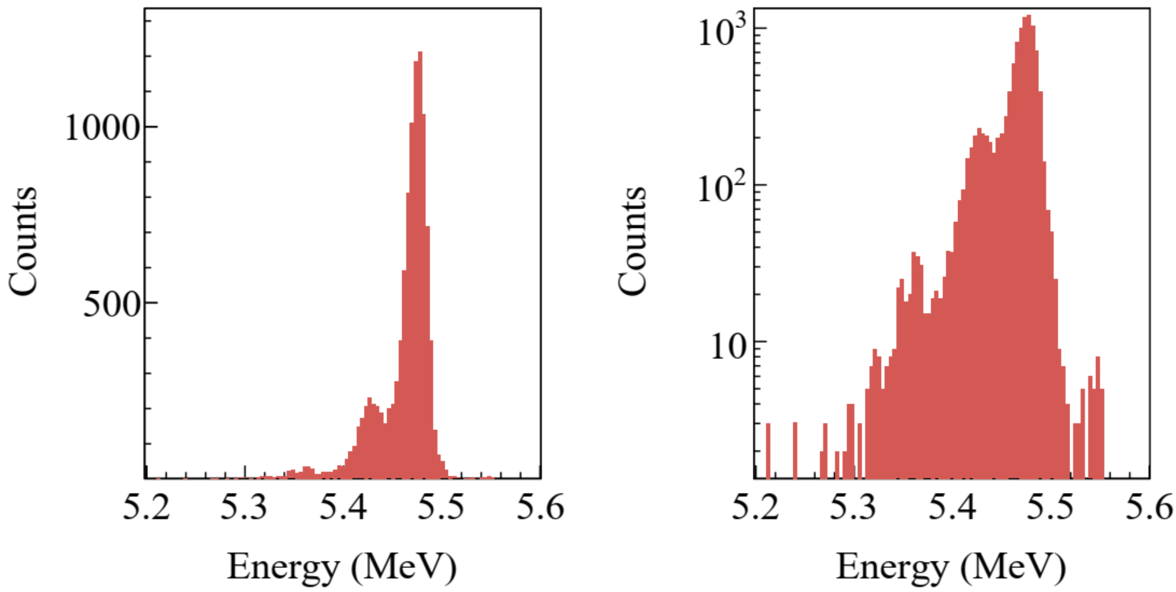

Figure 7. The response function of the PIN diode to the ^{241}Am α-source in linear (a) and logarithmic (b) scale. The FWHM at 5.486 MeV is equal to 21 keV.

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 8. The proton elastic scattering energy at this angle off ^{197}Au is 2.45 MeV. The target composition was derived by a simulation with SIMRA code [31]. By adjusting the target information, the RBS spectrum was well reproduced as the blue line. Note that, for the FWHM determination, the fitting quality is necessary. The Au marked a peak in Figure 8 was induced by 2.45 MeV protons form elastic scattering of p^{297}Au. The detector resolution is 12.2 keV FWHM corresponding to 0.5% energy.

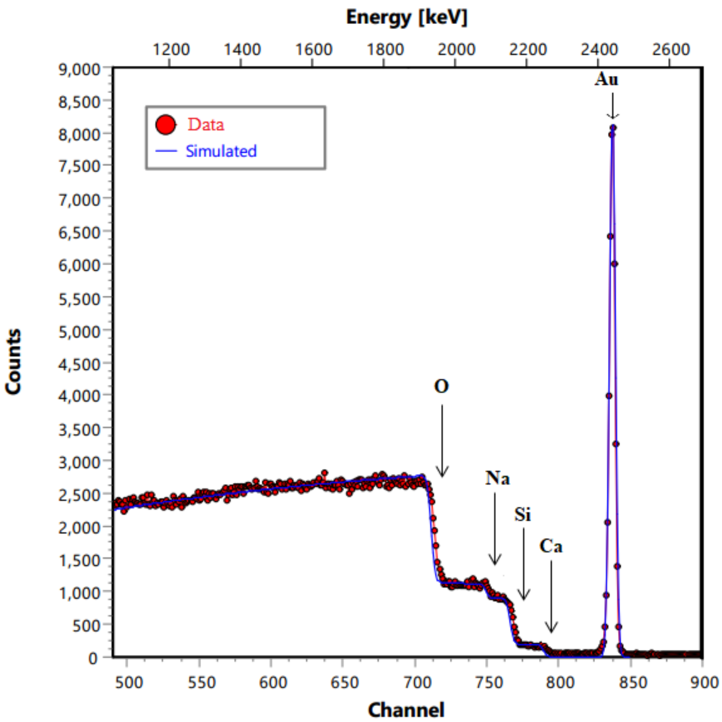

Figure 8. RBS spectrum of protons at 172 degrees scattered on the Au-on-glass target. The experimental data and SIMRA simulation fitting [31] are marked as red and blue, respectively. The arrows indicate the peaks induced by proton scattered of corresponding labeled nuclei.

For the $^{27}Al(p, \gamma)^{28}Si$ reaction with E_p=1.379 MeV, the preliminary gamma spectrum is shown in Fig. 9. This experiment is one of the experiments dedicated to the energy calibration for the HUS Pelletron. Comparing to the result in Ref. [32], two observed peaks were from the environmental ^{40}K and the reaction, respectively.

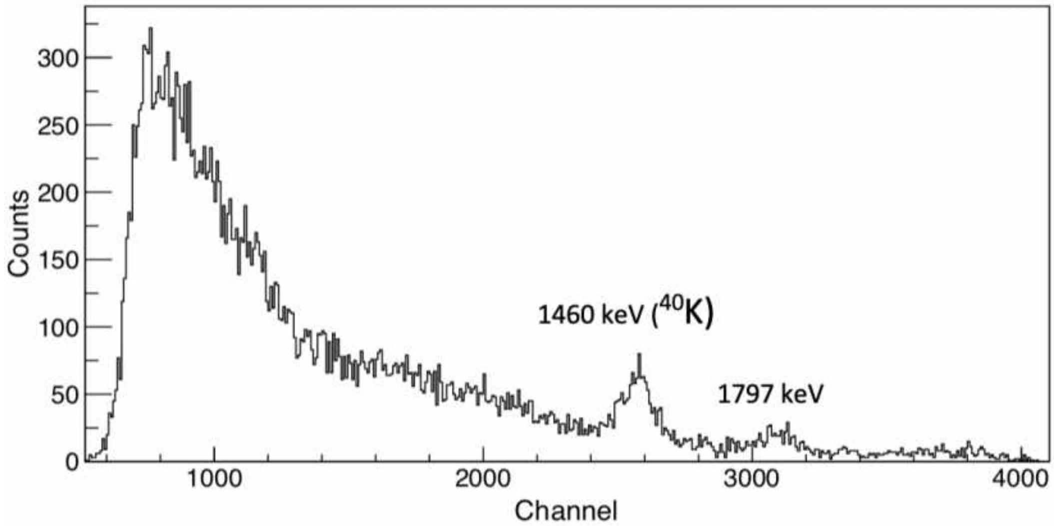

Figure 9. Gamma spectrum from $^{27}Al(p, \gamma)^{28}Si$ with Ep=1.379 MeV. A peak at 1797 keV is observed. Another peak at 1460 keV from ^{40}K is the environmental background.

5. Conclusion

A feasibility study for the upcoming ^{10}B (α, p)^{13}C experiment has been reported. A spectrometer with a VME controller was built and tested with charged and gamma detectors. The test of the PIN diode detector shown that its FWHM is less than 0.5% energy of charged particles, which can resolve $p_{0\text{-}3}$ mentioned in Fig. 2. As a result, both the spectrometer and the PIN diode detector can be used in the upcoming experiment. The information about the FWHM has been used to optimized the target thickness [33]. The spectrometer is also suitable for the study on coincident particles in the future.

Acknowledgment

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Xây dựng hệ đo VME và thử nghiệm các detector Si-PIN diode: Nghiên cứu tiền khả thi cho các thí nghiệm vật lý thiên văn hạt nhân sử dụng máy gia tốc 5SDH-2 Tandem Pelletron tại HUS

Le Xuan Chung[1], B. D. Linh[1], Mai Van Dien[1], Pham Duc Khue[1], Nguyen Duc Ton[1], Bui Thi Hoa[2], Vi Ho Phong[2], Nguyen The Nghia[2], Tran The Anh[2], Phan Viet Cuong[3], and Le Tuan Anh[3]

[1]*Viện Khoa học và Kỹ thuật Hạt nhân, 179 Hoàng Quốc Việt, Cầu Giấy, Hà Nội*
[2]*Đại học Khoa học Tự nhiên, 334 Nguyễn Trãi, Thanh Xuân, Hà Nội*
[3]*Trung tâm Nghiên cứu và Triển khai Công nghệ Bức xạ, Thủ Đức, TP. HCM*

Tóm tắt: Báo cáo trình bày thiết kế logic, kết nối giữa các mô-đun điện tử NIM, VME và chương trình thu thập dữ liệu để xây dựng một hệ thống hoàn chỉnh có nhiệm vụ đọc, ghi số liệu từ detector. Các thí nghiệm kiểm tra detector PIN diode S3590-09 được thực hiện bằng cách sử dụng nguồn ^{241}Am và chùm proton 2,5 MeVtrước khi việc đo đạc thí nghiệm bắn chùm proton 1,379 MeV vào bia Al để tạo phản ứng ^{27}Al(p, γ)^{28}Si được thực hiện; các bức xạ gamma từ phản ứng này được đo bằng detector nhấp nháy NaI. Kết quả thí nghiệm cho thấy sự hoạt động ổn định của hệ. Độ phân giải năng lượng của detector PIN Si nhỏ hơn 0,5% năng lượng của hạt tích điện tới, điều này đáp ứng yêu cầu của thí nghiệm sắp tới.

Từ khóa: thiết bị VME module, chùm proton, detector Si-PIN, máy gia tốc Pelletron, hệ ghi nhận dữ.