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Building a VME spectrometer and testing Si PIN diode detector: a feasibility study for the first nuclear astrophysical experiments using a pelletron

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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 Rutherford elastic backscattering (RBS) protons induced by 2.5 MeV proton beam bombarding on an Au-on-glass target, and with a NaI scintillation detector bombarded by gammas from ^{27}Al(p, γ)^{28}Si reaction with proton beam energy of 1.379 MeV. The test showed that the spectrometer operated steadily and its versatility for different kind of detector. 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.

Keywords: *VME module, proton beam, Si-PIN diode detector, Pelletron, data acquisition.*

I. INTRODUCTION

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. The astrophysical origin of the proton-rich isotopes of heavy elements (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 [1], has significantly solved this problem [2-3]. ^{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 = 1.5-3 GK, corresponding to alpha energy E_α from 0.84-3.4 MeV. Because its yeild is high as shown in Fig.1 in comparison with other reactions. Although this reaction is important the cross sections are still missing at E_α < 1.4 MeV [4, 5]. This 1.5-3 GK temperature range (energy from 0.84-3.4 MeV) is called the Gamov window which offers the highest probability for the ^{10}B(α,p)^{13}C reaction.

For the effort to utilize the Hanoi university of science (HUS) 5SDH-2 pelletron in fundamental nuclear 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. The aim of the upcoming experiment is to measure cross-sections of

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$^{10}B(\alpha,p)^{13}C$ reaction with energies from 0.85-1.4 MeV via the detection of protons from different outgoing channels similar to those reported in [4]. Because, as mentioned above, the data in this energy range is still missing. There are 4 proton types, denoted as p_{0-3}, corresponding to the channels where ^{13}C being in the ground or three first excited states, see Fig. 2. According to the kinematical calculation, their energies spread from about 1 MeV to more than 5.4 MeV depending on its emitted angle.

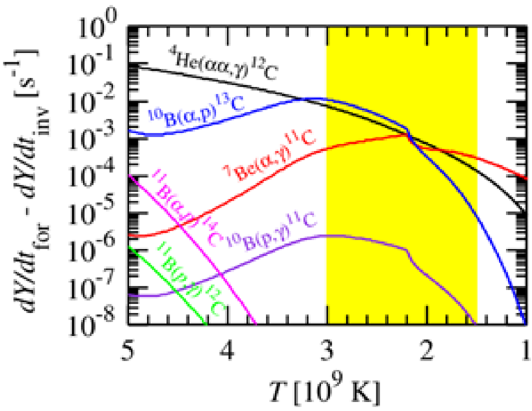

Fig. 1. Nuclear flows ($dY/dt_{for}-dY/dt_{inv}$) for the reactions which bridge from A < 12 to A > 12 as a function of temperature (T). The yellow band indicates the temperature range relevant to the νp-process (T = 1.5−3 GK). This figure is taken from [1]

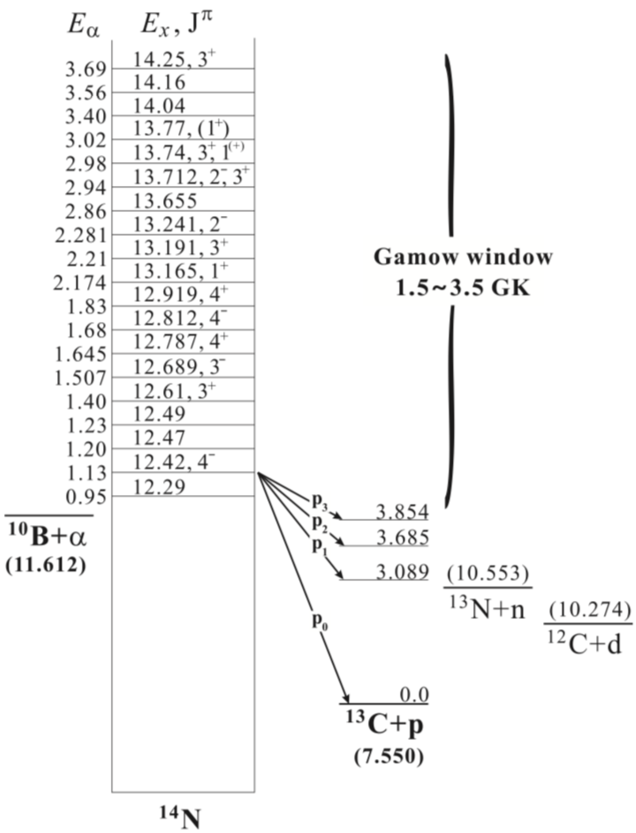

Fig. 2. p_{0-3} protons coincident with ^{13}C being in the ground and three other excited states. Firstly, ^{10}B and α form the ^{14}N compound nucleus. Finally, excited ^{14}N nuclei decay to p_{0-3} and ^{13}C being at the ground and excited states, correspondingly. The illustration is for α energy in the Gamov window. This figure is taken from Ref. [5]

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 to be used in future experiments for outgoing proton detection. In addition, the versatile ability of the readout system is also tested with a NaI scintillation detector for gamma-ray detection which allows the study on coincidences between charged and gamma particles.

II. DETECTOR AND ELECTONIC MODULES

The detectors for charge particles tested in this study and later on used in the experiment mentioned above were bare chip type of Si PIN photodiode S3590-09 [6]. 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 Fig. 3.

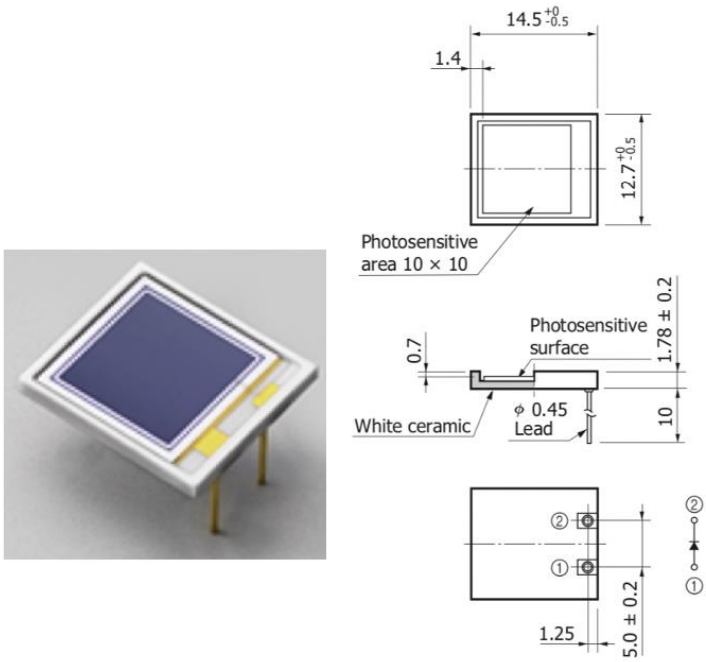

Fig. 3. Photo (left) and dimensional outline (right) of a Si PIN diode S3590-09 [6]

The NaI scintillation detector is a CANBERRA 802 model coupled with a CANBERRA model 2007P photomultiplier tube base (preamplifier). The NaI (Tl) crystal shape is cylindrical with the dimension of 51 mm in height and 51 mm in diameter. Nominal resolution specified at the 662 keV peak of ^{137}Cs is 8.5 % [7].

In the future experiments, $p_{0\text{-}3}$ 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 the last two modules are VME standard, the others are NIM standard. All these modules are produced by the CAEN company [8].

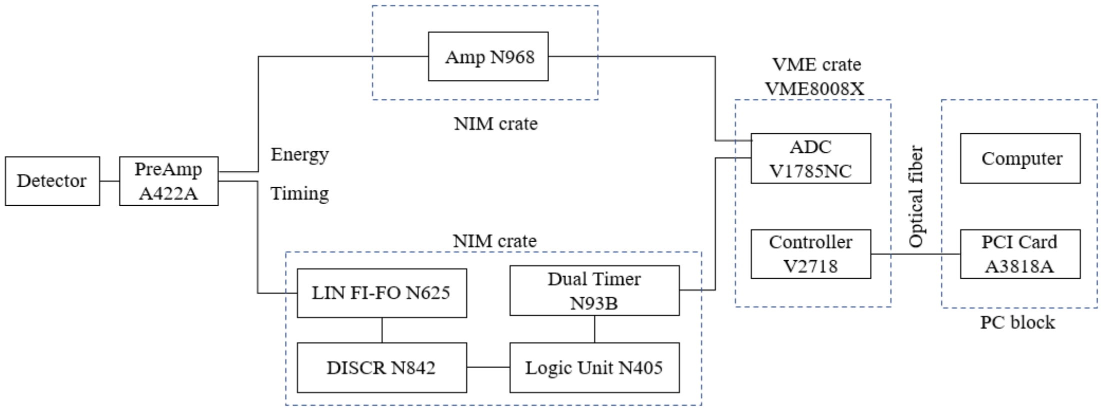

Fig. 4. Electronic scheme of the detector readout system. Details are explained in the text

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. Afterwards, 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 channels of the ADC and the VME controller are 8.

III. 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 [9].

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 frame-work [11].

To estimate the DAQ dead time, the test result shew that about 0.4 % events of the 50 Hz pulser signal was lost when it was fed together with an alpha source's random signal of about 30 events per second. In this test, these signals were connected to one channel (pulser's to the test input of the preamplifier). The OR gate of these signals was generated to trigger the DAQ. If the source signal was randomly coincident with the pulser's the later was lost. In the future experiment, due to very low cross sections of $^{10}B(\alpha,p)^{13}C$ reaction in the Gamov window (the yield is estimated to be less than 10 outgoing protons per second) the loss of detected proton caused by the DAQ dead time can be neglected.

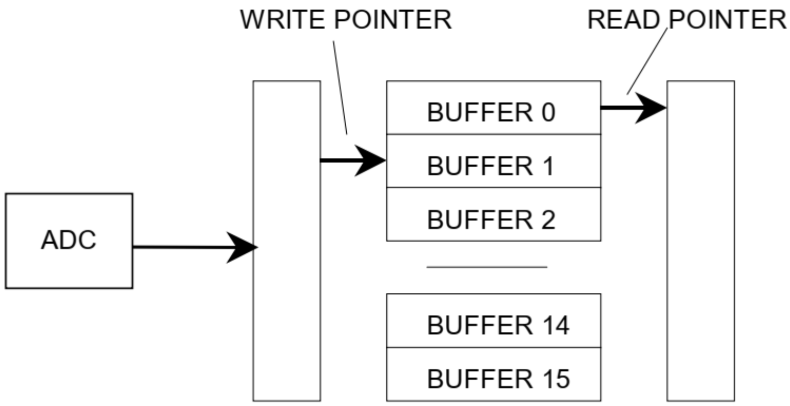

Fig. 5. Multi-event buffer [10]

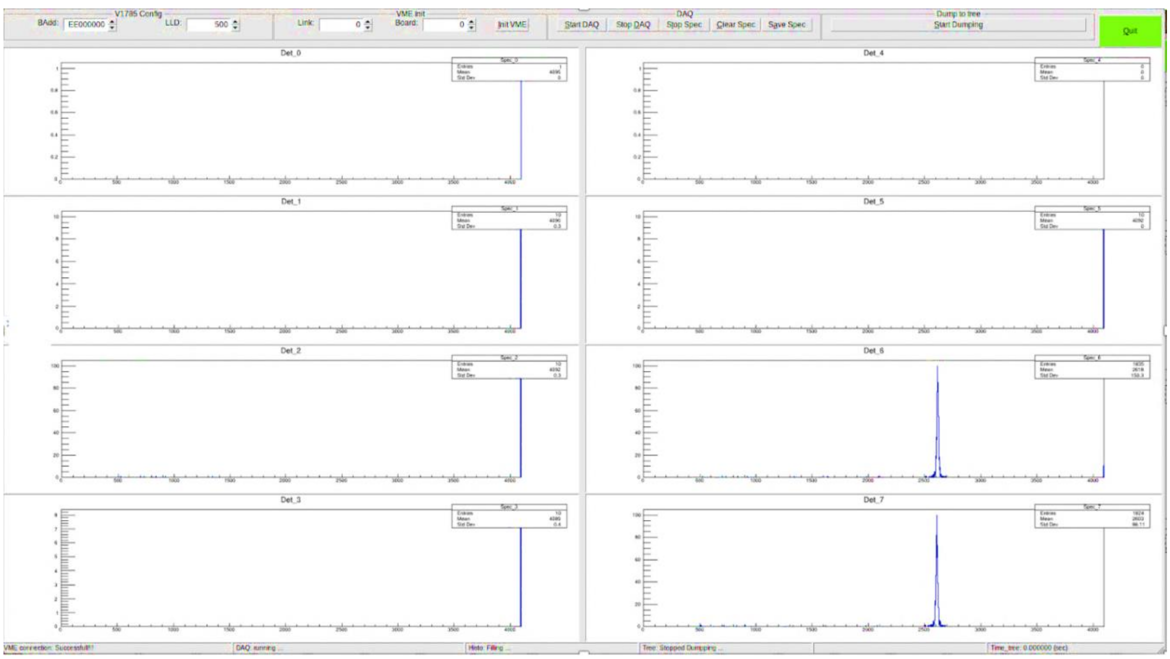

Fig. 6. The user interface of DAQ software. Channel 7 and 8 show the testing signal from a pulser

IV. EXPERIMENTS

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. A further test for change particle detection were done with RBS protons induced by 2.5 MeV proton beam bombarding on the Au-on-glass target. Finally, the $^{27}Al(p,\gamma)^{28}Si$ reaction were used to test the spectrometer for gamma detection with the use of the CANBERRA NaI scintillation detector placed at 42 mm far from the target.

Table I. The most intensive energies of particles emitted from the ^{241}Am α-source and their intensities [12]

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

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 [13]. This effect happens when a particle hits on 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 width half maximum (FWHM) is 21 keV for the 5.486 MeV peak, which is equal to 0.38 % energy.

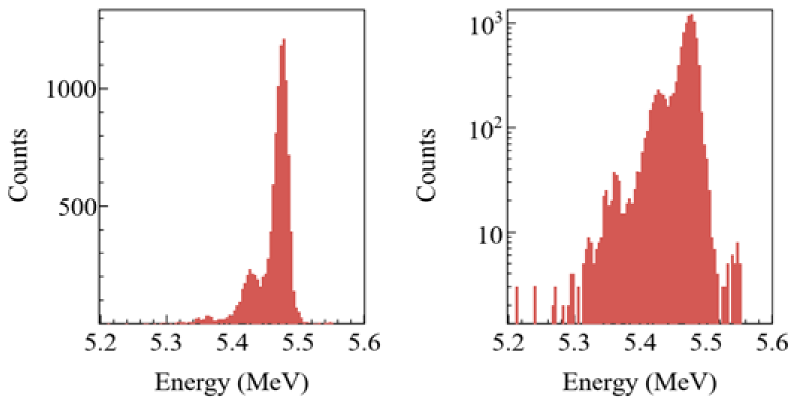

Fig. 7. The response function of the PIN diode to the ^{241}Am α-source in linear (a) and logarithmic (b) scale. The FWHM at 5.486 MeV is equal to 21 keV

The RBS spectrum of protons at 172 degrees induced by 2.5 MeV proton beam on the Au-on-glass target is presented in Fig. 8. According to the scattering kinematics 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 [14]. By adjusting the target information, the RBS spectrum was well reproduced as the blue line. Note that, for the FWHM determination, only the fitting quality is necessary. The Au marked a peak which was induced by 2.45 MeV RBS protons from p^{297}Au elastic scattering. The detector resolution for this peak is 12.2 keV FWHM corresponding to 0.5% energy.

For the cross section measurement in the future experiments, the detector efficiency is important information. The Si PIN diode efficiency for proton detection was estimated by simulation using SRIM code [15]. The results at several energies are presented in Fig. 9. It is seen that the proton transmission happens when its energy is higher than 5.8 MeV. As mentioned in the previous section, the energy range of p_{0-3} is from 1.0 - 5.4 MeV. Therefore, the detection loss due to detector efficiency is neglected.

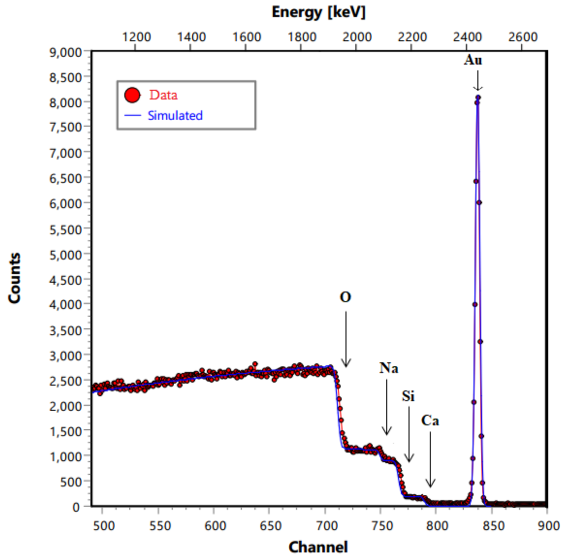

Fig. 8. The response function of the PIN diode to 172º RBS proton induced by 2.5 MeV proton beam on the Au-on-glass target. The experimental data and SIMRA simulation fitting [14] are marked as red and blue, respectively. The arrows indicate the peaks induced by proton scattered off corresponding labeled nuclei

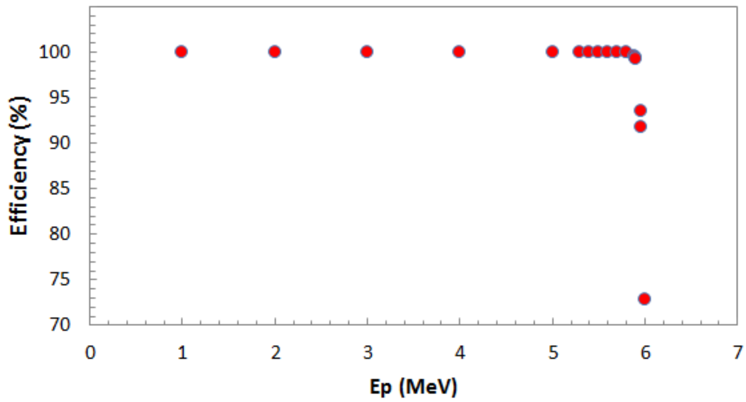

Fig. 9. The simulation of The PIN diode efficiency depending on proton energy

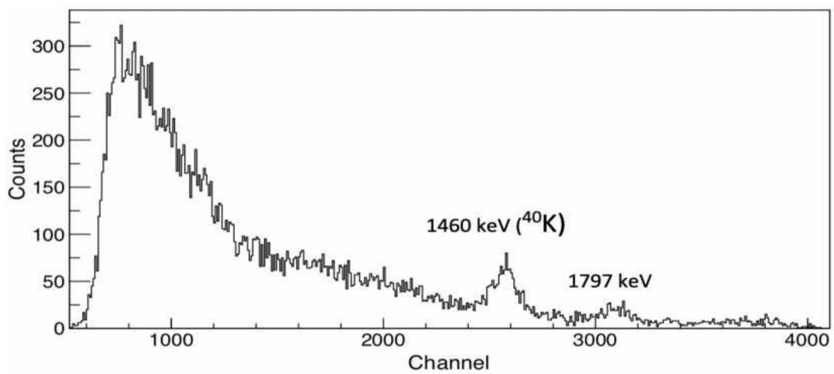

Fig. 10. Gamma spectrum from $^{27}Al(p, \gamma)^{28}Si$ with Ep=1.379 MeV detected by the scintillation detector. A peak at 1797 keV is observed. Another peak at 1460 keV from ^{40}K is the environmental background

For the $^{27}Al(p, \gamma)^{28}Si$ reaction with E_p=1.379 MeV, the preliminary gamma spectrum measured within 40 minutes by the CANBERRA NaI scintillation is shown in Fig. 10. This experiment is one of the experiments dedicated to the energy calibration for the HUS pelletron. Comparing to the result in Ref. [16], two observed peaks were from the environmental ^{40}K and the reaction, respectively.

V. CONCLUSIONS

A feasibility study for the future $^{10}B(\alpha,p)^{13}C$ 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 show that its FWHM is less than 0.5% energy of charged particles, which can resolve $p_{0\text{-}3}$ mentioned in Fig. 2. As the result, both the spectrometer and the PIN diode detector can be used in the future experiment. The information about the FWHM has been used to optimized the target thickness [17]. The results from the test with gamma detection show the spectrometer's versability. It is also suitable for the study on nuclear excited states via the coincidence of gamma and charged particles.

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