Development of Parallel Plate Avalanche Counter for heavy ion collision in radioactive ion beam

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Abstract

We have developed a position-sensitive Parallel Plate Avalanche Counter (PPAC) to detect the fission fragments and reconstruct the fission reaction plane in the experiment of studying nuclear equation of state (nEOS) by means of heavy ion collision (HIC). This experiment put forward high requirements for the performances of PPAC, such as the time resolution, efficiency and position resolution. According to these requirements we designed the PPAC with an active area of 240 mm × 280 mm working at low gas pressure. The results show that time resolution could be less than 300 ps. Position resolution is consistent with the theoretical calculation about 1.35 mm. Detection efficiency could be approaching 100% gradually with the voltage increasing in different gas pressures. The performances of PPAC have also been verified in beam experiment. Each set of anode wires can be accurately separated in the position spectrum. In the beam experiment, we also got the back-to-back correlation of fission fragments which is one of the direct signals characterizing binary decay.

Keywords:
PPAC
nEOS
Time resolution
Position resolution
Efficiency

1. Introduction

Nuclear equation of state (nEOS) is one of the most important research directions in nuclear physics and astrophysics. It links the nature of the atomic nucleus at femtometer scale with properties of the celestial objects in the universe. It characterizes the relationship among temperature, density, size, energy and N/Z composition of nuclear matters. But there are still many uncertain factors when studying the relation between the symmetry energy and the density of nucleons in the nEOS [1,2]. At the super-saturation region, results derived on the pion ratio and neutron-proton flow are model dependent, more experimental and theoretical studies are still needed [3]. At the sub-saturation region, although theories are quite consistent with the experimental results, there is still a lot of room to reduce the uncertainty. Heavy ion collision (HIC) is the most important method in laboratory to understand the symmetry energy [4,5]. It is for this reason that we designed the fission experiment with 30 MeV/n 40Ar beam bombarding on the 197Au in radioactive ion beam Line 1 in Lanzhou (RIBLL1) terminal of Heavy Ion Research Facility in Lanzhou (HIRFL). The main detectors for the experiment are Parallel Plate Avalanche Counters (PPACs), silicon strip detectors and CsI (TI) scintillator detectors [6]. In this experiment we used three PPACs with an active area of 240 mm × 280 mm, operated at low pressure to get the position and time information of the fission fragments [7–9]. The reaction plane can be obtained by the positions of the two fission fragments which are detected in two different PPACs in the two-body events. In this article, we present the PPAC equipped with newly designed two-dimensional position encoding delay-line readout. We have studied its main performances such as position resolution, time resolution and the detection efficiency [10,11], which all meet the expected experimental requirements. The performances of this detector in the beam experiment are given in the fourth part. Finally, a summary is given in Section5.

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2. Design and construction

2.1. Delay-line readout

Delay-line readout method has been widely used to identify the position of ionizing events in gas detectors [12–14]. We use this method for the readout of our large area PPAC. We adopted the commercial delay-line modules from Data Delay Device (3D) company [15], but there is a missing matching inductance between two delay blocks which may cause non-uniformity delay time and may lead to distortion in the position spectrum. In order to use small surface mounted devices (SMD), we design a delay line circuit with LC cells which are integrated at the edge of the anode plate, shown in Fig. 1 and Fig. 2. (b). The anode wires are connected to the multi-tapped delay-line, the position information is determined by the time difference that two signals transmit to either end of the delay-line.

The following factors should be taken into account for parameter selecting: 1) small size, 2) low intrinsic inductance resistance, 3) good thermal stability, 4) counting rate of the detector and rising time of the signal, 5) output impedance is 50Ω. All requirements are related to the quality and technology of the product [12]. Based on the above considerations, we choose the wire-wounded inductor coil on ferrite core (L = 95 ± 0.5% nH) and monolithic ceramic capacitors (C = 39 pF) from Murata. The size of the inductor is 1.6 mm × 0.8 mm (standard 0603) and the capacitor size is 2.0 mm × 1.2 mm (standard 0805).

The parameters of the delay-line, such as the delay time T, characteristic impedance Z, are given as follows:

\[ T = 1.2n\sqrt{\frac{1}{LC}} \]

\[ Z = \frac{1}{\sqrt{L/C}} \]

Where n represents the total number of delay-line cells. L and C represent inductance and capacitance respectively. The calculated characteristic impedance Z is 49.35Ω. The measured average delay time of each cell is 2.070 ns, calculated value is 1.925 ns.

2.2. Construction of PPAC

Fig. 2 (a) shows the structure of the PPAC. It has an active area of 240 mm × 280 mm, and consists of three electrodes: two anodes and one cathode. All the electrodes are kept in parallel to ensure a uniform electric field. The gaps between the electrodes are 4 mm each. At the both sides are the entrance window and the exit window.

The cathode plane, placed in the middle of the PPAC, is made of a double-sided aluminized (30 μg/cm²) Mylar foil and glued between two epoxy frames (PCB) stretching smoothly. The two anode planes consist of gold-plated tungsten wires. The gold-plated tungsten wires, 20 μm in diameter, are placed 1 mm apart and 4 wires are welded on one welding spot. The wires are stretched with a 25-N force and glued between two epoxy frames in parallel. Each group of the anode wires is connected to the delay-line readout circuit except the one set at the two edges, which are grounded for reducing the edge effect. The X and Y anode plates were assembled on each side of the cathode orthogonally. Both the entrance and exit windows which used to seal the filling gas are made of 2 μm thick single-sided aluminized Mylar foils, supported by fishing line grids and finally integrated on the aluminum frame. In this way, our PPAC can withstand a maximum pressure of about 15 mbar.

3. Test and performance

The alpha source(239Pu) tests are conducted to get the performances of the PPAC, including time resolution, position resolution, detection efficiency and long-term work stability. In order to get the relative detection efficiency and the time resolution, a small PPAC (The small PPAC [15,16] has similar structures to the PPAC which we tested, the major difference is the active area. The small PPAC’s active area is 100 mm × 100 mm. Hereinafter called Small PPAC) is placed behind the tested PPAC (Hereinafter called Large PPAC). The alpha source is placed in front of the entrance window of Large PPAC [17], shown in Fig. 3. The Large PPAC and the Small PPAC are connected together filling with flowing gas C4H10. In order to get the performances of the Large PPAC in different gas pressures, we change the pressure from 5 mbar to 8 mbar, with a step of 0.5 mbar.

In the tests, a negative voltage was applied on the cathode plane. And the voltage was changed several times at a certain gas pressure, for the purpose of getting the relationship between alpha detection efficiency and voltage accurately.

Fig. 4 shows the data acquisition scheme used in laboratory tests. There are five signals for a PPAC:T is the time signal from the cathode plane, X1 and X2 are the time signals from either side of the anode in X direction, while Y1 and Y2 are the time signals from either side of the anode in Y direction.

All the signals are amplified by Fast Timing Amplifiers (FTA820, ORTEC) with a gain of 200. Signals out from FTA are discriminated by Constant-Fraction Discriminators (CF8000, ORTEC). The T signal of the Small PPAC, is delayed and broadened by a logic unit (CO4020, ORTEC). After that, it is transmitted to a Time-to-Digital Converter (TDC, CAEN V775) as a trigger signal. All the other signals are sent directly from the ECL output of the CF8000 to the TDC with a 30-m twisted-pair cables.

3.1. Time resolution

Fig. 3 shows the arrangement of the tests. For a certain gas pressure, we adjusted the operating voltage of the Small PPAC to make its alpha detection efficiency be approximately 100%. And then adjusted cathode voltage of Large PPAC to test the time resolution at different pressures.
The time resolution is defined as follows. We use the T signal of the Small PPAC as trigger then acquire the T signal of the Large PPAC as time spectrum. Then use Gaussian function to fit it and the FWHM is defined as the time resolution of the Large PPAC. The range of the TDC is set to 400ns/4096 channels, the time resolution 261.9 ps is derived at 6.5 mbar gas pressure with 630 V as shown in Fig. 5(a). It is notable in Fig. 5(b) that the time resolution improves with the increasing voltage of Large PPAC at different pressures which changes from 5 mbar to 8 mbar.

3.2. Efficiency and long-term work stability

According to the setup of laboratory test (see in Fig. 3), we use the T signal of the Small PPAC as the trigger. Based on this, there are two situations for the detection of alpha particles. First, the alpha particle can be detected by Small PPAC only, we define this case as an invalid event. Second, alpha particle can be detected by two PPACs, which we define as an effective event. The detection efficiency \( \eta \) could be calculated by the formula:

\[
\eta = \frac{N_E & N_L}{N_S}
\]

Where \( N_S \) is the counts of the T signal of Small PPAC and \( N_L \) is the counts of the T signal of Large PPAC which we tested. \( N_E & N_L \) is the coincident event numbers of the two T signals from Large PPAC and Small PPAC, represents the alpha particles which can be detected by two PPACs. In the experiment, the Small PPAC was adjusted to work on the best condition, and the maximum voltage applied to two PPACs is kept on 10 V below the breakdown value to avoid sparking. Fig. 6(a) shows the efficiency as a function of the working voltage under different pressures. The efficiency of tested PPAC is about 100% when cathode working at voltages of \( \frac{655}{8} \) V (8 mbar) and \( \frac{600}{5.5} \) V (5.5 mbar). The efficiency test not only represents the performance of the detector, but also provides a reference to select the best working point of the PPAC used in the beam experiment. Since the long-term working stability of detector is very important, we measured the efficiency over 120 h under \( \frac{650}{7.5} \) V and 7.5 mbar pressure. As shown in Fig. 6(b), the efficiency curve fluctuates slightly and remains above 95%.

3.3. Position resolution

The position resolution of PPAC describes the positioning accuracy of the detector for incident particles, it represents the minimum space distance to separate two particles. PPAC determines the position of the incident particle by distinguishing the output signals on the anode wires. The distance between two adjacent wires is 1 mm, so for a set of wires we can calculate the position resolution by the formula:

\[
\sigma = \pm \frac{S}{\sqrt{12}} \times A
\]

Where S is the distance between the two sets of wires, and A is a correction factor less than one, \( \sigma \) is the variance of the Gaussian
distribution [18] which is defined as the position resolution of detector. The position resolution by theoretical calculation equals to 1.155 mm approximately. In the experiment we put the source 0.5 m away from the entrance window to provide a full detector image. The position spectrum of X plane is shown in Fig. 7(a). It can be observed that the signal on each set of wires corresponds to a peak on the position spectrum and two adjacent peaks can be well distinguished. Gaussian function fits are applied to all the 61 peaks in Y direction and 71 peaks in X direction. The variance adopted as position resolution for both layers, the result is distributed between 1.325 mm and 1.395 mm. It is in good agreement with the theoretical calculation.

4. Beam test

This section describes the performance of PPAC in the experiment in the Large Scattering Chamber (LSC) at the RIBLL1. The experiment uses 30MeV/n$^{40}$Ar beam bombarding on a self-sustained gold target with the thickness of 674 μg/cm². General design of the experiment is shown in Fig. 8. Three PPACs were placed 426.5 mm away from the target to test the fission fragments in the experiment. And we also used two telescopes consisting of silicon strip detectors and CsI(Tl) scintillator detectors as ΔE-E detector to detect the light charged particles emitted at small angles. The angles between the normal direction of the cathode of the PPACs and the beam was defined in Fig. 8(b).

In the beam experiment, PPACs were filled with C$_4$H$_{10}$, working at 4.5 mbar with the voltage -450 V. Fission events were selected by requiring that two PPACs were fired at the same time. Fig. 9 shows the energy spectrum of particle energy deposition in one of the PPACs. The front part of the energy spectrum (dividing line) should be intermediate mass fragments and the rear part comes from fission fragments. Based on this energy spectrum, we could set the threshold to be higher than the energy of the front part, which could help us to cut off the contributions from intermediate-mass fragments and light charged particles. It’s very helpful for us to do the subsequent data analysis, since we are only interested in the detection of fission fragments for PPACs.
Fig. 10. Displays the two-dimensional scatter plots of the fission fragments in beam experiment. The typical position spectra measurement for X direction (vertical with the bottom of LSC) and Y direction (horizontal with the bottom of LSC) are also shown in the figure.

Compared to other events, in the processes of medium or low energy nuclear reactions, the main feature is the two massive fragments produced with azimuthal angle correlation. Based on the principle of conservation of momentum, the azimuthal projection of the velocity vectors of the two fission fragments from the target-like fragment are anti-parallel. So it is significance to confirm the back-to-back correlation between two fragments by analyzing the data detected by PPACs. It is the direct signal not only characterizes binary decay but also characterizes the performance of the detector. Fig. 11 presents the azimuthal angle correlation of two fragments.

It is shown that in the decay events, the angle between two fission fragments is 180° centered and widened. There are two main reasons for the width. First, after deep elastic scattering between the projectile nucleus and the target nucleus, projectile like fragments keep flying with a small angle deviation along the X-axis. And the speed of target like fragments is not zero in transverse plane. Second, the fission fragments in the excited state keep evaporating light particles and the recoil of these particles will change the direction of the fission fragments.
different gas pressure with the voltage increasing. We also tested the long-term work stability with the cathode voltage ~650 V at pressure 7.5 mbar. The detector efficiency can maintain above 95% which proved that the large area PPAC on this condition could be reliably and efficiently operated. The performances have been verified in a beam experiment of the bombardment of 30MeV/n\textsuperscript{40}Ar on \textsuperscript{197}Au target. According to the experimental data from two PPACs on both sides of the beam, we measured the back-to-back correlation of two fission fragments accurately, which characterized the working status of PPAC and diagnosed the reliability of acquired data.

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