Performance Study of Low-Pressure Multi-Wire Proportional Chamber Detectors

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Abstract

As an anti-coincidence measurement module in the detection system of the SHANS (Spectrometer for Heavy Atoms and Nuclear Structure), the multi-wire proportional chamber is primarily used for the detection of heavy ions. Since heavy ions incur energy loss within the entrance window material, 1 μm thick aluminized Mylar was selected as the entrance window material in the experiment to balance energy loss and pressure-bearing capacity. To reduce the stress on the membrane and extend the detector' s lifespan, the experiments were conducted in a low-pressure environment, utilizing the delay-line method and the charge-division method for signal readout, respectively. By analyzing the performance of the multi-wire proportional chamber detector under these two different readout methods, the results demonstrate that under low pressure, the cathode-anode coincidence efficiency of the charge-division method can exceed 90%, with a position resolution better than 1 mm. When the gas pressure drops to 3 mbar, the charge-division method can still operate stably, achieving an optimal position resolution of 0.64 mm. Therefore, the multi-wire proportional chamber employing the charge-division method is more suitable for achieving long-term stable operation in SHANS experiments.

Full Text

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Abstract

As an anti-coincidence measurement module within the detection system of the Lanzhou Gas-Filled Recoil Separator (SHANS), the Multi-Wire Proportional Chamber (MWPC) is primarily utilized for the identification of heavy ions. Given that heavy ions experience significant energy loss when passing through incident window materials, the experiment employs a specific material for the incident window to balance energy loss with pressure-bearing capacity. To reduce the mechanical stress on the membrane and extend the operational lifetime of the detector, experiments were conducted under low-pressure environments. Signal readout was performed using two distinct methods: the delay-line method and the charge-division method.

This study analyzes the performance of the MWPC detector under these two different readout configurations. The results demonstrate that under low-pressure conditions, the coincidence efficiency between the anode and cathode using the charge-division method can reach 100%, with a position resolution superior to that of the delay-line method. Furthermore, the charge-division method maintains stable operation even at low gas pressures, achieving an optimal position resolution of 0.5 mm. Consequently, the MWPC utilizing the charge-division readout method is better suited for achieving long-term stable operation during experiments at the Lanzhou Gas-Filled Recoil Separator.

Keywords: Low-pressure multi-wire proportional chamber (MWPC); Delay-line method; Charge-division method; Coincidence efficiency; Position resolution.

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1. Introduction

In the field of nuclear physics, the synthesis of heavy nuclides and the study of their decay characteristics—particularly in regions far from the line of stability—represent critical research topics for understanding nuclear structure and nuclear force interactions. Investigating the decay paths and nuclear structure information of new nuclides is of great significance for expanding the boundaries of the nuclear chart and exploring the properties of unknown isotopes. The Spectrometer for Heavy Atoms and Nuclear Structure (SHANS), a high-precision nuclear spectrometer system located in Lanzhou, has been widely utilized in decay experiments for new nuclides.

To effectively extract decay information, the system must be equipped with detectors capable of providing Time-of-Flight (ToF) measurements to facilitate anti-coincidence measurements. The anti-coincidence measurement module requires detectors that achieve high spatial and temporal resolution while minimizing energy loss for heavy ions. Consequently, these detectors must operate under extremely low gas pressure, which further intensifies the requirements for the detector' s low-pressure adaptability. In 1968, based on the successful designs of spark chambers and proportional counters, physicists developed the Multi-Wire Proportional Chamber (MWPC). As a highly sensitive instrument, the MWPC has become a cornerstone of modern particle detection.

As a position-sensitive detector, the MWPC possesses excellent spatial resolution, fast response capabilities, and long-term stable performance, leading to its widespread use in international nuclear physics experiments for ToF measurements. Its ability to maintain stable performance specifically under low-pressure conditions makes it an ideal choice for detecting heavy ion processes. In experiments conducted at the SHANS spectrometer in Lanzhou, the superior time response characteristics of the MWPC provide critical support for ToF measurements. While systematic research on the MWPC continues to advance within domestic programs, there remains significant room for further evaluation regarding its operational stability under even lower pressure conditions and the impact of various readout methods on key performance metrics. This paper describes the assembly of two sets of MWPCs utilizing the delay-line method and the charge-division method, focusing on investigating their performance in low-pressure environments.

2. Ion Penetration Simulation using SRIM-TRIM

In heavy-ion detection experiments, incident particles collide with the detector' s entrance window, resulting in energy deposition. Because excessive energy loss can significantly degrade measurement precision, it is essential to carefully select the material and thickness of the entrance window. Gas detectors typically utilize Mylar film due to its high mechanical strength and excellent transmission properties. However, selecting the appropriate thickness requires a trade-off between energy loss and mechanical stability.

This study focuses on typical fusion-evaporation reactions involving superheavy elements, such as the production of ^{252}No. In this reaction, the total excitation energy of the products is approximately E^*, with a residual kinetic energy of approximately E_k. Taking ^{252}No as a representative ion, the impact of different thicknesses of aluminized Mylar films on its energy loss was calculated using the SRIM module. The results demonstrate a clear trend where energy loss increases with film thickness. Despite the advantages of Mylar in controlling energy loss, its mechanical stability is a concern; however, it provides superior stability compared to other ultra-thin alternatives. Considering both energy loss control and mechanical reliability, the experiment ultimately selected Mylar film as the entrance window material to achieve an optimal balance.

3. Experimental Setup

The experimental setup of the Low-Pressure Multi-Wire Proportional Chamber (LPMWPC) detector is divided into three primary components: the flow-type pressure-stabilized target chamber, the multi-wire proportional chamber detection system, and the electronics and data acquisition system.

3.1 Gas System and Detector Structure A pressure gauge is used for real-time monitoring of the gas pressure within the MWPC, while a vacuum gauge monitors the pressure of the vacuum chamber. During evacuation, a communication valve ensures pressure equilibrium to prevent window rupture. To satisfy the ionization and quenching requirements for low-pressure operation, isobutane (C_4H_{10}) is employed as the working gas, providing stable gain at relatively low operating voltages.

The detector consists of one cathode and two anodes, enabling the recording of two-dimensional coordinates. The anodes are composed of gold-plated tungsten wires arranged with uniform spacing. To demonstrate position resolution, an aperture (collimator) structure with a grid of small holes was placed over the incident window.

3.2 Readout Methods Two readout methods were tested: 1. **Delay-line method:** Each wire is treated as a delay unit. The relative position of the signal is determined by the time difference $(t_1 - t_2)$ between the signals reaching the ends of the delay line. 2. **Charge-division method:** This method utilizes a resistor chain. The incident radiation induces signals that undergo different voltage divisions across the resistors. By calculating the difference between these charge values and normalizing it against the total charge, the relative position is determined.

4. Results and Discussion

4.1 Coincidence Efficiency We evaluated the coincidence efficiency between the cathode and anode for both methods. The coincidence efficiency η is defined as:

$$\eta = \frac{\min(X, Y)}{N_{cathode}}$$

The results show that the charge-division method consistently maintains a coincidence efficiency exceeding 95% across a pressure range of 2–30 mbar. In contrast, the delay-line method shows a sharp decline in efficiency when the pressure falls below 10 mbar. This is primarily due to the fixed amplitude threshold of the constant fraction discriminator (CFD); as gas pressure decreases, the reduced number of primary ionized electrons leads to lower signal amplitudes that fail to trigger the electronics.

4.2 Position Resolution To test spatial resolution, a ^{241}Am alpha source was used. One-dimensional position spectra were obtained by applying Gaussian fits to the peaks generated by the aperture structure. The position resolution R is calculated as:

$$R = \frac{FWHM_i}{mean_{i+1} - mean_i} \cdot d$$

where d is the actual hole spacing.

Figure 2

Figure 1: Figure 2

Figure 3

Figure 2: Figure 3

Experimental data indicates that while the delay-line method provides high precision at moderate pressures, it fails to operate at extremely low pressures due to signal attenuation. The charge-division method, however, remains operational down to 3.1 mbar, maintaining a position resolution better than 1 mm (reaching an optimal 0.5 mm). This is because the charge-division method relies on charge ratios rather than absolute timing thresholds, making it more robust in low-ionization environments.

5. Conclusion

This study systematically investigated the performance of LPMWPCs under different readout configurations. The results demonstrate that the charge-division method offers superior detection performance under extreme low-pressure conditions. It maintains high coincidence efficiency and stable position resolution even when the gas pressure is reduced to approximately 3 mbar. These findings indicate that the charge-division readout method is the most suitable choice for the SHANS focal plane detection system, providing reliable support for the high-sensitivity detection of new nuclides and superheavy elements.

Figures

Figure 4

Figure 3: Figure 4

Figure 5

Figure 4: Figure 5