Simulation and Optimization of Key Technical Parameters of an Active-Target Time Projection Chamber

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Abstract

The active-target Time Projection Chamber (TPC) detection technology, by using the working gas simultaneously as both the reaction target and the detection medium, effectively resolves the contradiction between low beam intensity and high measurement precision in radioactive beam experiments. Starting from the operating principles of the detector, this paper systematically analyzes multiple factors that affect detection performance and measurement accuracy, including electric-field uniformity, electron drift velocity, suppression of ion backflow in the multiplication process, gating grid operation, noise induced by the δ electron effect, as well as the readout and reconstruction of electronic signals. Using the Garfield++ simulation software, the study performs systematic numerical simulations and optimizations of the above key parameters, and proposes a series of corresponding solutions and optimization strategies. The results show that a double-layer field-shaping ring structure can effectively improve the uniformity of the electric field; in a standard GEM structure, the single-layer ion backflow fraction is 31.95%, whereas in Micromegas under the same conditions it can be reduced to 8.18%, exhibiting superior ion-suppression capability; when the voltage difference between odd and even wires of the gating grid is 150 V, a fully closed state can be achieved, with the electron transmission rate approaching 0%, and the electron transmission rate can be flexibly controlled by adjusting the field ratio. Based on the comprehensive optimization of these detection techniques, the active-target Time Projection Chamber is expected to enable efficient measurements of direct nuclear reaction processes, thereby providing important experimental data for elucidating key astrophysical nucleosynthesis processes and exploring exotic nuclear structures and other frontier physics problems.

Full Text

Preamble

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Abstract

The active-target time projection chamber (TPC) detection technology, which uses the working gas as both the reaction target and detection medium, effectively resolves the inherent conflict between low beam intensity and measurement precision in radioactive beam experiments. Starting from the detector’ s operational principle, this paper systematically analyzes multiple factors that influence detection performance and measurement accuracy, including electric field uniformity, electron drift velocity, ion feedback suppression during the multiplication process, gating grid operation, noise interference from δ-electron effects, and electronic signal readout and reconstruction. Using the Garfield++ simulation software, this study conducts systematic numerical simulations and optimizations of these critical parameters and proposes a series of corresponding solutions and optimization strategies. The results demonstrate that adopting a dual-layer field-shaping ring structure can effectively improve electric field uniformity. In a standard GEM structure, the single-layer ion back-flow rate is 31.95%, while Micromegas can reduce this to 8.18% under identical conditions, exhibiting superior ion suppression capability. The gating grid can achieve a fully closed state with electron transmission approaching 0% when the voltage difference between odd and even wires is 150 V, and the electron transmission rate can be flexibly controlled by adjusting the electric field ratio. Based on the comprehensive optimization of these detection technologies, the active-target time projection chamber is expected to enable efficient measurement of direct nuclear reaction processes, thereby providing crucial experimental data for revealing key astrophysical nucleosynthesis processes and exploring exotic nuclear structures.

Key words: active-target time projection chamber; ion back-flow; δ-electron; Garfield++

1. Introduction

Since the 1980s, radioactive beams have been at the forefront of nuclear physics research. Based on radioactive beam technology, scientists have been able to study nuclei far from the β-stability line, providing new avenues for exploring novel phenomena and laws under extreme conditions. Among these, direct nuclear reaction studies using radioactive beams represent an important means for investigating exotic nuclear structures. Typical direct nuclear reactions (such as elastic/inelastic scattering and transfer reactions) provide rich nuclear structure information and serve as crucial tools for studying collective nuclear motion, magic number and shell evolution, and the formation of exotic structures. Simultaneously, direct nuclear reactions provide critical experimental data for frontier topics such as key element formation processes in astrophysical nucleosynthesis and symmetry theory verification.

Experimentally, radioactive beam experiments typically employ inverse kinematics, where radioactive heavy ion beams bombard light nuclear targets. However, radioactive beam intensities are often several orders of magnitude lower than stable beams. To obtain sufficient statistics, thick target materials are required. Traditional solid or liquid thick targets introduce significant energy straggling and reaction vertex positioning errors, severely impacting measurement precision, particularly for low-energy ejectile detection. The active-target time projection chamber (TPC) emerges as a transformative detection technology that effectively resolves the conflict between statistics and measurement precision by using the working gas as both reaction target and detection medium. This technology not only provides a large effective target thickness to accommodate low beam intensities but also enables three-dimensional particle track detection. By reconstructing reaction vertices, it significantly reduces precision errors caused by thick targets, offering an ideal measurement solution for radioactive beam experiments. These advantages have established the active-target TPC as an important tool in radioactive beam experiments.

The nearly 4π solid angle detection capability of active-target TPCs allows acquisition of relatively complete reaction angular distributions in a single experiment. Combined with low detection thresholds, they can efficiently identify reaction channels and reconstruct excitation spectra using the missing mass method, thereby enabling precise extraction of differential cross sections. As a critical link between experimental observations and theoretical models, experimental differential cross sections are compared with calculations from nuclear reaction theories such as the Distorted-Wave Born Approximation (DWBA) to quantitatively extract key nuclear properties like spectroscopic factors and deformation parameters, contributing to the understanding of frontier physics problems such as magic number evolution and cluster structures in exotic nuclei.

Structurally, time projection chambers are mainly divided into cylindrical and rectangular geometries. Rectangular TPCs typically arrange the readout plane parallel to the beam direction, allowing targeted design of the sensitive region size according to physics requirements. Cylindrical TPCs adopt a symmetric design with the readout plane generally perpendicular to the beam direction, achieving uniform detection region coverage. Additionally, introducing a magnetic field to constrain charged particle motion can significantly enhance TPC performance. Under magnetic fields, particles with different magnetic rigidities ($B\rho$) have different curvature radii, enabling momentum reconstruction and particle identification.

Currently, various TPCs have been built worldwide, such as AT-TPC at MSU, MATE-TPC at IMP, ACTAR TPC at GANIL, and MAIKo at RCNP. These detectors emphasize different technical routes and implementations, but their performance all depends on optimization of key technical parameters including electric field uniformity, working gas, ion feedback, electron transmission rate, and signal reconstruction algorithms. However, existing TPCs typically employ only partial technical solutions, lacking comprehensive simulation and systematic discussion of these methods.

With the upcoming completion of the new generation High-Intensity heavy-ion Accelerator Facility (HIAF), which will play a key role in frontier fields such as nuclear existence limits, exotic structures, nuclear matter properties under extreme conditions, and astrophysical r-process nucleosynthesis, these scientific goals impose higher requirements on detector performance. To achieve efficient and reliable application of TPCs in direct nuclear reaction studies at HIAF, this paper combines calculations and Monte Carlo simulations to systematically analyze and optimize several key technical parameters affecting performance, thereby enhancing experimental data quality.

2. Time Projection Chamber Detection Technology

During operation, the active-target TPC's sensitive volume is filled with working gas that serves as the reaction target, such as pure hydrogen (H_2), deuterium (D_2), or helium (He). Sometimes small amounts of polyatomic molecular gases are added to increase electron drift velocity, enhance ionization energy loss, and improve stability at high gain. As shown in Figure 1 [Figure 1: see original paper], beam particles undergo nuclear reactions with target nuclei in the sensitive region, producing recoil and residual nuclei. These ejectiles ionize gas atoms along their trajectories, creating free electron-ion pairs. Under an applied electric field, electrons and ions drift toward the multiplication electrode (readout plane) and cathode, respectively. When electrons reach the multiplication electrode, electron avalanches occur, and the multiplied electrons induce current signals on the readout plane. The readout plane consists of multiple independent pixelated pads. By analyzing the relative positions and signal timing of triggered pads, the particle track projection in the X-Y plane can be reconstructed. Combined with the electron drift time to the readout plane, the Z-coordinate of the track can be determined, enabling three-dimensional track reconstruction. Additionally, particle identification and energy reconstruction can be performed based on particle range and deposited energy using the Bethe-

Bloch energy loss model.

The reconstructed reaction vertex, particle energy, and scattering angle θ can be used to extract differential cross sections. Experimental differential cross section measurement is based on counting the angular distribution of scattered particles. As shown in Figure 2 [Figure 2: see original paper], for an incident particle flux I bombarding a reaction target (areal density n), the number of scattered particles detected within the differential solid angle $d\Omega = 2\pi \sin\theta d\theta$ at scattering angle θ is denoted as $dN(\theta)$, with event reconstruction efficiency η. By definition, the differential cross section can be calculated using Formula 1:

$$\frac{dN(\theta)}{I \cdot n \cdot \eta \cdot d\Omega}$$

Differential cross section is a key physical quantity characterizing the angular distribution of nuclear reaction probabilities. Its angular distribution features, such as the angle corresponding to the first extremum, strongly depend on the transferred or excited angular momentum l during the reaction. Therefore, differential cross sections serve as important probes for studying nuclear reaction mechanisms and nuclear structure.

However, achieving high-precision three-dimensional track reconstruction and differential cross section measurement requires overcoming several key technical challenges. Section 2.1 will first discuss electric field uniformity, which is fundamental for ensuring electron drift and achieving position resolution. Section 2.2 will analyze the characteristics and calibration methods of electron drift velocity, a parameter that determines the Z-coordinate reconstruction precision of particle tracks. Section 2.3 will focus on the multiplication electrode for electron signal amplification and discuss how to suppress positive ion feedback to reduce space charge effects. Section 2.4 will introduce gating grid technology, which can control electron transmission according to physics requirements. Section 2.5 will analyze the noise interference caused by δ-electrons from charged particles and corresponding mitigation strategies. Finally, Section 2.6 will elaborate on electronic signal processing and reconstruction procedures, including the establishment of front-end electronics response models, which are crucial for accurately extracting physical information from raw signals. The following sections provide detailed analysis and discussion of these technologies.

2.1 Electric Field Uniformity

The electric field uniformity of the detector’ s field cage is a critical factor affecting electron collection. When the electric field distribution is non-uniform, electrons experience non-uniform electric forces during drift, causing trajectory distortion and random deviations that degrade position resolution. Therefore, electric field uniformity must be carefully considered and optimized in detector design. For instance, to address electric field distortion that commonly occurs near field cage edges, field-shaping rings are typically used to equalize the field. This technique applies a gradient voltage across adjacent rings through series-connected equal resistors, creating equipotential surfaces where the potential drops uniformly between rings, thereby establishing a uniform electric field within the field cage. This design shields external fields and reduces edge region distortion, improving field cage uniformity and position resolution. In engineering implementation, final parameters for this structure are typically determined through finite element software modeling and iterative parametric optimization based on the aforementioned principles. Taking the AT-TPC developed by Michigan State University as an example, its dual-layer field-shaping ring design further optimizes the electric field distribution, resulting in highly uniform electric field lines within the field cage.

2.2 Electron Drift Velocity

Electron drift velocity is a key operating parameter in gas detectors. Faster drift velocity helps reduce electron recombination probability and collection time, thereby improving detector response capability, while slower drift velocity benefits time positioning precision. In active-target TPCs, the electron drift time from the production point to the readout plane determines the Z-coordinate of particle tracks, making slower drift velocity advantageous for improving Z-position resolution.

Understanding the characteristics of electron drift velocity as a function of electric field provides an important basis for reasonable detector operating voltage settings. Garfield++ is an object-oriented software toolkit developed by CERN that can simulate particle transport processes and signal formation mechanisms in gas or semiconductor detectors in detail. Using Garfield++' s MediumMagboltz class to simulate electron drift velocity in gases, the generated gas files also include parameters such as transverse diffusion coefficient, longitudinal diffusion coefficient, and electron attachment. These simulated gas properties have high accuracy and have been validated in numerous publications. Simulations were performed for commonly used TPC working gases: pure hydrogen (H_2), deuterium (D_2), and the commonly tested P10 gas (90% Ar + 10% CH_4). With operating pressure set to 600 Torr, temperature 293.15 K, and tracking simulation collision count of 10^8, the electron drift velocity simulation results are shown in Figure 3 [Figure 3: see original paper].

The results show significant differences between H_2 and D_2 electron drift velocity curves. This phenomenon arises because the Magboltz program primarily considers scattering processes between free electrons and gas molecules when calculating electron transport parameters, with interaction cross sections determined by molecular electron wavefunctions. Since electron drift velocity is essentially a statistical result of numerous collision processes, the difference mainly stems from momentum transfer variations caused by different atomic masses. Furthermore, H_2 and D_2 have relatively low electron drift velocities. When mixed with polyatomic molecular gases or electronegative gases, gas properties —drift velocity and electron attachment—are easily affected. These two parameters determine the TPC’ s Z-position resolution and energy resolution, which are core performance indicators. Therefore, to ensure stable working gas properties, detector gas tightness and purification systems are crucial. Typically, a dual-shell structure can be employed with protective nitrogen filling between shells to enhance sealing isolation, and purifiers can be configured in the gas circulation system to physically or chemically adsorb impurity gases such as water vapor and oxygen, thereby maintaining the purity and stability of the working gas composition.

After gas composition stability is achieved and electron drift velocity remains constant, drift time-position calibration is required. Specifically, the drift time start moment can be provided by trigger signals, while the end moment is recorded by readout plane pads. To reconstruct the Z-coordinate of particle tracks, at least one known reference quantity is needed: either the initial position of incident particles or the electron drift velocity in the gas. TPCs with readout planes perpendicular to the beam direction (as shown in Figure 1) have advantages in this regard: since nuclear reactions can occur at any Z-position, events from different reaction vertices will have different drift times. By statistically analyzing the drift time distribution spectrum of all reaction events, the distribution boundaries correspond to the maximum drift time for the full Z-length of the sensitive volume, allowing the electron drift velocity to be deduced. Other TPC geometries require determination of this parameter through Garfield++ simulation or experimental measurement, or rely on auxiliary calibration using external detectors/beam spot positions. In recent years, real-time calibration using UV lasers has become a trend. Laser light is guided into the detector sensitive volume, where two-photon ionization effects at specific locations generate electron-ion pairs for drift velocity calibration. This method can calibrate not only Z-positions but also study electric field distortions caused by field cage edge effects or space charge effects, providing important basis for detector performance optimization.

2.3 Multiplication Electrode and Ion Feedback

The number of primary electrons produced by particle ionization is limited, and the resulting signal amplitude is typically below the electronics detection threshold. To achieve effective detection, multiplication electrodes are required to avalanche-amplify primary electrons so that induced current signals can be triggered and recorded by the electronics system. Notably, while avalanche multiplication amplifies electron signals, it also induces positive ion feedback (ion back-flow), where positive ions drift backward toward the drift region under the electric field. Since positive ion drift velocities are about three orders of magnitude slower than electrons, their accumulation in the drift region causes space charge effects that distort the electric field and degrade detector performance.

Currently, mainstream multiplication electrodes include the Gas Electron Multiplier (GEM) shown in Figure 4 [Figure 4: see original paper] and the Micromesh Gaseous Structure (Micromegas) shown in Figure 5 [Figure 5: see original paper].

2.3.1 GEM Structure and Characteristics The standard GEM structure consists of a polyimide (Kapton) film with copper layers on both sides, where regular micro-holes are formed through photolithography or chemical etching. During operation, a strong electric field is established within the micro-holes when voltage is applied between the upper and lower copper electrodes. Electrons entering the holes undergo avalanche multiplication under this strong field, achieving signal amplification. The GEM structure effectively suppresses ion feedback, as the upper and lower copper electrodes can adsorb most ions. Consequently, multi-layer GEM cascade structures are commonly employed. This configuration enables multiplication of gains at each stage and progressively suppresses ion back-flow to the drift region, thereby increasing total gain while effectively reducing ion feedback by adjusting potential differences between stages.

Using Garfield++, simulations were performed on the standard GEM structure from reference [19], with results shown in Figure 4. This GEM uses a 50 µm thick Kapton substrate with 5 µm copper layers on both sides, featuring hexagonal arrays of etched micro-holes (outer diameter 70 µm, inner diameter 50 µm, pitch 140 µm). The drift region electric field was set to 500 V/cm, collection region field to 2000 V/cm, and GEM electrode voltage difference to 300 V. The working gas was 80% Ar + 20% CO_2 at 760 Torr. In the simulation, 100,000 primary electrons were tracked through the GEM electric field, yielding a single-layer GEM ion feedback rate of 31.95%.

2.3.2 Micromegas Structure and Characteristics Micromegas consists of a metal mesh and readout board with a typical spacing of tens to hundreds of micrometers. Within this narrow gap, a strong electric field of tens of kV/cm can be generated with relatively low applied voltage. When electrons enter this multiplication region, rapid avalanche multiplication occurs, achieving signal gain. Thanks to its fine mesh structure, Micromegas offers higher gain and superior ion back-flow suppression capability, as most ions produced in avalanches can be captured by the mesh wires, effectively reducing ion feedback to the drift region.

As shown in Figure 5, Garfield++ was used to simulate Micromegas performance. This Micromegas has a mesh period of 38 µm, wire diameter 20 µm, and a 125 µm gap between mesh and readout board with 400 V applied voltage. Using the same settings as for GEM, the simulation tracked primary electrons in the multiplication region and yielded an ion feedback rate of 8.18%.

In direct nuclear reaction experiments, high-energy light particles (such as p, d, t) have low energy loss in gas. To effectively detect such particles, active-target TPCs require high gain. However, high gain conditions exacerbate ion feedback, leading to space charge effects that degrade detector performance. Simulation results show that both GEM and Micromegas can balance gain and partial ion suppression: GEM achieves synergistic optimization of high gain and ion suppression through multi-layer cascade structures, while Micromegas, with its narrow-gap strong-field configuration, possesses higher intrinsic ion suppression capability. Therefore, in practical detector design, multi-layer GEM and Micromegas structures are often combined according to physics objectives to achieve optimal energy resolution and counting rate performance.

2.4 Gating Grid

In detector design, the small energy loss of high-energy light particles requires a detection scheme that balances high gain and ion feedback suppression. Furthermore, in nuclear reaction experiments, unreacted background beam events far outnumber rare reaction events. Recording all events can easily cause data acquisition system overload. The mainstream solution is beam blanking technology—physically masking the beam region or creating low-gain zones to prevent intense beam signals from saturating the data acquisition system. However, fixed beam blanking designs cannot adapt to varying experimental conditions. The gating grid technology provides a dynamic and flexible solution. Composed of alternating odd and even wires (see Figure 6 [Figure 6: see original paper]), it controls electron and ion transmission through differential voltages, offering two main functions: (1) preventing beam ionization electrons from generating trigger signals, and (2) suppressing ion drift back to the drift region to reduce space charge effects. In practical applications, gating grids operate in two main modes [20]. Dynamic gating mode is suitable for accelerator beams with pulse structures, using external trigger signals to real-time switch grid voltage polarity: transparent during electron drift and blocking during ion feedback, effectively suppressing ion feedback. This mode requires high control precision and is suitable for experiments with severe ion feedback. Static gating mode maintains fixed grid voltage, with two common settings: one maintains electron transmission while blocking partial ion back-flow; the other completely blocks electrons and is commonly used for beam blanking. Therefore, the key performance of gating grids lies in their adjustable electron transmission rate, which is influenced by grid geometry and electric field distribution. The following sections analyze several key parameters affecting electron transmission.

2.4.1 Electron Transmission Rate The controllability of gating grid electron transmission requires effective blocking in the closed state while ensuring efficient, undisturbed electron passage in the open state. Specifically, when electrons approach grid wires within a certain distance, they are inevitably collected by the wires. This distance is called the trap radius. To prevent electrons from drifting into traps and being collected, the electric field ratio between regions on both sides of the grid can be adjusted to make the field strength behind the grid larger. This way, the applied electric force can drive electrons through the gaps between wires and away from the trap radius. Therefore, an optimal field ratio can effectively reduce the probability of electron collection by wires and improve electron transmission. Theoretically, the minimum field ratio $R_{\min}$ required for near-100% electron transmission is given by [21]:

$$R_{\min} \geq 1 + \frac{\rho}{1-\rho}, \quad \rho = \frac{r}{d}$$

where E_c and E_d are the collection region and drift region electric fields, respectively, r is the wire radius, and d is the spacing between two odd-even wires. This formula applies to theoretical calculation of minimum field ratio for parallel wires. In practice, to avoid excessive field ratio settings and high operating voltages that may cause sparking (breakdown discharge) risks in the open state, the gating grid structural parameters r and d should make the minimum field ratio $R_{\min}$ approach 1. Among these parameters, wire spacing d is an easily adjustable variable. Therefore, with fixed wire radius $r = 25$ µm, the relationship between wire spacing and required minimum field ratio for optimal electron transmission was calculated. As shown in Figure 7 [Figure 7: see original paper], the curve indicates that as wire spacing increases, $R_{\min}$ gradually approaches 1, which helps reduce operating voltage and avoid gas breakdown.

However, considering that excessively large wire spacing requires stronger electric fields for effective electron collection in the closed state, a wire spacing of $d = 0.2$ cm was selected. While theoretical Formula 2 sets a lower limit for field ratio, the actual optimal operating point must also consider effects such as random collisions during electron drift. To accurately obtain optimal operating parameters, Garfield++ Monte Carlo simulations were employed to comprehensively track electron drift through the gating grid. In the simulation setup, the distance from gating grid to the next electrode was 0.7 cm. The even wire voltage was fixed as reference (0 V), and odd wire voltage was varied to control the closed state. In the open state, odd and even wire voltages were kept equal while adjusting the field ratio on both sides of the grid to optimize electron transmission. For each operating parameter, 10,000 electron events were simulated to statistically determine electron transmission rate, with results shown in Figures 8 [Figure 8: see original paper] and 9 [Figure 9: see original paper].

Figure 8 shows that electron transmission efficiency increases with field ratio, approaching maximum collection efficiency. The theoretically calculated minimum field ratio is $R_{\min} = 1.17$, where collection efficiency is near maximum but detector operation may be unstable. Therefore, the selected field ratio should exceed the theoretically calculated minimum $R_{\min}$. Figure 9 demonstrates that when a voltage difference exists between odd and even wires, an electric field forms between wires. Electrons in this field experience a force directed toward the wires, deviating from their original drift path and eventually entering the wire trap radius for collection. At voltage differences of \$±\$150 V, the grid achieves a fully closed state. In summary, optimizing the gating grid' s field ratio and operating voltage can effectively regulate electron transmission to control ionization electrons. These simulation analyses provide effective design guidance for practical gating grid applications, ensuring detector stability and performance under various experimental conditions.

2.5 δ-Electron Effects

When high-energy charged particles traverse gas media, besides ionizing low-energy electrons, they also produce higher-energy electrons (keV scale and above) through collisions. These electrons can further ionize secondary electrons and are therefore called δ-electrons. During secondary ionization by δ-electrons, the process can be approximated as electron-electron scattering. Since the interacting particles have identical mass, momentum is randomly distributed after each collision, causing δ-electron trajectories to become disordered. Such chaotic trajectories not only diffuse the ionization point distribution but also increase noise in track reconstruction, even causing electrons to spread throughout the sensitive volume and creating numerous spurious noise signals on the readout plane that significantly interfere with track reconstruction, particle identification, and energy measurement. Therefore, studying δ-electron production mechanisms and distribution characteristics can provide guidance for active-target TPC performance optimization, particularly in track reconstruction and particle identification.

δ-Electron production follows statistical laws that can be described by theoretical models [22]. Specifically, when charged particles traverse gas detectors, the number of ionized electrons with energy $E \geq E_0$ can be calculated using:

$$N(E \geq E_0) = \frac{2\pi N_A e^4}{m_e c^2} \cdot \frac{z}{a} \cdot \frac{\rho X}{Z^2 \beta^2} \cdot \left(\frac{1}{E_0} - \frac{1}{E_{\max}} \right)$$

where N_A is Avogadro' s constant, m_e is electron mass, z and a are the gas atomic number and mass number, ρ is gas density, X is gas thickness in the detector, and Z and β are the atomic number and velocity of incident particles. $E_{\max}$ is the maximum energy of ionized electrons, which is a function of incident particle velocity:

$$E_{\max} = \frac{2 m_e c^2 \beta^2}{1 - \beta^2}$$

Additionally, the electron emission angle is related to its energy:

$$\cos\theta = \sqrt{\frac{E + m_e c^2}{E_{\max} + m_e c^2}}$$

Based on the above theoretical model, calculations were performed for a 300 MeV/u and 30 MeV/u proton traversing 1 atm, 1 cm H_2 gas, showing the number of ionized electrons with energy $E \geq E_0$ as a function of E_0, and the relationship between electron emission angle and energy. Figure 10 Figure 10: see original paper shows the variation of δ-electron yield with energy threshold: high-energy protons (300 MeV/u) produce significantly more δ-electrons than low-energy cases (30 MeV/u), and the electron count decays rapidly with increasing energy threshold E_0. Figure 10(b) reveals the angular distribution characteristics of ionized electrons: high-energy δ-electrons prefer small-angle emission, while low-energy electrons are mostly emitted at 90°.

These distribution characteristics directly impact detector performance. In data acquisition systems using readout pad multiplicity as trigger conditions, δ-electrons can cause false triggers. Due to their high energy, gating grids designed for low-energy free ionization electrons cannot effectively suppress their interference. Therefore, the influence of δ-electrons must be fully considered in direct nuclear reaction experimental design and data analysis. For example, for 300 MeV/u protons traversing 1 atm H_2, the δ-electron yield above 1 keV is approximately 2.6 electrons/cm. These δ-electrons can diffuse over large ranges without a magnetic field, sufficient to produce signals on multiple readout pads. Estimates indicate that a 10 cm long proton track may generate up to a hundred spurious noise signals. To reduce this interference, the following measures can be taken: first, evaluate δ-electron yield based on beam energy and gas type to reasonably set trigger energy thresholds; second, optimize trigger logic using their angular distribution characteristics to improve efficient event selection.

Furthermore, the most effective technical approach is introducing an external magnetic field. Due to the low magnetic rigidity $B\rho$ of electrons, a magnetic field can effectively constrain their diffusion, thereby reducing noise signals on the readout plane. Figure 10(c) shows the relationship between electron energy and magnetic rigidity. For 1 keV δ-electrons, applying a 0.01 T magnetic field can confine them within a 1 cm wide beam region, a field strength achievable with permanent magnets. To constrain higher-energy δ-electrons, such as in high-energy radioactive beam lines (e.g., HIAF-HIRIBL), superconducting solenoid solutions can provide stronger magnetic fields, enabling TPCs to effectively suppress δ-electron effects.

2.6 Signal and Electronics

After detector optimization and experimental data acquisition, information reconstruction becomes the core process for extracting physical results. Electronic signals, as carriers of particle information, are central components of the detection system. When electrons induce current signals on readout pads, the charged particle information is completely encoded in the $i(t)$ signal. Rich physical information can be extracted through time-domain signal analysis [15,23]: timing analysis can determine electron drift time for Z-coordinate reconstruction; signal distributions on different readout electrodes enable X-Y coordinate positioning; induced current waveforms correlate with ionized electron distributions; and the total charge of induced current signals corresponds to particle energy.

However, induced current signals are extremely small (hundreds of nA). Such weak signals must be preliminarily amplified by charge-sensitive preamplifiers before effective measurement. Main amplifiers then perform filtering, shaping, and further amplification to optimize signal-to-noise ratio. Finally, signals are digitized by analog-to-digital converters (ADC) for subsequent algorithmic analysis. To quantitatively describe the electronics system' s influence on signals, its response model must be established. The typical time-domain response function of a preamplifier can be expressed as:

$$h(t) = \begin{cases} 0 & t < 0 \\ \frac{1}{\tau} e^{-t/\tau} & t \geq 0 \end{cases}$$

The system' s output voltage pulse $V_{\text{out}}(t)$ is obtained by convolving the induced current $i(t)$ with this response function $h(t)$. For efficient processing, analysis is typically performed in the frequency domain. According to the convolution theorem, the frequency-domain output signal is:

$$V_{\text{out}}(f) = I(f) \cdot H(f)$$

Accordingly, the original input current signal $i(t)$ can be reconstructed on an event-by-event basis through frequency-domain deconvolution. Compared with methods that only extract energy information, complete current signals preserve all characteristics of charged particles and provide richer physical details. Furthermore, the event reconstruction efficiency η in differential cross section calculations primarily relies on simulation estimation; therefore, electronics system response characteristics are also key factors affecting η. However, in current mainstream simulation frameworks, accurate simulation of electronics response remains a relatively weak link: convolution with response functions is typically used as an approximation, while for complex signals after multi-stage amplification, often only approximate analytical forms of response functions can be obtained [24-25]. This is considered an important reason for discrepancies between existing simulations and some experimental data [26].

To build more reliable electronics response models, two technical approaches can be adopted: (1) Experimental determination: Using the differential characteristics of test capacitors, known equivalent input currents are generated through voltage source excitation, and the system' s measured response function $H(f)$ is directly calibrated according to the frequency-domain response formula. This method is direct and accurate, serving as the best standard for verifying simulation results. (2) Circuit simulation: Based on mature circuit simulation software (such as SPICE-based LTspice, PSpice), front-end electronics circuits are modeled and simulated [27]. The core of SPICE simulators lies in solving nonlinear differential equation systems (circuit equations), enabling precise simulation of complete circuit responses including transistors, resistors, capacitors, and parasitic effects. This method is a powerful tool for predicting response functions from the design stage. In summary, establishing reliable electronics response models is a key step toward improving the credibility of the full simulation chain, laying the foundation for subsequent signal reconstruction and physical analysis, and is of great significance for systematically reducing discrepancies between simulation and experimental data.

Thus far, the complete physical process from particle incidence, ionization, drift, amplification, to signal analysis has been simulated and optimized. The final extraction of physical information depends on processing these raw signals: through clustering algorithms (such as Density-Based Spatial Clustering of Applications with Noise, DBSCAN) analyzing triggered pad signals, reaction vertices and three-dimensional particle tracks can be progressively reconstructed; combined with Bethe-Bloch formula analysis of track range-energy deposition relationships, particle identification (PID) can be completed [28], ultimately enabling precise measurement of differential cross sections and other physical quantities.

3. Summary and Outlook

This paper systematically investigated direct nuclear reaction detection technology based on active-target time projection chambers, focusing on analyzing key factors affecting detector performance, including electric field uniformity, electron drift velocity, ion feedback, gating grid, δ-electron effects, and electronic signals and reconstruction. Through combined theoretical analysis and Garfield++ simulation, optimal designs for each parameter were developed. Based on these simulations and designs, experimental data can be processed through standard track reconstruction and particle identification procedures, and differential cross sections can be extracted using Formula 1 and combined with theoretical calculations to reveal nuclear microscopic structure information.

Looking forward, the new generation High-Intensity heavy-ion Accelerator Facility (HIAF) will soon be completed and is expected to play important roles in frontier topics such as exotic nuclear structure and astrophysical nuclear processes. To achieve HIAF' s scientific goals, constructing a new generation of active-target TPCs is urgently needed. In this context, the simulation and optimization work on key technical parameters for active-target TPCs completed in this study will provide a foundation for future detector design and construction.

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