# Performance study of THGEM-based semi-cylindrical TPC for intermediate-energy charge exchange reaction experiments in inverse kinematics

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## Abstract

The semi-cylindrical Time Projection Chamber (scTPC) is designed to measure the angular distribution of the cross section of the intermediate-energy (3He,t) charge exchange reaction in inverse kinematics. The scTPC prototype has been constructed, consisting of a cathode, a field cage, a drift region, an amplification structure based on multi-layer thick gas electron multiplier (THGEM), and a readout plane with 886 zigzag-shaped pads. The gain uniformity of the THGEM and the drift velocity of electrons were calibrated. Then the track recognition based on the Hough transform was developed to reconstruct cosmic ray tracks and extract their position resolution. The position resolution of the secondary particle tracks from collisions between the heavy-ion beam and 3He target was also reported, with an x-resolution of 0.71 mm and a z-resolution of 0.73 mm. The scTPC is able to achieve sufficient energy resolution and spatial resolution to support the charge exchange reaction experiments in inverse kinematics.

## Full Text

## Preamble

### Performance Study of a THGEM-Based Semi-Cylindrical TPC for Intermediate-Energy Charge Exchange Reaction Experiments in Inverse Kinematics

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The semi-cylindrical Time Projection Chamber (scTPC) is designed to measure the angular distribution of cross sections for intermediate-energy ($^3$He,t) charge exchange reactions in inverse kinematics. A prototype scTPC has been constructed, consisting of a cathode, field cage, drift region, amplification structure based on multi-layer thick gas electron multiplier (THGEM), and a readout plane with 886 zigzag-shaped pads.

The gain uniformity of the THGEM and the electron drift velocity were calibrated. Track recognition based on the Hough transform was developed to reconstruct cosmic ray tracks and extract their position resolution. The position resolution of secondary particle tracks from collisions between heavy-ion beams and a $^3$He target was also measured, yielding an x-resolution of 0.71 mm and a z-resolution of 0.73 mm. The scTPC achieves sufficient energy resolution and spatial resolution to support charge exchange reaction experiments in inverse kinematics.

**Keywords:** Charge exchange reaction, Time projection chamber, Track recognition, Track reconstruction

## Introduction

Charge exchange reactions, a type of direct nuclear reaction, serve as experimental tools for investigating the intricate structure of atomic nuclei through spin-isospin excitations [1, 2]. The ($^3$He,t), (t,$^3$He), and (d,$^2$He) reactions are commonly employed in charge exchange reaction studies due to their high resolution and detection efficiency [3–7]. On the theoretical side, the Distorted Wave Born Approximation (DWBA) is widely applied in the analysis of reaction cross sections. Additionally, a research group from Peking University has developed an improved Eikonal method whose results show better agreement with experimental data across a wide energy range [8, 9].

On the experimental front, ($^3$He,t) and (t,$^3$He) charge exchange reactions have been carried out for various nuclei using $^3$He and triton beams from accelerators. For example, researchers from the Institute of Modern Physics measured the Gamow-Teller strength distribution of the odd-mass nucleus $^{93}$Nb using a triton beam from the Coupled Cyclotron Facility (CCF) at the National Superconducting Cyclotron Laboratory (NSCL) at a beam energy of 115 MeV/u [10]. Exclusive measurements of the $^{59}$Co(t,$^{3}$He+$\gamma$)$^{59}$Fe charge exchange reaction were also performed, enabling the first measurement of Gamow-Teller strengths from low-lying states in $^{59}$Fe to its ground state $^{59}$Co [11]. These efforts have yielded significant findings in nuclear astrophysics, particularly regarding the late evolution of core-collapse supernovae.

Charge exchange reactions also play a key role in studying nuclear structure, including spin-isospin excitations, giant resonances, $\beta$-decay, and neutron skin thickness of atomic nuclei. However, experimental studies have primarily been limited to stable nuclides due to current technical constraints. Consequently, conducting charge exchange reaction experiments on unstable nuclides in inverse kinematics remains challenging but offers numerous prospects for further investigation. For the first time, a research team at Michigan State University successfully extracted Gamow-Teller transition strength B(GT) in the $\beta^{+}$ direction from an unstable nucleus using the (d,$^{2}$He) reaction in inverse kinematics. The application of an active-target time projection chamber (AT-TPC) and magnetic spectrometer in that experiment provided a successful solution for inverse kinematics experiments [12, 13].

The Heavy Ion Research Facility in Lanzhou (HIRFL) is an important nuclear physics experimental facility in China where numerous experiments have been conducted. A research group from Beihang University measured a series of charge-changing cross sections of exotic nuclei at the Radioactive Ion Beam Line in Lanzhou (RIBLL) to extract charge radii and study the structure of exotic nuclei [14, 15]. Researchers from the Institute of Modern Physics successfully measured cross sections for single-neutron removal, two-neutron removal, and one-proton knockout reactions on a carbon target at around 240 MeV/u at the External Target Facility (ETF) [16–18]. Additionally, researchers from the Institute of Modern Physics and Lanzhou University measured the breakup reaction of $^{9}$Li on a Pb target at 32.7 MeV/u for the first time at RIBLL [19]. Therefore, HIRFL is anticipated to provide significant support for investigating charge exchange reactions [20].

We proposed conducting ($^{3}$He,t) charge exchange reaction experiments in inverse kinematics by bombarding a $^{3}$He target with radioactive beams generated by HIRFL to study unstable neutron-rich nuclides. Consequently, we designed and constructed a system for detecting large-angle scattering tritons (t) to verify the feasibility of ($^{3}$He,t) experiments in inverse kinematics using heavy-ion beams. The detection system is based on a $\Delta$E-E telescope, where the $\Delta$E detector is a semi-cylindrical time projection chamber (scTPC) and the E detector is a CsI(Tl) array [21]. CsI(Tl) crystals have good properties for energy detection, thereby facilitating particle identification [22].

The time projection chamber (TPC) is capable of accurately measuring the scattering angle  of secondary particles by detecting three-dimensional tracks and can measure energy precisely [23]. Therefore, TPCs have been widely used in nuclear physics experiments [24–31]. Researchers from Peking University developed a compact active target time projection chamber (CAT-TPC) to measure resonant scattering associated with cluster structures in unstable nuclei with an angular resolution of approximately 0.45 degrees [27, 28]. To meet the requirements of the cooling storage ring external-target experiment (CEE), a TPC prototype was constructed and tested with pulsed ultraviolet laser beams, demonstrating good performance in track resolution and energy resolution [29]. The High-energy Fragment Separator (HFRS) under construction will adopt multiple sets of position-sensitive twin TPC detectors for particle identification and beam monitoring [30]. Additionally, a Multi-purpose time projection chamber (MTPC) has been developed to measure cross sections of neutron-induced nuclear reactions at the Back-streaming white neutron facility (Back-n) at the China Spallation Neutron Source [31].

The semi-cylindrical detector design reserves space for future heavy-ion nuclear reaction experiments with a polarized $^3$He target. The spin of nuclei in the $^3$He gas can be polarized (made to align in the same direction) through a spin exchange optical pumping (SEOP) process [32], after which the polarized $^3$He target will be bombarded by intermediate-energy or high-energy heavy-ion beams. This experimental scheme can select specific coupling terms and reveal the spin-related components of nuclear interactions [33]. Experiments in inverse kinematics can especially expand the types of atomic nuclei studied. The polarized $^3$He target will be similar to the $^3$He glass cell used in work from Lanzhou University [34], featuring a spherical glass chamber above the target tube made of aluminosilicate (GE180) glass, as shown in Fig. 1 [Figure 1: see original paper]. The $^3$He gas will be polarized in the spherical chamber and pass through a transmission pipe into the cylindrical target chamber. A set of Helmholtz coils can provide a magnetic field of about 50 G, which will be applied to the $^3$He target to maintain polarization and will inevitably affect the TPC. However, the magnetic field is low enough to have only a tiny effect on charged particle tracks. Hence, a semi-cylindrical structure is necessary considering these factors. We plan to perform experiments with a non-polarized $^3$He target initially, so the actual target used now is a non-polarized target as described in Sec. III F.

This paper focuses on the performance test of the scTPC component of the detector. The scTPC performance was measured using a radioactive source, UV laser, cosmic ray muons, and heavy-ion beam. First, we tested the energy resolution and gain inhomogeneity of the THGEM with a $^{55}$Fe X-ray source, providing a normalized gain correction factor for every channel. Then, we calibrated the drift velocity of electrons in the scTPC using both laser and cosmic ray methods; the measured drift velocities from these two approaches were generally consistent. A track recognition method based on the Hough transform was used for track reconstruction in both cosmic ray and beam tests. The position resolution of cosmic ray tracks was reported. Subsequently, the heavy-ion beam was directed toward a $^3$He target, and secondary charged particles produced by collisions were measured by the scTPC. Their tracks were reconstructed to determine position resolution and angular resolution. The detector structure is described in Sec. II, performance tests and results are discussed in Sec. III, and a summary is provided in Sec. IV.

## II. Experimental Setup

The TPC section of the detector (please refer to Ref. [21] for a comprehensive description of the detector construction), as shown in Fig. 2 [Figure 2: see original paper], consists of a cathode board, field cage, two layers of THGEM films, and a readout electrode. Detailed parameters of the scTPC are listed in Table 1 .

The cathode is a single-sided copper-coated PCB (printed circuit board). The field cage is a semi-cylindrical structure with an inner radius of 25 mm and an outer radius of 197 mm, constructed from flexible PCB. Uniformly distributed copper-coated electrode strips are present on both sides of the PCB. The width of the electrode strips is 1.5 mm, and the pitch between centers of adjacent electrode strips is 2 mm. The voltage gradient for the field cage is supplied by a voltage divider circuit consisting of 198 1 MΩ series resistors.

The amplification structure is a double-layer THGEM [35, 36], with high voltage supplied by a voltage divider circuit as shown in Fig. 3 [Figure 3: see original paper]. To limit the total charge during discharge [37], one side of the THGEM was partitioned into 6 fan-shaped segments with a 1 mm gap between adjacent segments, as illustrated in Fig. 4 [Figure 4: see original paper]. Each segment is connected to the common high-voltage distribution via a 10 MΩ resistor, ensuring that the potential of each segment remains consistent. The THGEM 1 has its partitioned side on the lower surface, while THGEM 2 has its partitioned side on the upper surface.

The readout electrode consists of 886 zigzag-shaped pads [38]. Each pad measures 7.29 mm in the vertical direction and 3.43 mm in the horizontal direction. The readout electronics and data acquisition system for the scTPC are based on ASIC for General Electronics for TPC (AGET) chips [39, 40]. The gas mixture of Ar-i$C_4H_{10}$ has been utilized in THGEM tests typically [41, 42] due to its high gain and fast drift velocity. Specifically, the Ar-i$C_4H_{10}$ (95:5) mixture [42] has been selected as the operating gas for the THGEM-based scTPC.

## III. Performance Test

### A. Waveform Fit

The output waveform from the AGET has an asymmetric shape, as shown in Fig. 5 [Figure 5: see original paper]. A fitting function is used to extract information from the signal waveform, primarily time information (e.g., peak position) and amplitude. The waveform can be fitted with the following function [31]:

$$f(t) = B + A\left(\frac{t-t_0}{\tau}\right)^3 \exp\left(\frac{t-t_0}{\tau}\right)\Theta(t-t_0),$$

where $B$ represents the baseline of the waveform, $A$ is a quantity related to the amplitude, $t_0$ is the starting time, $\tau$ is the electronics shaping time, and $\Theta$ is the Heaviside step function with the functional form:

$$\Theta(t-t_0) = \begin{cases} 0 & t-t_0 < 0 \\ 1 & t-t_0 > 0 \end{cases}$$

The maximum value of the fitting function in the region where the waveform is located is calculated, and the baseline is subtracted to obtain the Amplitude. The position where the Amplitude occurs is the peak position (peakPos). Time information for charged particles is also extracted using constant fraction discrimination (20% of the Amplitude), i.e., CFDRisingTime. The initial values of the fitting function parameters vary depending on the sampling frequency and shaping time settings of the AGET. Signals from X-rays and charged particles ($\alpha$ particles) were fitted respectively, as shown in Fig. 5. The X-ray is a point source, and the raw pulse signal induced on the readout pad can be regarded as a $\delta$-like function. However, for charged particles such as $\alpha$ particles, the raw pulse has a certain width because the signal collected by a pad is actually a short section of the track. The adopted fitting function can describe waveforms of both signal types very well.

### B. X-ray Test

For the $^{55}$Fe source test, the field cage was temporarily removed. The voltage divider circuit for THGEM power supply remained consistent with other tests, as depicted in Fig. 3. The cathode was a 25 µm thick double-aluminized Mylar film, and the $^{55}$Fe source was placed outside the drift region, directly in front of the cathode film. The drift region length was 4 mm.

The X-ray deposits its entire energy at a single point in the operating gas, producing a small electron cloud from single X-ray photon ionization that typically generates signals on one or two pads. Different positions of the THGEM were irradiated with the X-ray source. By selecting events where only one pad was triggered per event, we reconstructed the energy deposition spectrum generated by the X-ray on each pad, as shown in Fig. 6 [Figure 6: see original paper], where the full-energy peak and Ar escape peak of the X-ray are clearly visible. The escape peak is located at half the energy of the full-energy peak. Due to the small drift region, annihilation photons are more likely to escape the sensitive region of the TPC, resulting in a high count of the escape peak. With the cathode voltage set to 2400 V, at a THGEM operating voltage of -2500 V (-663 V for THGEM 1 and -612 V for THGEM 2), a sampling frequency of 25 MHz, and a shaping time of 1 µs, the scTPC achieves an energy resolution (FWHM) of approximately 22% for 5.9 keV X-rays.

Due to manufacturing processes of the THGEM, detector assembly, readout electrode collection efficiency, transmission through the electronics and data acquisition system, and other factors, gain non-uniformity may occur across different channels. Therefore, the full-energy peak position in the X-ray energy spectrum for each pad can be extracted to characterize gain non-uniformity. By normalizing peak positions of all channels, fluctuations between channels can be calibrated, as shown in Fig. 7 [Figure 7: see original paper] (a). The gain fluctuations across the readout plane indicate that gain is relatively lower for central electrodes and higher for peripheral electrodes. This discrepancy may be attributed to differences in tension experienced by peripheral and central electrodes during THGEM manufacturing and detector assembly. When processing charged particle events, the normalized gain correction factors determined from the X-ray test, as shown in Fig. 7 (b), can be applied in data analysis to partially correct for degradation in energy measurement caused by channel fluctuations.

### C. Drift Velocity

The drift velocity of electrons in the scTPC drift region is crucial for reconstructing three-dimensional tracks of charged particles. Two methods were adopted to measure the drift velocity.

The first method used a 266 nm UV laser. The laser beam was split into two beams through a half lens (50% transmissive and 50% reflective). These two laser beams entered the drift region of the scTPC through two collimating holes (approximately 1 mm in diameter) in the inner wall of the field cage, and the drift velocity was calculated from the time difference between the two laser beams. Although an attempt was made to keep both laser beams parallel to the readout plane, achieving this strictly was difficult, and there remained an angle between the two beams. Therefore, we extrapolated the two laser tracks back to their respective vertices (i.e., positions of the two collimating holes). The distance between collimating holes was 16 cm. At each of the two collimating hole locations, there is a distinct and pronounced peak in drift time, as shown in Fig. 8 [Figure 8: see original paper] (a). The drift velocity can be calculated based on the time difference between collimating holes. The measured drift velocity is 3.95 cm/µs with an electric field of 200 V/(cm · atm) in the Ar(95%)+i$C_4H_{10}$(5%) gas mixture.

The second method employed cosmic ray muons to calculate the drift velocity. There was no strict restriction on the direction of cosmic rays, which could pass through the scTPC from any position in the drift region. A 20 cm × 20 cm plastic scintillator was placed on the top side of the scTPC as the trigger and common zero time for all cosmic ray events. In this way, the time distribution in the drift direction of all cosmic ray tracks was extracted, as shown in Fig. 8 (b). This drift time shows a platform-like distribution with steep leading and trailing edges denoting the closest point (infinitely close to the upper surface of THGEM 1) and the farthest point (infinitely close to the cathode surface) from the upper surface of THGEM 1, respectively. The leading and trailing edges are fitted with the following edge function [43]:

$$f(t) = B + \frac{Ae^{-t/\tau_1}}{1 + e^{(t-T_0)/\tau_2}}$$

where $T_0$ is the time point of the leading edge (or trailing edge), which is the point with maximum slope. The time difference between the leading and trailing edges results from the total length (20 cm) of the drift region. The measured drift velocity is 3.91 cm/µs with an electric field of 200 V/(cm · atm) in the Ar(95%)+i$C_4H_{10}$(5%) gas mixture. The drift velocities tested by the two methods are very close to each other, and the drift velocity calculated by Garfield++ [44] is 4.12 cm/µs. The deviation between calculated and measured results may be due to gas impurities.

The equipment for measuring drift velocity with the laser is complex and can only provide the drift velocity at a specific position. In contrast, the method using cosmic rays allows characterization of the average drift velocity with a simple setup. Due to the adoption of a flow-type gaseous chamber, the gas pressure in the chamber fluctuates with external air pressure and the purity of the operating gas is uncertain. Therefore, calibration of the electron drift velocity is necessary for every test and experiment. With cosmic rays, real-time measurement of the drift velocity can be easily and quickly achieved.

### D. Track Reconstruction

The particle track is three-dimensional and can be projected onto the xy-plane and zy-plane, respectively. The x-axis is aligned with the pad row, while the y-axis is aligned with the pad column, as shown in Figs. 2 (c) and 7 (a). The z-axis is the direction of the drift electric field, opposite to the electron drift direction and perpendicular to the readout plane. The xy-plane is parallel to the readout plane, while the zy-plane is perpendicular to the readout plane.

A pad with a detected signal is classified as a hit. The x-coordinate and y-coordinate of the hit equal the geometrical center in the horizontal and vertical directions of the pad. All hits in the same row are considered a cluster. The y-coordinate of the row is defined as the y-coordinate of the cluster. The x-coordinate of the cluster is the average of the x-coordinates of all hits, weighted by the deposited charge (i.e., the Amplitude). The z-coordinate of the hit is calculated by multiplying the drift time and drift velocity. The drift velocity is determined to be 3.91 cm/µs according to Sec. III C. The drift time is determined by the leading edge of the signal waveform to the zero-th time bucket, i.e., the CFDRisingTime in Fig. 5 (b). This drift time is not an absolute value and needs to subtract a relative common zero. The z-coordinate of the cluster is the average of z-coordinates of all hits, weighted by the Amplitude as well. The reconstructed track is a straight line fitted through a series of clusters.

Track resolution includes spatial resolution on the xy-plane (hereafter called x-resolution) and spatial resolution on the zy-plane (hereafter called z-resolution). Spatial resolution is measured by the residual, defined as the distance from the charge center of the cluster to the fitting line. For example, on the xy-plane:

$$\text{residual}_x = \frac{|ky_i + b - x_i|}{\sqrt{k^2 + 1}}$$

where $(x_i, y_i)$ is the charge center of the cluster, and $k$ and $b$ are parameters of the fitting line. The $\sigma$ (referring to standard deviation throughout the full text) of the residual distribution is equivalent to the x-resolution [23, 45]. Processing on the zy-plane follows the same procedure. Track reconstruction and position resolution measurement of long tracks for the scTPC were achieved using cosmic ray muons and heavy-ion beams.

### E. Cosmic Ray Test

Cosmic ray muons traverse the scTPC in stochastic directions and positions, enabling thorough assessment of the scTPC's overall performance. The energy deposition of cosmic rays within the scTPC is low, resulting in a suboptimal signal-to-noise ratio. Therefore, higher amplification is necessary to clearly discern cosmic ray tracks. In this case, muon tracks may be accompanied by unrelated hits, leading to positional inaccuracies, as shown in Fig. 9 [Figure 9: see original paper] (a). Additionally, due to the large size of the plastic scintillator, there are instances where multiple tracks are detected within the same sampling time window, although such occurrences are rare. Therefore, track recognition must be performed before track reconstruction [46–51]. To address this, we employed the Hough transform for track recognition and derived a flag value $d$ in Hough space as a means of distinguishing effective and ineffective hits [52, 53].

The Hough transform has been widely applied and extended in particle track recognition due to its simple and intuitive basic transformation. The particles investigated in our future experiments exhibit characteristics similar to cosmic rays, namely long tracks that penetrate the TPC, with typically only one track present per event. In this case, the classical Hough transform is sufficient for recognition and reconstruction of secondary particle tracks.

The original coordinate system $(x, y, z)$ (in Euclidean space) is consistent with the coordinate system defined in Sec. III D and Fig. 2 (c). The $(x, y)$ coordinates of hits in Euclidean space are first transformed to Hough space, where a point in Euclidean space corresponds to a curve in Hough space. When multiple hits are situated along the same linear track, their corresponding curves in

Hough space intersect at a common point. Conversely, Hough curves of ineffective hits located away from the track do not converge at this common point, as illustrated in Fig. 9 (a) and (b). The coordinate of the common point in Hough space, $(\theta_{xy,com}, r_{xy,com})$, is found, and the minimum distance $d_{xy}$ from each Hough curve to the common point is calculated. For a point on a track, its $d_{xy}$ value should be nearly equal to or slightly greater than 0, while the $d_{xy}$ value of a stray point will be larger, as shown in Fig. 9 (c). After comparison across multiple tracks, points with $d_{xy} \leq 4.0$ are considered effective hits and those with $d_{xy} > 4.0$ are deemed ineffective. Following $d_{xy}$ discrimination, stray hits can be rejected and track recognition can be effectively achieved on the xy-plane, as shown in Fig. 9 (d) and (e). Note that this judgment may need adjustment depending on detector design and refinement in events involving multiple tracks.

Track recognition on the zy-plane based on Hough transform follows a similar procedure. The $(z, y)$ coordinates of hits in Euclidean space are transformed to Hough space, as shown in Fig. 10 [Figure 10: see original paper]. The coordinate of the common point in Hough space, $(\theta_{zy,com}, r_{zy,com})$, is found, and the minimum distance $d_{zy}$ from each Hough curve to the common point is calculated. On the zy-plane, points with $d_{zy} \leq 2.0$ are considered effective hits, while points with $d_{zy} > 2.0$ are deemed ineffective.

With discrimination by $d_{xy}$ and $d_{zy}$ based on the Hough transform, stray hits are discarded. Then, residual distributions on the xy-plane and zy-plane are extracted to evaluate the x-resolution and z-resolution of cosmic ray tracks, as shown in Fig. 11 [Figure 11: see original paper]. The residual distribution is not a standard Gaussian function, so we fit it with the sum of two Gaussian functions, both with means close to 0. The fitting function [54] is:

$$f(x) = \frac{A_1}{\sqrt{2\pi}\sigma_1} \exp\left(-\frac{(x-\mu_1)^2}{2\sigma_1^2}\right) + \frac{A_2}{\sqrt{2\pi}\sigma_2} \exp\left(-\frac{(x-\mu_2)^2}{2\sigma_2^2}\right)$$

where $A_1$ and $A_2$ are the integrals of the two Gaussian functions, $\mu_1$ and $\mu_2$ are their means, and $\sigma_1$ and $\sigma_2$ are their standard deviations. The track resolution is the weighted root mean square of $\sigma_1$ and $\sigma_2$:

$$\sigma = \sqrt{\frac{A_1\sigma_1^2 + A_2\sigma_2^2}{A_1 + A_2}}$$

If the residual distribution can be fitted by a single Gaussian function, we may simply consider the $\sigma$ parameter of that Gaussian. Otherwise, it is necessary to employ two Gaussian functions for fitting. In the case of cosmic rays, efficient tracks are identified and reconstructed, resulting in a track resolution of 0.86 mm and 0.79 mm in the x and z directions, respectively. In the z direction, an angular resolution of approximately 0.2° for can be achieved when considering a track length of about 20 cm. This level of precision is crucial for calibrating the energy- relationship of tritons generated from ($^3$He,t) nuclear reactions and reconstructing the angular distribution of the cross section.

### F. Beam Test

To validate the functionality of the scTPC in a heavy-ion beam background environment, a beam test was conducted at HIRFL. The detector was fully assembled, as shown in Fig. 12 [Figure 12: see original paper]. A non-polarized $^3$He gas target, encapsulated in a sealed stainless steel container containing 3 atmospheres of $^3$He gas (with an effective target thickness of about $2.2 \times 10^{21}$ atoms/cm$^2$), was positioned at the center of the scTPC. The stainless steel container is cylindrical, measuring 20 cm in length and 3.8 cm in diameter, with a side wall thickness of 200 µm (i.e., the exit window for secondary particles is 200 µm thick). The two end faces of the stainless steel cylindrical container, with a thickness of 2 mm, serve as the incoming and outgoing windows for the beam. Since the beam energy is high while the intensity remains low, the energy loss in the beam window is small compared to the total beam energy, rendering the heating power negligible. The target was placed on a 3D-printed holder to keep the center axis of the target aligned with the beam center. The heavy-ion beam did not pass through the TPC but rather through the $^3$He target. Large-angle scattering secondary particles penetrated through the sidewall of the stainless steel container and entered the scTPC. The detector was housed in a stainless steel chamber.

The beam was a 350 MeV/u Kr beam with an intensity of approximately $10^6$ particles per second. The beam entered the chamber through a 25 µm thick aluminized Mylar film window with a diameter of 40 mm, and exited through another 25 µm thick aluminized Mylar film window with a diameter of 55 mm. Eight CsI(Tl) crystals, each 2 cm thick and 20 cm long, were positioned in a curved array surrounding the scTPC outside. Signals from the CsI(Tl) were sequentially extracted, amplified, and discriminated by a preamplifier (Mesytec MPR-16) and a shaping/timing filter amplifier (Mesytec MSCF-16). Following an OR operation, signals from eight crystals are transformed into TTL signals to serve as the trigger for the AGET. Consequently, the scTPC signal recorded by the AGET should represent the long track that traverses through the scTPC and deposits energy in the CsI(Tl).

As shown in Fig. 13 [Figure 13: see original paper], the track is often accompanied by numerous background particles, which are mainly distributed in the upper part of the readout electrode (near the target). Therefore, track recognition is critical for data analysis of the beam test. The track recognition based on Hough transform has been applied to reconstruct particle tracks, as shown in Fig. 14 [Figure 14: see original paper], with $d_{xy} \leq 4.0$ and $d_{zy} \leq 2.0$, the same criteria as for cosmic ray tracks. Fitting the residual distribution of secondary particle tracks with the double-Gaussian function, as shown in Fig. 15 [Figure 15: see original paper], yields x-resolution and z-resolution of 0.71 mm and 0.73 mm, respectively, for the beam test. Consistent with cosmic ray test results, the angular resolution of the scattering angle can reach up to 0.2°. This good angular resolution is essential for establishing a finer relationship between scattering angle and differential cross section in the center-of-mass system, particularly for specific features of the cross section such as local maxima or minima. The detailed shape of the angular distribution contributes to improved extrapolation of measurements to small-angle scattering regions and reduces extrapolation errors.

Due to limitations such as the duration of the beam test, triton identification could not be performed. However, this test verified detector operation. First, the scTPC was able to work normally without discharging under the high-background environment caused by the heavy-ion beam while maintaining sufficient performance. Second, the CsI(Tl) signal was successfully utilized to trigger the AGET and detect secondary particle tracks effectively.

The current Kr beam experiment was performed to validate detector operation. We are actually interested in C and O isotopes instead of Kr. Although small-angle scattering near 0° in the center-of-mass frame provides more detailed information on transition dynamics and nuclear structure, detecting tritons is technically challenging because triton kinetic energy approaches zero in the laboratory frame at this angle range. Consequently, nuclear reaction experiments were designed to measure recoiled tritons with relatively large kinetic energy in inverse kinematics. Combined with theoretically calculated angular distributions of reaction cross sections, data for the small-angle range will be extrapolated from measured results to the greatest extent possible. According to Geant4 simulation [21], the current detector system is capable of measuring tritons with $E_{t,lab} > 20$ MeV and $\theta_{t,lab} < 85°$, taking into account energy loss of tritons in the insensitive zone of the detector (including the target window and field cage structure). The maximal energy deposition of tritons in CsI(Tl) is approximately 140 MeV, as determined by the CsI(Tl) thickness.

The $\delta$-electron background must be considered for control and veto in beam experiments. The maximum kinetic energy that can be transferred in a single collision is limited, depending on the kinetic energy of the incident particle. If the kinetic energy of the incident nucleus is considered to be 500 MeV/u, the calculated maximum kinetic energy of the $\delta$-electron is about 1.4 MeV. Results from Geant4 simulation (see Fig. 16 [Figure 16: see original paper]) and kinematic calculation are in good agreement. Moreover, the higher the kinetic energy of the $\delta$-electron, the lower its generation probability. The vast majority of $\delta$-electrons will not enter the TPC due to blocking by the $^3$He target sidewall and scTPC field cage structure. For $\delta$-electrons that enter the sensitive region of the detector, they can be rejected by CsI(Tl) because they cannot trigger the CsI(Tl). The $\delta$-electrons either do not enter the scintillators or the energy deposited in the scintillators is generally less than the trigger threshold.

According to theoretical calculation (see the preprint [55]), for a $^{20}$O beam with intensity of $10^6$ particles per second, the yield rate of our charge exchange reaction of interest (the transition between isobaric analogue states) is about 10 particles per hour with 3 atmospheres of $^3$He gas. To achieve the statistics required for experimental precision (above 1000 counts), approximately 100 hours of beam time are required to accumulate the data.

## IV. Summary

This paper focuses on the performance test of the scTPC. The energy resolution and gain non-uniformity of the THGEM were tested using a $^{55}$Fe X-ray source. The drift velocity of electrons was tested using both laser and cosmic ray muons. At a reduced electric field of 200 V/(cm · atm), a drift velocity of 3.95 cm/μs was obtained using the laser test and 3.91 cm/μs using the cosmic ray test. The position resolution of long tracks was measured using cosmic rays and heavy-ion beams. For cosmic ray tracks, the position resolution is 0.86 mm on the xy-plane and 0.79 mm on the zy-plane, resulting in an angular resolution better than 0.2°. The heavy-ion beam was directed to bombard the $^3$He target, and secondary charged particles were measured by the scTPC. For secondary particles, the position resolution on the xy-plane is 0.71 mm, and on the zy-plane is 0.73 mm, giving an angular resolution better than 0.2°. The performance of the scTPC meets the requirements for measuring product particles from ($^3$He,t) reactions and can support the next step of the experiment.

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