Design and Simulation Optimization of the Detector System for Inverse Kinematics (3He, t) Charge-Exchange Reaction Experiments: Postprint

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Abstract

Charge-exchange reactions in the intermediate energy region provide a means to investigate the complex structure of atomic nuclei from the perspective of spin-isospin excitations. By employing the radioactive beam line at the Institute of Modern Physics, Chinese Academy of Sciences, and conducting charge-exchange reaction experiments using the inverse kinematics method, the scope of nuclides under investigation can be extended to neutron-rich nuclei and even unstable nuclei. Accordingly, a detector system for charge-exchange reaction experiments has been designed, which primarily consists of a 3He gas target, a TPC, and a CsI(Tl) array, with the TPC and CsI(Tl) array forming a ΔE-E system. Utilizing simulation software such as Geant4 and Garfield++, the operating conditions of the TPC have been optimized, the kinematic region for the experimental studies and the fundamental design of the detector have been established, and the particle identification capability of the detection system has been evaluated. Based on this simulation-based optimization, the detector system has been constructed.

Full Text

Development of a Detection System for (^{3}He, t) Charge Exchange Reaction Experiments in Inverse Kinematics

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Abstract: Intermediate-energy charge exchange reactions serve as a powerful experimental probe for investigating the complex structure of atomic nuclei from the perspective of spin-isospin excitations. By utilizing the radioactive beam line at the Institute of Modern Physics, Chinese Academy of Sciences, charge exchange reaction experiments conducted in inverse kinematics can extend the scope of studied nuclides to neutron-rich and even unstable nuclei. Accordingly, we have designed a detector system for such experiments, consisting primarily of a ^{3}He gas target, a Time Projection Chamber (TPC), and CsI(Tl) scintillator arrays, where the TPC and CsI(Tl) arrays form a ΔE-E telescope system. Using simulation software such as Geant4 and Garfield++, we optimized the operating conditions of the TPC, determined the kinematic coverage and basic detector design for the experimental study, and evaluated the particle identification capabilities of the detection system. Based on these simulations, we constructed the detection system and measured the spatial resolution of the TPC using a UV laser. The position resolution is approximately 422 m in the readout electrode plane and about 681 m along the electron drift direction. The TPC performance is sufficient to support track reconstruction of nuclear reaction secondary particles and, in particular, can achieve high scattering angle resolution.

Keywords: detection system; Geant4; simulation; charge exchange reaction

Charge exchange reactions constitute an important experimental tool for studying the complex structure of atomic nuclei through spin-isospin excitations [1]. Among these, reactions such as (^{3}He, t), (t, ^{3}He), and (d, ^{2}He) are conventional experimental methods offering high resolution and detection efficiency. Using accelerator-produced ^{3}He and t beams, charge exchange reaction experiments have been conducted on a series of nuclides [2], yielding fruitful results in studies of nuclear spin-isospin excitations, giant resonances, β-decay, and neutron skin thickness. However, due to experimental design limitations, nearly all such studies to date have been confined to stable nuclides. Charge exchange reaction experiments on unstable nuclides using inverse kinematics remain technically challenging yet full of opportunities. A research team at Michigan State University successfully extracted β^{+}-direction Gamow-Teller transition strengths B(GT) from unstable nuclei for the first time via inverse kinematics (d, ^{2}He) reactions; their experimental scheme, based on an active target time projection chamber and magnetic spectrometer, opened new avenues for addressing a series of scientific problems [3−4]. A research team at Beihang University proposed systematic measurements of charge exchange reaction total cross sections for unstable nuclides in inverse kinematics and attempted to establish a relationship between total cross sections and total B(GT) [5]. Building upon this, we propose to conduct inverse kinematics (^{3}He, t) charge exchange reaction experiments using radioactive beams produced by the accelerator facility at the Institute of Modern Physics, Chinese Academy of Sciences [6] to bombard a ^{3}He target, thereby extending the range of studied nuclides to unstable neutron-rich species. Consequently, we have designed and constructed a detection system for measuring large-angle scattered tritons to verify the feasibility of conducting inverse kinematics (^{3}He, t) experiments with heavy-ion beams [7]. The detection system is based on a ΔE-E telescope configuration, with the ΔE detector being a Time Projection Chamber (TPC) and the E detector being CsI(Tl).

This paper focuses on the design and optimization of the detector system. First, we designed the basic detector structure according to the physics objectives. Then, based on kinematic calculations and using software tools including Geant4, Garfield++, and COMSOL, we simulated the detector configuration and reaction backgrounds, optimized the design accordingly, and determined the kinematic region for experimental study. Finally, guided by these simulation and optimization analyses, we completed the construction of the detection system.

1 Experimental Design

As shown in Figure 1: see original paper, the detection system primarily consists of a ^{3}He gas target, TPC, CsI(Tl) scintillator array, front-end electronics, and data acquisition system. Heavy-ion beams bombard the ^{3}He target to produce tritons through charge exchange reactions. These scattered tritons, carrying specific kinetic energies, traverse the TPC and deposit their remaining energy in the scintillator array. During actual collisions, other byproducts may also be produced. The ΔE-E system formed by the TPC and CsI(Tl) array enables particle identification to discriminate tritons from other particles.

The TPC offers several advantages: low energy threshold, high detection efficiency, good energy resolution, and excellent position resolution (particularly for scattering angle resolution). It can precisely measure energy loss and reconstruct three-dimensional particle tracks, and is more economical than silicon strip detectors, facilitating fabrication in large sizes. Furthermore, the TPC working gas itself can serve as the target—an active target TPC (AT-TPC)—which presents significant advantages and potential for nuclear physics experiments [8]. Therefore, we adopted a TPC based on Thick Gas Electron Multipliers (THGEM) [9—10] as the ΔE detector to measure three-dimensional particle tracks and energy loss [11]. CsI(Tl) offers good energy resolution, high detection efficiency, and ease of processing and packaging, making it our choice for the E detector to effectively measure the residual energy of charged particles [12].

Neglecting isospin flip and excitation energy of final-state particles, the charge exchange reaction can be treated as elastic scattering. Based on relativistic kinematics for elastic collisions between heavy ions and light nuclei (^{3}He), Figure 1: see original paper shows the relationship between the scattered triton' s energy and laboratory scattering angle (, b). When , b approaches 90°, this corresponds to center-of-mass scattering angles (, . .) near 0° with minimal momentum transfer. However, tritons scattered at such small angles have insufficient kinetic energy to overcome target self-absorption, making this region experimentally inaccessible. The measured cross sections can be extrapolated to , . . = 0° based on the actual angular range detected. As , b decreases, the scattered triton kinetic energy increases, requiring thicker CsI(Tl) crystals for complete energy deposition. Therefore, the kinematic region for experimental study requires further simulation optimization and careful consideration in conjunction with the specific detector design.

2.1 TPC Simulation

When charged particles traverse the TPC, they ionize the working gas, creating electron-ion pairs. Electrons drift toward the THGEM under the electric field, undergo avalanche multiplication when passing through THGEM micropores, and the avalanche electrons are collected by the readout electrodes in the induction region to produce signals. Throughout processes such as electron drift and avalanche, TPC performance is affected by working gas properties and THGEM gain [13], making preliminary simulation optimization crucial. We used Garfield++ [14] to simulate electron behavior in the working gas. Figure 2: see original paper shows the simulated electron drift velocity in Ar + iC_4H_{10} mixtures. In TPC operation, we desire electron drift velocity to be minimally sensitive to the reduced electric field, ensuring that minor field fluctuations do not cause dramatic velocity changes. Ar(95%) + iC_4H_{10}(5%) proves to be a suitable working gas; at a drift field strength of 200 V/(cm · atm), the electron drift velocity approaches saturation at approximately 4.2 cm/ s. Higher iC_4H_{10} proportions require stronger fields to reach saturation velocity. Meanwhile, COMSOL [15] and Garfield++ [14] were employed to simulate the complete process from electron generation to collection, providing reference for appropriate THGEM voltage configurations. As shown in Figure 2: see original paper, the avalanche gain increases exponentially with THGEM voltage difference. The Ar(95%) + iC_4H_{10}(5%) mixture achieves high avalanche gain at relatively low voltage. With double-layer THGEM operation, high gain can be achieved without applying excessively high voltage to individual layers, effectively preventing discharges.

Considering the TPC’ s irregular shape and stringent requirements for electric field uniformity, a dedicated field cage must be designed. Field cage electrodes were fabricated using printed circuit board technology due to its flexibility in producing various shapes. COMSOL calculations of the field cage electric field guided the design: the field cage uses double-sided copper-clad PCB with electrode strip widths of 1.5 mm, strip gaps of 0.5 mm, and a periodicity of 2 mm between electrode strip centers. The inner and outer electrodes form an interleaved mirror structure. Reference lines were established in COMSOL to extract electric field distributions. These lines run parallel to the cathode plate at the mid-plane of the field cage, and we statistically analyzed the electric field uniformity within 2 mm, 5 mm, and 10 mm from the inner field cage edge. The calculations reveal that field non-uniformity is approximately 2‰ at 2 mm from the edge and reaches 0.1‰ at 5 mm from the edge. The drift field exhibits slight distortion within 5 mm of the edge. For tritons scattered with energies of 20-150 MeV, approximately 5-30 keV of energy is lost in this 5 mm region of working gas, representing about 2.5% of the total energy deposition in the TPC—this can be corrected for or rejected during data analysis. Field distortion in the remaining region is minimal and can be considered an effective drift region. If we treat the region within 5 mm of the field cage edge as distorted, the distorted field region accounts for about 5% while the uniform field region comprises approximately 95%.

2.2 Geant4 Simulation

We developed a Monte Carlo simulation package based on Geant4 [16] to determine the detector system structure and kinematic coverage. The detector system constructed in Geant4 is shown in Figure 3: see original paper, where the central blue cylinder represents a stainless steel chamber containing ^{3}He gas at 3 atmospheres (1 standard atmosphere equals 101.325 kPa). The heavy-ion beam spot diameter after passing through the ^{3}He gas is approximately 30-40 mm, so the gas target radius was set to 24.8 mm with a stainless steel wall thickness of 0.2 mm. The middle yellow semi-cylinder represents the TPC, comprising primarily the field cage and working gas, as illustrated in Figure 3: see original paper. The TPC has an inner radius of 25 mm and outer radius of 197 mm. The field cage structure uses 0.66 mm thick FR4 substrate with 0.02 mm copper cladding on both sides. The field cage is filled with Ar(95%) + C_4H_{10}(5%) gas at 1 atmosphere pressure. The outermost layer is the CsI(Tl) scintillator array, with red indicating CsI(Tl) crystals 20 mm thick and 200 mm long, and white representing a 0.135 mm thick Teflon reflective layer.

First, we performed "fast simulations" by generating tritons and other products such as protons, deuterons, ^{3}He, and α particles directly from the target volume to investigate the detectable energy range and particle identification capabilities. Collisions were treated as elastic scattering processes, with triton energy-angle correlations following the relationship shown in Figure 1: see original paper. To simplify the simulation, we assumed that the energy-angle relationships for protons, deuterons, ^{3}He, and α particles were identical to those for tritons. The TPC working gas and CsI(Tl) crystals were designated as "sensitive detectors" to extract energy depositions. Assuming typical energy resolutions of 10% for the TPC and 8% for the scintillator, the simulated ΔE-E distribution is shown in Figure 3: see original paper, where tritons are clearly distinguished from other byproducts. With this detector design, the maximum detectable triton energy is approximately 130 MeV. Figure 3: see original paper shows the relationship between the initial triton kinetic energy and the sum of energy deposited in the ^{3}He gas, stainless steel chamber, and inner field cage. Tritons require at least

20 MeV to overcome target self-absorption and exit the stainless steel side wall into the TPC; higher-energy outgoing tritons experience smaller energy losses in the detector dead region. Therefore, this detector design is suitable for tritons with kinetic energies of approximately 20–130 MeV, corresponding to scattering angles of about 76°–86°.

After finalizing the detector design, we simulated the reaction background from heavy-ion beam bombardment by modeling 500 MeV/nucleon ^{17}C beams impinging on the ^{3}He gas target. The Geant4 physics processes employed the FTFP_{{{BERT}}_{{ATL}}} physics list. The ^{17}C beam was directed along the z-axis with a circular distribution of 20 mm radius incident on the ^{3}He gas target. While Geant4 simulations cannot provide detailed charge exchange reaction cross sections, particularly for spin-isospin excitation processes involving reaction mechanisms, they do provide statistical descriptions of triton and other byproduct production from heavy-ion collisions with target nuclei, treating reactions as elastic or inelastic scattering. Based on the reconstructed ΔE-E distribution for ^{17}C-^{3}He collision products from the simulation (shown in [Figure 4: see original paper]), various charged particles can be clearly distinguished within the 76°–86° emission angle range.

Assuming a beam intensity of 10^{6} pps, the simulated production rates for various particles are listed in . Protons exhibit the highest production rate, while elastic scattering products ^{3}He are relatively scarce. We therefore conclude that ^{3}He is likely fragmented by the 500 MeV/nucleon heavy-ion beam, making protons and deuterons the dominant species. Although the triton yield is smaller compared to protons and deuterons, with approximately 32 events per second, tritons can still be effectively measured and identified. The detector design has been validated as reasonable. Moreover, despite the high total event production rate from collisions, the effective count rate accepted by the detector is only about 1,000 pps, posing modest demands on detector and electronics response.

3 TPC Construction and Performance Testing

Based on simulation optimization, we constructed the detector system for charge exchange reaction experiments. The TPC detector [17] comprises primarily a cathode plate, field cage, THGEM foil, and anode readout board, as shown in [Figure 5: see original paper]. The cathode is a single-sided copper-clad PCB plate held at negative high voltage and connected to the first electrode strip of the field cage. The field cage has a semi-cylindrical geometry with an inner radius of 25 mm and outer radius of 200 mm. The outer field cage was shaped using a mold and UV-curing adhesive, while the inner field cage was formed using an aluminum alloy mold; the inner and outer cages were welded into an integrated unit. The TPC readout detector employs THGEM designed by our group and fabricated by the University of Science and Technology of China. The THGEM active area is approximately 270 cm^{2}. To reduce discharge signals, the copper cladding on one THGEM face was segmented into six fan-shaped regions. The readout electrode adopts a zigzag pad configuration [18] with a total of 886 effective channels. In the sensitive region, pads have a 7.5 mm long dimension parallel to the incident particle direction and a 4 mm short dimension perpendicular to it. The readout electronics and data acquisition system utilize the AGET chip-based electronics system developed by the University of Science and Technology of China [19].

We tested the basic TPC performance using a 266 nm UV laser, measuring position resolution in the readout electrode plane (xy-plane) and along the electron drift direction (zy-plane). The laser track projections onto the xy and zy planes (shown in [Figure 6: see original paper]) exhibit no significant distortion, indicating uniform electric fields in the TPC drift region. Pads in the same row with signals form a signal cluster; the y-coordinate of the cluster uses the geometric center of that pad row, while the x- and z-coordinates represent the charge centers in the x-direction and z-direction, respectively. The z-position is calculated from drift time and drift velocity, with drift velocity taken from Garfield++ simulation results of 4.12 cm/ s at a drift field of 200 V/(cm·atm). Position resolution is expressed in terms of track residuals [20], where the standard deviation (σ) of the residual distribution gives the position resolution in the corresponding plane, as shown in [Figure 7: see original paper]. In the xy-plane, the position resolution is approximately 422 m. In the zy-plane, the position resolution is about 681 m.

4 Summary and Outlook

This paper presents the design and optimization of a TPC-CsI(Tl) detection system for inverse kinematics (^{3}He, t) charge exchange reactions. First, we discussed the experimental requirements for the detection system. Given the stringent performance demands on the TPC as the ΔE detector, we simulated its operating characteristics using Garfield++, COMSOL, and other software. The simulations demonstrated that an Ar(95%) + iC_4H_{10}(5%) gas mixture offers advantages including high electron drift velocity, small diffusion coefficients, and low operating voltage, leading to its selection as the TPC working gas. Through electric field analysis and electron transport simulations, we determined the detailed design of the field cage' s mirrored electrode structure and the operating voltage for THGEM. Combined with Geant4 simulations, we established the detector dimensions, operational dynamic range, and evaluated its particle identification capabilities. Next, using Geant4 to simulate heavy-ion beam bombardment of the target, we examined the species, energy distributions, and production rates of product particles under collision conditions—that is, the reaction background distribution. Finally, we determined that the detector is suitable for measuring tritons with scattering angles of approximately 76°–86° and scattered kinetic energies of about 20–130 MeV. Based on these simulation and optimization studies, we completed construction of the TPC detector component and measured its spatial resolution using a laser. The position resolution is approximately 422 m in the xy-plane and about 681 m in the zy-plane.

A larger TPC facilitates higher angular resolution. Considering a particle track length of 20 cm, a position resolution better than 2 mm in the drift direction is sufficient to achieve 0.5° angular resolution in the laboratory frame, a requirement easily met by the current TPC performance. Based on the energy-angle relationship of recoil tritons, the "missing mass method" will be used to reconstruct excited states of unstable nuclides. While the TPC-CsI(Tl) system detects large-angle scattered tritons, the existing experimental setup at the RIBLL-2 beam line and external target terminal will simultaneously detect outgoing heavy nuclear products, enabling inclusive measurements over a certain angular range. Time stamps will be used to reconstruct coincidence events during offline analysis, allowing selection of charge exchange reaction products and effective background subtraction. Beam line detectors can measure heavy nuclear products at small center-of-mass angles, and combined with theoretical model analysis and experimentally measured angular distributions at larger angles, this will enable more accurate extrapolation to obtain reaction cross sections at small center-of-mass angles for different resonant states.

The next step involves conducting charge exchange reaction experiments on unstable nuclides using the RIBLL-2 beam line and external target terminal at the Institute of Modern Physics, Chinese Academy of Sciences.

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Note: Figure translations are in progress. See original paper for figures.