MATEROOT: A Simulation and Analysis Tool for Experiments with MATE

Authors: LI, Mr. Lu, Zhang, Dr. Zhichao, Zhang, Mr. Ningtao, ONG, Prof. HOOI-JIN, Terashima, Dr. Saturo, Zhang, Mr. Jinlong, Gao, Dr. Bingshui, Lu, Dr. Chengui, Liu, Dr. Enqiang, Lv, Dr. Bingfeng, Ma, Mr. Junbing, Tang, Dr. Xiaodong, Wang, Dr. H., Xu, Dr. Xiaodong, Zhang, Dr. Zhichao

Date: 2026-03-18T21:49:35+00:00

Abstract

A simulation and analysis platform, MATEROOT, has been developed for MATE (multi-purpose active-target time projection chamber for nuclear physics experiments). The platform is built on the ROOT, GEANT4, and FAIRROOT, featuring a modular design enabling realistic Monte Carlo simulations with flexible detector configurations, and efficient data analysis for TPC experiments. The tracking performance of MATE was systematically investigated using the MATEROOT platform. To illustrate the approach without unnecessary complexity, we employed the widely used RANSAC algorithm as a representative example. By optimizing its parameters within the MATE geometric framework, we evaluated tracking efficiency as a function of particle range and track multiplicity. To demonstrate the functionality of MATEROOT, we further evaluated the detector' s performance metrics, including range resolution, angular resolution and particle identification, through simulations and comparisons with some test results. A benchmark simulation and data analysis study was performed for validation, utilizing 12C+α elastic scattering at an incident energy of 32.5 MeV/u. The reconstructed differential cross-sections exhibit excellent agreement with the input experimental data, thereby establishing MATEROOT as a reliable tool for the design and analysis of MATE experiments.

Full Text

Preamble

ATEROOT : A Simulation and Analysis Tool for Experiments with MATE Lu Li, Zhi-Chao Zhang, Ning-Tao Zhang, 1, 2, Hooi-Jin Ong, 1, 2, 3, 4, 5, Satoru Terashima, 1, 4, 5 Jin-Long Zhang, Bing-Shui Gao, Chen-Gui Lu, En-Qiang Liu, Bing-Feng Lv, Jun-Bing Ma, Xiao-Dong Tang, 1, 2, 3 He Wang, and Xiao-Dong

Xu 1 State Key Laboratory of Heavy Ion Science and Technology, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, China Joint Department for Nuclear Physics, Lanzhou University and Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan Nishina Center for Accelerator-Based Science, RIKEN, 2-1 Hirosawa, Wako, 351-0198 Saitama, Japan A simulation and analysis platform, M ATEROOT , has been developed for MATE (multi-purpose active-target time projection chamber for nuclear physics experiments). The platform is built on the R 4, and AIRROOT , featuring a modular design enabling realistic Monte Carlo simulations with flexible detector con- figurations, and efficient data analysis for TPC experiments. The tracking performance of MATE was systemat- ically investigated using the M ATEROOT platform. To illustrate the approach without unnecessary complexity, we employed the widely used RANSAC algorithm as a representative example. By optimizing its parameters within the MATE geometric framework, we evaluated tracking efficiency as a function of particle range and track multiplicity. To demonstrate the functionality of M ATEROOT , we further evaluated the detector’ s perfor- mance metrics, including range resolution, angular resolution and particle identification, through simulations and comparisons with some test results. A benchmark simulation and data analysis study was performed for validation, utilizing elastic scattering at an incident energy of 32.5 MeV/u. The reconstructed differential cross-sections exhibit excellent agreement with the input experimental data, thereby establishing M ATEROOT a reliable tool for the design and analysis of MATE experiments.

Keywords

Active target, Time Projection Chamber, Simulation and analysis, MATE

INTRODUCTION

Over the past two decades, active target Time Projection Chambers (TPCs) have undergone rapid development. These detectors, using the working gas as both target and track- ing medium, excel in three-dimensional track reconstruction, low-threshold particle identification, and nearly 4 solid- angle coverage, enabling their widespread use in nuclear

physics experiments. Active targets have significantly en- 8

hanced experimental luminosity in spectroscopy and nuclear reaction studies using radioactive-isotope (RI) beams in in- verse kinematics [ ]. Consequently, several active-target TPCs are under development or deployment at accelerator fa- cilities worldwide: AT-TPC at NSCL [ ], ACTAR TPC at GANIL [ ], CAT at CNS [ ], MAIKo at RCNP [ ], CAT-TPC

Supported by the National Natural Science Foundation of China (Nos. 12175009, 12175280, 12250610193, 12505146), the Na- tional Key Research and Development Program of China (Nos. 2022YFA1602304), the CAS “Global Initiative on Common Challenges” (No. 016GJHZ2023063GC), the Major Science and Technology Projects in Gansu Province (No. 24GD13GA005), and the Natural Science Foun- dation of Gansu (No. 23JRRA676). H. J. Ong acknowledges the support of the CAS Light of West China Program. The authors acknowledge the MATE Collaboration for their continuous support and contributions to this work.

Zhang Zhi-Chao, Nanchang Road 509, Lanzhou Zhang Ning-Tao, Nanchang Road 509, Lanzhou Ong Hooi Jin, Nanchang Road 509, Lanzhou

at Peking University [8], fMeta-TPC at Fudan University [9], 15

MTPC at CSNS [ ], and MATE at IMP-CAS [Advances in RI-beam experiments, coupled with increas- ing granularity and size of active-target TPCs, have generated vast experimental datasets, typically several to tens of terabytes, posing major challenges for data processing and analysis. Robust, flexible simulation and analysis tools are thus indispensable for efficient experiment design, extracting physical observables from these datasets, and interpreting re-

sults. The nuclear physics community has developed several 24

dedicated frameworks to address these challenges. For ex- ample, A TTPC-ROOTV] and S PYRAL] have been de- veloped to support AT-TPC data analysis and simulations for cylindrical TPCs; A CTARS] was constructed to support ACTAR TPC project; and B] was designed to enable studies of neutron-induced charged-particle emission with MTPC at CSNS. Similarly, for the MATE (multi-purpose active-target time projection chamber for nuclear physics ex- periments) project, we have developed M ATEROOT] over the past few years. This dedicated platform offers a robust, modular framework integrating data decoding, event recon-

struction, and G EANT 4-based [18] simulations, streamlining 36

the full data-to-physics pipeline for MATE experiments.

The M ATEROOT project was initiated to support MATE- 38

related experiments, including C fusion measurements at stellar energies [ ] and above the Coulomb bar- rier [ ], as well as C fusion near the Coulomb barrier [ ] using the prototype MATE with 1000-channel read- outs. The platform has since been expanded to accommodate upgraded MATE with 4000-channel readouts and applied in a

commissioning experiment with a 14 N beam to verify MATE 45

performance [ ], and a recent C spectroscopy study. In addition, new analysis methods are being developed based on this platform, such as the recent implementation of machine learning techniques for event reconstruction [22]. 49

In this paper, we introduce the M ATEROOT platform, report a systematic evaluation of the track reconstruction and MATE performance, and present its validation. Section overviews the simulation and data-analysis framework. Section vestigates the track reconstruction efficiency using simulated -particle tracks. Section evaluates the performance of MATE using simulated particles. Section provides com- prehensive validation via elastic scattering reaction.

Finally, a summary is given in Section ARCHITECTURE The M ATEROOT platform is designed with a modular architecture, where the simulation and analysis packages, MATES im and MATEA ib, operate independently while sharing common data structures implemented within the analysis framework [ ]. The F AIRROOT] base part is also incorporated as an external dependency. schematic architecture is illustrated in Fig.

Simulation module: MATES MATES im is designed to simulate nuclear reactions, parti- cle transport processes, and corresponding detector responses based on the G 4 Monte Carlo toolkit. For this purpose, we adopted the simulation functionality provided by N], an open-source, freely distributed Monte Carlo simula- tion and data analysis package for low-energy nuclear physics experiments.

Unlike the standard N ool simulation part, we im- plemented a modular configuration system based on the] syntax, as shown in Fig. (a). This format provides a highly readable and flexible interface, enabling users to efficiently modify key parameters, such as detector geome- try, material properties and reaction settings, without the need for code recompilation.

To streamline data collection and subsequent decoding, we adopt a simplified strategy: only two standard data containers and two corresponding G primitive scorers are provided. Furthermore, newly devel- oped fusion and decay models allow for the simulation of complex multi-step nuclear reactions or decay chains. The key features of MATES im are detailed below.

Detector Factory : The primary function is to define detector configurations.

In the construction file, users construct detector geometries, assign spa- tial coordinates, define raw data storage, and asso- ciate Geant4 physics processes. Following the N paradigm, new detector modules (e.g., Fig. (b)) are registered via the DetectorManager and can then be shared among all users. The detector project can also

be run locally, remaining invisible to other users, dur- 96

ing ongoing detector improvement or for protection reasons. Specific detector components can be selec- tively toggled via Boolean flags in a input file.

Physics Processes : To ensure precise control over reaction kinematics and decay processes, we de- veloped several commonly used nuclear reaction mod- els and decay models, which are derived from G standard models (Fig.). Two complementary modes are provided:

FullSimulation FastSimulation , both of which are driven by common kinematics extracted either user-defined phase space or direct sampling from input differential cross-sections. The full mode per- forms a rigorous particle transport calculation, includ- ing detailed energy loss and realistic sampling from user-defined cross section data, while the fast mode prioritizes computational speed by applying reaction models forcedly.

A special feature of our platform is the support for multi-step reactions and/or decays.

This mechanism allows primary reaction products to 115

undergo interactions with the target atoms before next reaction or decay process was triggered. This capa- bility is particularly crucial for simulating the in-flight decay and evaluating background contributions, such as elastic-scattering-induced background in transfer re- actions, and background channels in low-cross-section nuclear-astrophysics measurements.

Data Container : To modularize and simplify the storage, decoding and analysis processes from simu- lated data to experimental data formats, TClonesArray based objects are used to record interaction informa- tion from the nuclear reactions and/or decays. Follow- ing the strategy of the GenFit package [ ], only two specialized TClonesArray types are used: a calorime- ter type for momentum measurements and a tracking type for space-point measurements. 4 scorers automatically transfer hit information to these containers.

Output Manager : A centralized Output Manager governs the structure of the resulting R tree, em- ploying users to easily register a TClonesArray object into the TTree branch list. This design ensures a stan- dard simulated data across various detector subsystems and full compatible with with downstream analysis fol- lowing F AIRROOT standards.

- Online Monitor : A fast and flexible online moni- 141

tor is developed using the JavaScript R library [While simulated data are persisted in R files, a par-

allel monitoring stream processes events in real time, 144

and transmits them via ZeroMQ sockets. This allows web-based, real-time visualization of detector subsys- tems and user-defined histograms via specified TCP ports.

Input Files Process Manager Physics Process Parameters Files DecayModel Detector Files Target FusionReaction Daughter Nucleus TwoBodyReaction G4RUN ReactionRegion Standard G4Physicslist TGenPhaseSpace (Reaction&Decay) ReactionModel G4EVENT G4TRACK Detector Manager Detector Construction G4STEP Parameters Stored Module Name (YMAL)

ReactionConditions Geometry Object TTrees Material Calorimeter Object InitialConditions TObject StepHit Object Hit Type Scored DetectorData Calorimeter Type TClonesArray Raw Event MATESim Analysis module:

MATEA To accommodate the complex, multi-stage analysis re- quirements of MATE data and ensure efficient event-by-event information extraction, MATEA ib has been developed in adherence to the F AIRROOT standard. This architecture en- ables users to define and configure a sequence of hierarchi-

cal tasks, spanning raw-data decoding, pulse-shape analysis 155

(PSA), pattern recognition, and subsequent track analysis. 156

Specifically, the decoding stage converts raw GET electron- ics [ ] data into digitized hits; PSA extracts physical infor- mation such as charge and timing from waveforms; pattern MATEAnaLib

Experiment

Electronic Response

Experimental Run Manager

Experiment

Digitization Par Manager MCPointAvalanche MCPointToEventHit Parameters File MCPointPulse Simulation Geo Manager Mapping File(txt,xml) Reconstruction RANSAC Cluster IO Manager EventHit Tracking Ana Hough KalmanFilter Read StepHit Track Analysis VertexFinder TPCTracks Fair RunAna TrackFitting

recognition utilizes robust algorithms like Hough Transfor- 160

mation [ ] or Random Sample Consensus (RANSAC) [to identify particle trajectories; and track analysis performs final kinematic reconstruction and particle identification.

Execution of these tasks is handled by RunManager

F AIRROOT , which drives the initialization, runs the event 165

loop, employs the I/O manager. To ensure flexibility and traceability across different experimental setups, detector- specific configurations, including pad-to-channel mapping, pad geometries, and experimental parameters such as drift ve- locity and diffusion coefficient are read directly from param- eter containers by using the runtime database (RTDataBase Configuration Files Event Generator Root File PulseAnalysis Schematic architecture and data flow of the M ATEROOT framework. (a) (b) (c) Simulation of elastic scattering. (a) Example of a input file defining the beam and reaction parameters. (b) The MATE module constructed using MATES im. The purple volume indicates the sensitive region of the TPC, while the green planes represent auxiliary silicon detectors. (c) A typical simulated event in the TPC. The three-dimensional trajectories are projected onto the readout pad plane (YZ), together with the corresponding charge deposition.

This design allows the framework to support various detector configurations, such as the 4000-channel triangle pad plane used in MATE, without requiring code recompilation.

TRACK RECOGNITION Extracting reliable physical observables from TPC data re- lies heavily on accurate track reconstruction and classifica- tion. To overcome the difficulties of track identification in high-noise environments, various algorithms have been pro- posed in the literature, such as the Hough transform applied to MAIKo [ ], RANSAC and hierarchical clustering for AT- TPC [ ], Kalman filter for ALICE [ ], and Celluar au- tomation for PANDA [ ]. In practice, however, the complex- ity of experimental scenarios often demands the integration of multiple algorithms, combining their respective strengths to ensure robust performance. For simplicity and to illustrate the methodology, in this work we employ only the widely used RANSAC algorithm as a representative example, implemented via the MateRansac class in MATEA ib. By optimizing its key parameters, we performed a systematic study of track recognition efficiency as a function of particle range. This evaluation is essential for defining the sensitivity and dynamic range of the MATE detector in nuclear reaction measurements. Parameters optimization The RANSAC algorithm is a robust parameter estimation technique designed to fit mathematical models to datasets containing a substantial fraction of outliers [31]. Unlike standard least-squares methods, RANSAC generates candidate solutions by iteratively selecting a minimum number of random data points required to estimate the model parameters.

For each iteration, the algorithm identifies inliers –points that fall within a predetermined distance tolerance –and selects the model with the largest consensus, i.e., the highest fraction of inliers.

In the MateRansac class, we utilize the implementation provided by the Point Cloud Library (PCL) [ ], which en- ables efficient classification of multiple tracks, vertex recon- struction, and effective rejection of random noise. The track recognition performance is governed by the Distance parameter, which defines the maximum allowable distance between a hit point and the estimated track model for it to be consid- ered an inlier. The maximum number of iterations was set to 1000, corresponding to a success probability of 0.99.

In active-target TPC experiments, physical events typically involve multiple charged-particle trajectories rather than a single track. A representative case is the elastic scat- tering reaction, as illustrated in Fig. (c), which is char- acterized by three distinct tracks. The presence of multiple tracks significantly increases the complexity of track recognition and may lead to track overlap, fragmentation, or misclas- sification. To systematically evaluate the robustness of the RANSAC-based approach under realistic experimental con- ditions, dedicated simulations were performed with increasing track multiplicities. Specifically, events containing one to -particle tracks were generated using the M ATEROOT package.

For each track multiplicity, systematic scans over the tance parameter were performed. The track reconstruction efficiency (tracking) is defined as the fraction of simulated tracks that are correctly identified by the RANSAC algorithm.

The resulting efficiencies as functions of the parameter are presented in Fig. . The simulations were performed using mono-energetic particles with a fixed range of 79 mm, emit- ted isotropically from the geometric center of the MATE sen- sitive region ( ). This configuration was chosen to avoid boundary effects, and to provide a uniform benchmark for evaluating the intrinsic performance of the track reconstruction. tracking

1 T

Distance (cm) Sensitivity of the RANSAC parameter Distance on track reconstruction efficiency in M ATEROOT . Mono-energetic particles with a fixed range of 79 mm were isotropically emitted.

As shown in Fig. , the results indicates that the Distance parameter exhibits high sensitivity to track reconstruction ef- ficiency, in agreement with findings reported in Ref. [ ]. For single-track events, tracking increases rapidly with Distance and reaches a plateau of nearly 100% at approximately 0.6 cm. This value coincides with the size of the pads (equilateral triangles with a side length of 0.7 cm). However, as the mul- tiplicity increases, the optimal plateau gradually narrows and the optimal point slightly shifts, indicating an increased probability of track merging and noise inclusion. For all multiplic- ity cases, the reconstruction efficiency drops sharply when Distance is set below 0.5 cm. This is because an overly re- strictive tolerance excludes sufficient inliers, leading to the recognition of spurious tracks. Conversely, an excessively large Distance results in a monotonic decrease in efficiency, as hits from adjacent tracks are incorrectly associated as in- liers of the current linear model. This interference degrades the fitting precision and can lead to the erroneous merging of multiple tracks.

Overall, the study indicates that the optimal parameter of the RANSAC algorithm for MATE lies within a Distance range of 0.5 - 0.7 cm. Within this window, the system effec- tively balances high identification rates with the suppression of inter-track interference in high-multiplicity cases.

Analysis of reconstruction quality To further characterize the quality of the reconstructed tracks, we investigated the composition of track reconstruc- tion outcomes for different particle ranges and track multi- plicities. For simulated events with one to four tracks, the reconstruction results were classified into four categories ac- cording to track recognition success and the angular residuals) between simulated and reconstructed trajectories:

a. Successful recognition with high precision ($|\Delta \theta| < 1^{\circ}$, for all tracks).

b. Successful recognition with acceptable precision ($1^{\circ} \leq \Delta \theta| < 3^{\circ}$, at least for one track).

c. Successful recognition with low precision ($|\Delta \theta| \geq 3^{\circ}$, at least for one track).

d. Incorrect recognition.

The absolute values below 1 correspond to high- precision reconstruction, comparable to the intrinsic detector resolution, while residuals below 3 remain acceptable for most differential cross-section analyses, where angular bin widths are typically a few degrees. The results for three dif- ferent -particle ranges –Group I (168 mm), II (83 mm) and III (30 mm) –are presented in Fig.

Composition of track reconstruction outcomes for different particle ranges and track multiplicities. Categories correspond to successfully recognized tracks with different angular residuals: | | < 3 , and | , respectively, while represents incorrect track recognition. Groups I-III represent different track ranges.

The particle range is identified as the primary factor determining the reconstructed quality. For long-range tracks (Group I, 168 mm), single-track events achieve a near-perfect high-precision reconstruction ratio of 96%. Even as the mul- tiplicity increases to four tracks, a dominant fraction of 58% still falls into category . As the range decrease to Group II (83 mm) and Group III (30 mm), the proportion of category a drops significantly. For single tracks, this value falls to 27% in Group III. Physically, shorter tracks consist of fewer hit points, thus even minor spatial fluctuations caused by diffusion can lead to disproportionately large values. This demonstrates that sufficient track length provides strong geometric constraints, enabling robust separation and accurate direction reconstruction.

Across all range categories, a clear correlation exists between track multiplicity and reconstruction quality. Specifically, for short-range tracks (Group II and III), the reconstruction quality deteriorated with increasing track multiplicity. As the multiplicity increases, pronounced increases in the proportions of categories indicate growing angular deviations. Moreover, incorrect reconstructions (category) also increase rapidly –in Group III, for instance, reaching 49%. This trend can be attributed to the reduced number of available hit points, and increased spatial overlap between tracks, both of which limit the effectiveness of geometry-based recognition algorithms such as RANSAC.

In practical experimental analysis, the effect of the detector geometrical acceptance should also be considered. Therefore, besides the track reconstruction efficiency (tracking) discussed above, we evaluated two further efficiencies as functions of particle range, as shown in Fig. : the geometric efficiency), defined as the fraction of total events that stop within the TPC sensitive region, and the total efficiency ( ), defined as:

$$\epsilon_{sum} = \epsilon_{tracking} \cdot \epsilon_{geo} . \quad (1)$$

The track reconstruction efficiency, shown in Fig. (a), increases with the particle range for all track multiplicities, and gradually saturates beyond approximately 80 mm. As multiplicity increases, tracking decreases due to tracks overlap and clustering ambiguities. In contrast, the geometric efficiency, shown in Fig. (b), exhibits the opposite trend. When the particle range is short, most tracks stop within the sensitive region, resulting in values close to 100%. However, as the range increases, a growing fraction of tracks escape the sensitive region before stopping, leading to a rapid drop in beyond 80 mm, and a decline to zero around 180 mm, which is consistent with the dimension of sensitive region, as shown in Fig. (c). This effect becomes more pronounced at higher multiplicities, since the probability that at least one track penetrates the detector boundaries increases with the number of emitted particles. As a result, the total efficiency , shown in Fig. (c), reflects the competition between these two effects. The maximum efficiency occurs at intermediate ranges, where the track range is sufficient for reliable reconstruction while most tracks still stop within the detector. In practice, auxiliary detectors, such as silicon detector, are typically integrated with the TPC to capture escaping particles [Overall, the

RANSAC implementation in M ATEROOT demonstrates excellent reliability for long-range and low-

tracking

1 T

Range (mm) multiplicity events. However, the reconstruction quality is highly sensitive in short-range and high-multiplicity scenar- ios. In practical analyses, multiple algorithms are often com- bined to address complex situations, thereby achieving im-

proved track recognition performance. 349

PERFORMANCE EVALUATION OF MATE VIA SIMULATION Following the guidelines established in the previous sec- tion, we demonstrated the functionality of M ATEROOT systematically evaluating MATE' s range resolution, angular resolution, and particle identification capabilities using sim- ulated data. This evaluation provides a benchmark for sub- sequent experimental analyses, such as spectrum reconstruc- tion.

Range resolution The track range –defined here as the spatial distance be- tween the start and end points of a trajectory –directly af- fects the reconstruction of particle energy loss.

To assess reconstruction performance, the range resolution calculated from reconstructed tracks (denoted as "Tracking") was com- pared with that derived from raw simulated data (denoted as "Raw"), which serves as a reference, as shown in Fig.

The range resolution (range) is defined as the standard devia- tion of the range distribution for mono-energetic alpha parti- cles, while the corresponding relative range resolution values are represented by red filled circles. The intrinsic spread of the simulated ranges increases gradually with track range due to the particle straggling and accumulated fluctuations along the trajectories. In contrast, the reconstructed range resolu- tion remains relatively stable. Consequently, the relative res- olution improves markedly with increasing range, decreasing to below 2% for ranges longer than 150 mm.

To further investigate the primary sources of range uncer- tainty, the residual distributions of the reconstructed start and end points were analyzed for several representative ranges, as illustrated in the box plots in Fig. (b). The startpoint resid- Range (mm) uals are consistently small and remain centered around zero across all ranges, indicating a high stability of the track ori- gin. In contrast, the endpoint residuals exhibit larger widths and increase with particle range. Accordingly, the residual distribution for the "Range" range closely follows that of the endpoints. This result demonstrates that the range resolution

is primarily dominated by the uncertainty in determining the 387 endpoint. triple- source (Cm) obtained from exper- iment and simulation. The simulation reproduces the mea- sured spectrum well, achieving a relative range resolution of 1.2%. This close agreement further validates the range- dependent resolution discussed in the preceding analysis.

Angular resolution The angular resolution (angle) directly impacts the precision of reconstructed excitation spectra in experimental anal- ysis. In this work, angle is defined as the standard deviation of the residual between the reconstructed and simulated polar angle . Fig. shows the dependence of angle on the particle

range. A significant improvement is observed as the range 401

increases. For the shortest range of 30 mm, the resolution is approximately , but it improves rapidly with increasing range. Once the range exceeds 100 mm, the resolution grad- ually approaches a plateau and stabilizes at approximately . This trend is primarily attributed to the larger number of hit points provided by longer trajectories, which enables the tracking algorithm and subsequent fitting to constrain the direction vector more accurately. A measurement point ob- tained with ultra-violet laser beam is also shown in Fig. exhibits a slightly lower resolution. This deviation is mainly due to the forward incidence of the laser beam, as opposed to the isotropic emission of the simulated particles, and is consistent with the angular dependence of the resolution dis- cussed below.

To further investigate the angular response, a detailed study was performed for the 155-mm range, where both range and angular resolutions are sufficiently good and stable. Fig. presents the angular resolution as a function of the . The Range (mm) (a) Track reconstruction efficiency, (b) geometrical acceptance, and (c) total efficiency as functions of particle range for different track multiplicities.

Tracking Relative Resolution (%) range Range (mm)

Experiment

Simulation

Experiment

Simulation Counts Range (cm) Reconstructed range spectrum for a triple- source (Cm) measured with a He+CO (10%) gas mixture at 500 mbar. Comparison of experimental (black) and simulated (red) data yields a relative range resolution of approximately 1.2%. resolution remains relatively stable over most angles, fluctu- ating around . However, a prominent peak appears near

$\theta = 90$ $\circ$, and two smaller peaks around 35 $\circ$ and 145 $\circ$ are ob- 422

served. The former is likely an artifact of tracks oriented par- allel to the drift direction, which can complicate the vertex determination and hit association.

The latter may be related to the geometric structure of the readout pads, where diffu- sion effects can slightly influence reconstruction around the transverse direction.

To verify these effects, a two-dimensional angular distri- bution of reconstructed tracks in space is shown in

θ are overlaid, demonstrating uni- 431

form coverage of the full solid angle, while also revealing

the non-uniform features discussed above. Additionally, the 433

residuals as a function of the azimuthal angle Start Range Residual (mm) Range (mm)

Experiment

Simulation Range (mm)

Angular resolution as a function of particle range. The sim- ulated results are represented by red points. A measurement point (black star) obtained with an ultra-violet laser at $\theta = 10\ \circ$ is shown.

plotted in Fig. (c) and (d), respectively. Here, represent the azimuth of the track projections onto the drift plane and pad plane, respectively. It is evident that the tracks aligned parallel to the drift direction exhibit degraded angular resolution in Fig. (c). A dependence on the pad geometry is also apparent in Fig. (d), which is attributed to the equilat- eral triangular structure and the orientation of the pad plane.

Particle identification As a typical active-target detection system, MATE pro- vides particle identification (PID) capabilities for particles that either stop within or traverse the sensitive volume of the

TPC. Technical details about the MATE setup can be found 446

(a) Range resolution as a function of particle range. Open circles are derived from raw simulated data, while filled circles correspond to values extracted from reconstructed tracks. The red symbols indicate the relative resolution of the reconstructed tracks. (b) Box plots of the residual distributions for reconstructed start points, end points, and track ranges at four different particle ranges. The solid and dashed lines inside each box represent the median and mean values, respectively.

(b) Angular resolution vs. polar angle . (b) Two-dimensional distribution of polar angle residuals in the space. (c) Polar angle residual vs. azimuth . (d) Polar angle residual vs. . Here denote the azimuth angles of the track projections on the drift plane and pad plane, respectively. Events with fewer than 5 hits on the pad plane were excluded from the analysis. in

Ref. [ ]. To systematically investigate the PID capabil- ities of MATE, simulations were performed for several light particles at various energies.

For particles stopping within the sensitive region, PID is performed by correlating the energy deposited in the TPC with the reconstructed track range, as illustrated in Fig Well-separated bands are observed for different elemental particles from hydrogen through carbon. The red- and black- dashed curves represent the particle energies calculated using the ATIMA 1.4 model (implemented in LISE++ [ ]) and the SRIM code [ ], respectively. Both models show good agree- ment with the simulated distributions for light nuclei, specif- ically hydrogen and helium. For ions heavier than helium, however, the particle energies calculated from these range- energy models deviate from the deposited energies obtained from M ATEROOT . This discrepancy underscores the inherent challenges in accurately modeling energy-loss processes for heavy ions in material [For high-energy particles that penetrate the TPC sensitive region and are subsequently stopped by the surrounding aux- iliary silicon detector array, the E-E telescope method is employed, as shown in Fig. . The combination of energy loss in TPC and silicon detectors provides sufficient separa- tion for a wide range of light ions. As with particles that stop within the TPC, iostopic separation for light particles (remains achievable.

It is important to emphasize that the simulations pre- sented above are intended to demonstrate the capabilities of ATEROOT . In realistic experimental conditions, the PID resolution would be degraded by effects such as diffusion,

delta electrons and electronic noise. 477

VALIDATION AGAINST THE BENCHMARK To validate the performance of the reconstruction frame- work, a benchmark simulation was performed using elastic scattering at an incident energy of 32.5 MeV/u. The

Particle identification in MATE using deposited energy in the TPC versus corresponding reconstructed track range. The isotopes were simulated with the M ATEROOT platform. Red- and black-dashed lines represent calculations with LISE++ (ATIMA 1.4 model) and SRIM.

Particle identification in MATE using the Δ E-E telescope method, combining energy loss in the TPC with residual energy in the auxiliary silicon array. The simulated isotopes were generated using the M ATEROOT platform.

angular distribution of the generated events was sampled ac- cording to the differential cross-section data from Ref. [ensuring that the simulated event distribution reflects real- istic kinematics. Because this simulation employed inverse kinematics, recoil alpha particles with low momentum trans- fer dominate the yield. Consequently, two gas pressure were

considered for the operating gas (He:CO 2 = 96:4): 0.3 bar 488

and 0.9 bar. This combined configuration reduces the “dead region” between the TPC and silicon detectors, thereby en- hancing the kinematic acceptance for recoil particles.

Accurate determination of particle energies is crucial for subsequent analysis. Therefore, we calculated the total en- ergy of recoil particles ( ) using the following expression:

E α = E Si + E gas = E Si + $\int$ r ′

dx | E = E (r) dr, (2) 495

where is the energy loss in the silicon detector array, is derived from the reconstructed trajectory length in the gas ( ) using the energy-range relationship calcu- lated with the ATIMA 1.4 program [ ]. For particles that stop within the TPC, corresponds directly to the recon- structed range. For particles that reach the silicon array, is defined as the distance from the reaction vertex to the hit position on the silicon detectors.

Reconstructed kinematics of recoil particles. Red and blue dots correspond to events that stop within the TPC at gas pres- sures of 0.3 bar and 0.9 bar, respectively. Green dots represent events detected by the silicon array. The black curves show the kinematics elastic scattering calculated using LISE++. particles. The reconstructed events (colored points) are in ex- cellent agreement with the expected kinematics calculated us- ing the LISE++ program. Reaction events were recorded by the TPC at 0.3 bar (red) and 0.9 bar (blue) for low-energy recoils, while higher-energy particles were detected by the silicon array at 0.3 bar (green).

Using the reconstructed kinematic information, the excita- tion energy spectrum was calculated for the full angular cov- erage, as shown in Fig. . The excitation energy for the elas- tic channel is well centered at 0 MeV, and follows a Gaussian distribution. Contributions from different detection settings are shown separately, along with the combined spectrum. The reconstructed peak width reflects the combined effects of the detector resolution, including range resolution, angular reso- lution, and the energy resolution of the silicon array, which may be considered as sources of systematic uncertainty.

Subsequently, the differential yield was ex- tracted by integrating the counts of the reconstructed excita- tion energy peak at different scattering angles. However, prior to calculating the differential cross-section, an evaluation of the total efficiency is required. This efficiency is pri-

marily governed by track recognition, geometric acceptance 526

Total Counts / 0.2 MeV Excitation energy (MeV) Excitation energy spectra of C reconstructed from the kinematic data shown in Fig. , integrated over the full detected angular coverage. The black line shows the combined spectrum from all detection settings, centered at 0 MeV for the elastic channel. and the excitation-energy reconstruction analysis. Therefore, values were determined by evaluating the ratio of reconstructed yield to the number of generated events within the same excitation-energy gate, with the results presented in used for the total efficiency evaluation were generated under identical experimental conditions, assuming an isotropic an- gular distribution.

TPC (0.9 bar) (0.3 bar) Total efficiency for the elastic scattering as a function of the center-of-mass angle. The colored markers correspond to the same detection settings defined in Fig.

Finally, the differential cross-section for elastic scattering was derived according to where represents the total number of simulated events, denotes the area density of target nuclei, and (mb/sr) Differential cross-section of the elastic scattering at 32.5 MeV/u. The red points show the simulated results, while the black circles denote the experimental data from Ref. [the solid angle coverage. Since the simulated generation was only following the relative experimental angular distribution, a normalization factor ( ) was introduced to scale the simu-

lated results. The value of L was determined by minimizing 543

the chi-square. The resulting differential cross-section is presented in perimental data. The simulation successfully reproduces the characteristic oscillations of elastic scattering, includ- ing the distinct peaks and valleys. This consistency demon- strates that the data recorded by both the TPC and the sili- con array were correctly integrated and processed within the ATEROOT framework. Both statistical and systematic un- certainties were taken into account in the present analysis.

Despite the high statistics of the simulation, statistical er- rors remain visible, particularly at large center-of-mass an- gles where the cross-section is low. Systematic uncertainties were estimated by varying the integration window used for yield extraction (from around the peak center), and were found to dominate at small center-of-mass angles.

SUMMARY

We have developed M ATEROOT , a comprehensive soft- ware framework for the MATE detector.

Built on R 4, and F AIRROOT , it features a modular architecture comprising M im for flexible Monte Carlo simulations, and M ib for efficient data analysis, offering scala- bility for high-granularity TPC experiments. The track recog-

nition performance was systematically evaluated using simu- 567

lated particles. By optimizing the RANSAC algorithm pa- rameters within the MATE geometric constraints, the tracking efficiency and reconstruction quality were assessed for vary- ing particle ranges and track multiplicities. The results show

that reliable track recognition can be achieved for long-range 572

tracks, while reconstruction quality degrades for short tracks and high multiplicities. The functionality of M ATEROOT was demonstrated through simulations evaluating key detec- tor performance metrics, including range resolution, angular resolution, and particle-identification capability. The frame- work was validated using the elastic scattering at 32.5 MeV/u as a benchmark, where simulations reproduced exper- S. Beceiro-Novo, T. Ahn, D. Bazin, et al., Active targets for the study of nuclei far from stability, Prog. Part. Nucl.

Phys. 84 (2015) 124–165, Y. Ayyad, D. Bazin, S. Beceiro-Novo, et al., Physics and technology of time projection chambers as active targets, Eur.

Phys. J. A 54 (2018) 181, epja/i2018-12557-7 D. Bazin, T. Ahn, Y. Ayyad, et al., Low energy nuclear physics with active targets and time projection chambers, Prog. Part.

Nucl. Phys. 114 (2020) 103790,

[4] J. Bradt, D. Bazin, F. Abu-Nimeh, et al., Commissioning of the 598

active-target time projection chamber, Nucl. Instrum. Methods Phys. Res. A 875 (2017) 65–79, B. Mauss, P. Morfouace, T. Roger, et al., Commis-

sioning of the active target and time projection cham- 603

ber (ACTAR TPC), Nucl. Instrum. Methods Phys. Res. A 940 (2019) 498–504,

nima.2019.06.067 . 606

S. Ota, H. Tokieda, C. S. Lee, et al., CNS active target (CAT) for missing mass spectroscopy with intense beams, J. Ra- dioanal. Nucl. Chem. 305 (3) (2015) 907–911, T. Furuno, T. Kawabata, H. Ong, et al., Performance test of the MAIKo active target, Nucl. Instrum. Methods Phys. Res.

A 908 (2018) 215–224,

nima.2018.08.042 . 614

L.-S. Yang, J.-Y. Xu, Q.-T. Li, et al., Performance of the CAT-TPC based on two-dimensional readout strips, Nucl. Sci.

Tech. 32 (8) (2021) 85, s41365-021-00919-6 H.-K. X.-Y.

Wang, Y.-M. Wang, Fudan multi-purpose active target time projection chamber (fMeta- TPC) for photonuclear reaction experiments, Nucl. Sci.

Tech. 35 (11) (2024) 200, s41365-024-01576-1

[10] W. Jia, Y. Lv, Z. Zhang, et al., Gap uniformity study of a 624

resistive Micromegas for the Multi-purpose Time Projection Chamber (MTPC) at Back-n white neutron source, Nucl. In- strum. Methods Phys. Res. A 1039 (2022) 167157, https:

Z. C. Zhang, X. Y. Wang, T. L. Pu, et al., Studying the heavy-ion fusion reactions at stellar energies using time pro- jection chamber, Nucl. Instrum.

Methods Phys. Res. A 1016 (2021) 165740, X.-B. Li, L.-H. Ru, Z.-C. Zhang, et al., Construction and per- formance test of charged particle detector array for MATE, Nucl. Sci. Tech. 35 (8) (2024) 131, 10.1007/s41365-024-01500-7 imental differential cross-sections, kinematic loci, and stop- ping powers with excellent agreement. M ATEROOT thus of- fers a versatile and operational tool for nuclear physics exper- iments with MATE. The platform will be continuously devel- oped to support further MATE upgrades, such as MicroMegas TPC and cylindrical TPC in a solenoid.

A. Anthony, Y. Ayyad, A. Ceulemans, et al., ATTPCROOT, (2023).

G. W. McCann, N. Turi, D. Bazin, et al., Spyral: scalable analysis framework for active-target time projection chamber data, Nucl. Instrum. Methods Phys. Res. A 1081 (2026) 170872, P. Konczykowski, B. Fernández-Dominguez, H. Alvarez-Pol, et al., Validation of the energy-loss response of particles in with ACTARSim, Nucl. Instrum. Methods Phys. Res.

A 927 (2019) 125–132,

nima.2019.02.013 .

CSNS Back-n MTPC, BLUET-v5, (2024). N.T. Zhang, Z.C. Zhang, MATEROOT repository, (2026).

S. Agostinelli, J. Allison, K. Amako, et al., Geant4—a simulation toolkit, Nucl. Instrum. Methods Phys. Res. A 506 (3) (2003) 250–303, S0168-9002(03)01368-8 S. Wang, Y.-Z. Li, L.-H. Ru, et al., c fusion reac- tion at astrophysical energies using hopg target, Nucl. Sci.

Tech. 36 (8) (2025) 143, s41365-025-01714-3 X. Y. Wang, N. T. Zhang, Z. C. Zhang, et al., Studies of the channels of the c reaction in the range

of e cm = 8 . 9 mev to 21 mev using the active target time

projection chamber, Chin. Phys. C 46 (10) (2022) 104001, J.-L. Zhang, C.-G. Lu, Z.-C. Zhang, et al., Fusion reaction of c studied with an active-target time projection cham-

ber in the energy range 9.7 < e c.m. < 16.9 mev, Chin. Phys.

C 50 (4) (2026) 044005, 1674-1137/ae368b

[22] M.-H. Zhang, X.-B. Li, J. Chen, et al., Machine learning meth-

ods for event classification and vertex reconstruction of the c reaction with the mate-tpc, Nucl. Sci. Tech. (2026).

R. Brun, F. Rademakers, ROOT: An object oriented data analysis framework, Nucl. Instrum. Methods Phys. Res.

A 389 (1997) 81–86, S0168-9002(97)00048-X

[24] M. Al-Turany, D. Bertini, R. Karabowicz, et al., The Fair-

Root framework, in: J. Phys.: Conf. Ser., Vol. 396, 2012, p. 022001, 396/2/022001 A. Matta, P. Morfouace, N. De Séréville, et al., NPTool: a simulation and analysis framework for low-energy nu- clear physics experiments, J. Phys. G: Nucl. Part. Phys. 43 (4) (2016) 045113, 0954-3899/43/4/045113 YAML Development Team, YAML Ain' t Markup Language (YAML™) Version 1.2, available at

spec/1.2/ (2009). Jojosito, T. Schlüter, M. Prim, et al., Genfit/genfit: release-02-00-05, (Dec. 2023).

B. Bellenot, S. Linev, Javascript root, Journal of Physics: Con- ference Series 664 (6) (2015) 062033, 10.1088/1742-6596/664/6/062033 J. Giovinazzo, T. Goigoux, S. Anvar, et al., Get electron- ics samples data analysis, Nucl. Instrum. Methods Phys. Res.

A 840 (2016) 15–27,

nima.2016.09.018 . 701

P. V. C. Hough, Machine analysis of bubble chamber pictures, in: Proceedings of the International Conference on High En- ergy Accelerators and Instrumentation, CERN, 1959, pp. 554–M. A. Fischler, R. C. Bolles, Random sample consen- sus: a paradigm for model fitting with applications to im- age analysis and automated cartography, Commun. ACM 24 (6) (1981) 381–395, Y. Ayyad, W. Mittig, D. Bazin, et al., Novel particle tracking algorithm based on the random sample consensus model for the active target time projection chamber (AT-TPC), Nucl. Instrum.

Methods Phys. Res. A 880 (2018) 166–173, C. Dalitz, Y. Ayyad, J. Wilberg, L. Aymans, D. Bazin, W. Mit-

tig, Automatic trajectory recognition in active target time pro- 717

jection chambers data by means of hierarchical clustering, Comput. Phys. Commun. 235 (2019) 159–168, F. Battisti, M. Ivanov, X. Lu, A kalman filter for track re- construction in very large time projection chambers, Com-

puter Physics Communications 308 (2025) 109443, https: 723

J. Taylor, M. Papenbrock, T. Stockmanns, R. Kliemt, T. Jo-

hansson, A. Akram, K. Schönning, P. Collaboration, 4d track 726

reconstruction on free-streaming data with panda at fair, Com- puting and Software for Big Science 8 (1) (2024) 18, https:

R. B. Rusu, S. Cousins, 3D is here: Point cloud library (PCL), in: Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), IEEE, 2011, pp. 1–4, O. B. Tarasov, D. Bazin, LISE++: Radioactive beam produc- tion with in-flight separators, Nucl. Instrum. Methods Phys.

Res. B 266 (2008) 4657–4664, J. F. Ziegler, M. D. Ziegler, J. P. Biersack, SRIM –the stopping and range of ions in matter (2010), Nucl. Instrum. Methods Phys.

Res. B 268 (2010) 1818–1823, S. Ishikawa, H. Geissel, S. Purushothaman, H. Weick, E. Haet- tner, N. Iwasa, C. Scheidenberger, A. Sørensen, Y. Tanaka, T. Abel, et al., Accurate simultaneous lead stopping power and charge-state measurements in gases and solids: Bench- mark data for basic atomic theory and nuclear applications, Physics Letters B 846 (2023) 138220, S. Adachi, et al., Systematic analysis of inelastic scat-

tering off self-conjugate a = 4 n nuclei, Phys. Rev. 750

C 97 (2018) 014601, PhysRevC.97.014601 H. Weick, ATIMA: Atomic stopping powers and range distributions calculator, ~weick/atima (2024).

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

Source: ChinaXiv —Machine translation. Verify with original.