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Next-generation experiments with the Active Target Time Projection Chamber (AT-TPC)

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ABSTRACT

The Active Target Time Projection Chamber (AT-TPC) project at the National Superconducting Cyclotron Laboratory (NSCL) is a novel Active Target designed to study nuclear reactions induced by low-intensity exotic beams. The AT-TPC acts as a tracking medium and target at the same time, providing excellent angular (1°) and energy resolution (3% FWHM) and high luminosity. The AT-TPC offers a broad range of applications within the low-energy nuclear physics domain. Resonant scattering and transfer reactions are typically performed with Active Targets using beams with energies spanning from 1 to 10A MeV and with intensities as low as 100 pps. The AT-TPC is also a promising tool for experiments where the observables of interest require higher beam energies (above 100A MeV). In particular, inelastic scattering reactions on light targets, where the recoil particle has a very low kinetic energy (less than 1 MeV), can be performed with such a device. In this work, we discuss aspects of the AT-TPC experimental program, focusing on experiments that leverage the outstanding capabilities this detector offers. In addition, we introduce a conceptual design for a new Time Projection Chamber detector for specific measurements of reactions using special gases as targets.

Contents

1. The Active Target Time Projection Chamber and its experimental program

Time Projection Chambers (TPC) operated in Active Target mode (AT) have introduced a new detection concept in the low-energy nuclear physics domain. AT's consist of a field cage that encloses a gaseous volume in which a strong electric field (around 100 V/cm) is applied along one of the directions (usually the beam axis z). The gas medium must contain the target of interest (proton, deuterium, ^{4}He...) and provide good gain and drift velocity. The beam is injected into the AT and ionizes the gas as it is slowed down. Ionization electrons drift to the field cage anode where they are detected by a highly segmented pad plane. The pad plane generates a three-dimensional image of the beam track by measuring the drift time of each electron (z coordinate) that arrives to a pad, providing the x and y coordinates. The products

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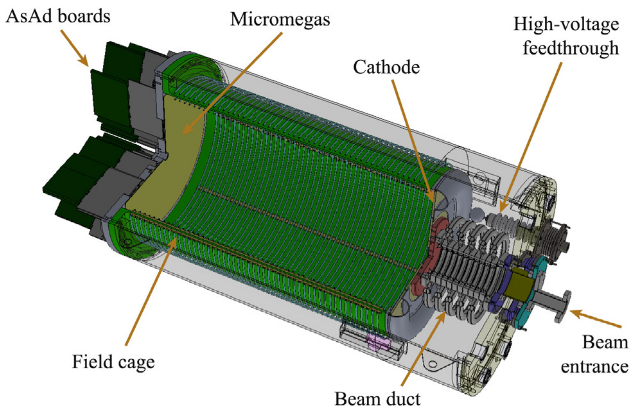

Fig. 1. Sketch of the AT-TPC showing the different parts of the detector.
Source: Figure from Ref. [8].

of the reaction of the beam with a target nucleus are also tracked, including those that are emitted with a very low kinetic energy. This is one of the most interesting features of AT's, since it allows for the performance reactions that would require an extremely challenging setup using conventional solid targets. At the same time, AT's provide almost full 4π efficiency for those particles that are fully stopped in the gas medium with angular and energy resolutions of the order of 1° and 3% (FWHM), respectively [1]. Depending on the geometry and the purpose of the detector, auxiliary detectors, such as silicon or inorganic scintillators can be installed surrounding the field cage, enabling the detection of those particles that punch through the active volume. A comprehensive list of existing (and future) AT detectors, including their characteristics and scientific highlights, can be found in Refs. [2,3].

The AT-TPC of the NSCL (Fig. 1) features a cylindrical geometry (100 cm height and 50 cm diameter) in which the beam is injected from the cathode end-cap along the height z axis. This geometry offers two advantages: Since every reaction partner is detected inside the detector, the thickness of the gas target can be increased (up to two orders of magnitude larger than solid targets) without increasing the number of electronic channels of the pad plane. In addition, the detector can be placed inside a solenoid magnet, enabling the measurement of the rigidity of the particles, allowing for increased precision in the determination of the kinematics and for the identification of those particles that punch through the detector. The AT-TPC is currently installed inside a large-bore solenoid magnet that provides up to 2 T of magnetic field. Currently, this setup is available for experiments at the ReA3 re-accelerator of the NSCL [4]. Ionization electrons are amplified upon reaching the pad plane by a hybrid micro pattern gas detector (MPGD) system comprised of a Micromegas device [5] coupled to a multi-layer Thick Gas Electron Multiplier (MTHGEM) [6], capable of providing gains up to 10^6 for pure elemental gases. The pad plane is segmented into triangular pads of 0.5 and 1.0 cm of size, arranged in an inner and outer region, respectively. The pulses generated by the charge collected in each pad are digitized by a dedicated data acquisition system (General Electronics for TPCs [7]) featuring 256 12-bit ADC per channel/pad. Further information about the details and performances of the detector can be found in Ref [8]. In order to push the limits of the technology and address the most common problems encountered when operating AT's, the AT-TPC collaboration is leading the development of novel MPGD's by studying the effect of different substrates in the long-term gain stability of the detector [9] and by designing hybrid configurations with the aim of greatly reducing ion backflow that may affect the performance of the detector [10]. In addition, studies about proper gas mixtures and about aging of the detector are also conducted.

The AT-TPC was commissioned with a ^{4}He stable beam (2014) [1] and a ^{46}Ar radioactive beam (2015) [11], both at low-energy (below 5A MeV) and using ^{4}He and proton (isobutane) targets, respectively. While the former provided high-quality data to benchmark the performance of the detector, the latter was the first experiment to utilize resonant elastic proton scattering in that mass region. The ^{46}Ar + p reaction populates the isobaric analogue states (IAS) of the ^{47}K–^{47}Ar system. The experiment allowed us to infer the spectroscopic factors from excited states and provided a complementary approach to study single-particle states that are normally investigated using (d,p) transfer reactions [12], while affording the advantage of having a much thicker target. In fact, resonant scattering is one of the reactions where AT outperforms conventional setups. Since the beam stops inside the target, only a unique beam energy (or setting) is needed to continuously measure the excitation function. The vertex of the reaction, and thus the energy of the resonance, can be reconstructed with a precision of the order of mm and few hundred keV, respectively. The elastic channel of the reaction can be unambiguously determined by measuring the angular correlation between both reaction partners. This technique was employed to find evidence of the linear-chain cluster structure of ^{14}C by means of the ^{10}Be +^{4}He reaction [13] and to study the α cluster structure of ^{10}Be through ^{6}He resonant scattering on ^{4}He [14]. The experiments were performed at the TwinSol facility of the University of Notre Dame using the prototype AT-TPC [15]. Several follow-up experiments were proposed to investigate the cluster phenomena along the carbon isotopic chain, with particular attention to ^{16}C.

AT's are also exceptional detectors when applied to reactions of astrophysical interest due to the possibility of extracting the relevant observables within the effective energy windows [16]. Usually, such challenging reactions require the use of a mass spectrometer such as DRAGON (TRIUMF) [17] or the future SECAR (FRIB) [18] to identify the very low-energy heavy recoil particle emitted in reactions in inverse kinematics such as (p,γ), (α,p) or (α,γ). AT's offer an alternative approach: The beam of interest is gradually stopped inside the detector until the energy of interest is reached. Depending on the reaction, the heavy recoil can be detected in coincidence with other reaction products (charged particles). Recently, an experiment to investigate the role of ^{22}Mg in the αp-process was conducted at the ReA3 accelerator using the AT-TPC. ^{22}Mg is considered to be a waiting point in the ^{21}Na(p,γ) ^{22}Mg(α,p) ^{25}Al(p,γ) ^{26}Si reaction chain that allows the process to escape from the CNO cycle and synthesize neutron-deficient isotopes up to the Ca/Ti region [19]. The experiment was conducted by injecting a ^{22}Mg beam at 5A MeV into the AT-TPC filled with He + CO_2 at 600 torr to directly measure the ^{22}Mg(α,p) ^{25}Al reaction. The dominant reaction channels at that energy, namely (α,p), (α,α) and $(\alpha,2p)$, were clearly identified, highlighting the large dynamic range and efficiency that the AT-TPC provides. An example of ^{22}Mg(α,α) and ^{22}Mg$(\alpha,2p)$ events are shown in the upper and lower panel of Fig. 2, respectively. In the pad plane projection (right panels), the beam spot and both proton and alpha tracks are clearly distinguishable. The data of this experiment is currently under analysis. A similar experiment, but measuring the heavy recoil instead, will be performed at the NSCL to elucidate the Asymptotic Normalization Coefficient (ANC) and the spectroscopic factor of the ground state of ^{13}O, relevant for the rap process[1] [20], through the ^{12}N(d,p) ^{13}O reaction [21]. In this experiment, the aim is to measure the ^{13}O angle and range in the AT-TPC, and to extract the differential cross sections, allowing for the inference of the spectroscopic factors. In this case, the beam will be provided by the A1900 fragment separator [22] and will be stopped inside the AT-TPC filled with deuterated methane (CD_4) at 1 bar.

[1] The rap process refers to alternative ways to bypass the triple alpha process and produce CNO material via ^{7}Be(p,γ) ^{8}B(p,γ) ^{9}C(α,γ) ^{12}N(p,γ) ^{13}O(β^+,ν) ^{13}N(p,γ) ^{14}O, ^{7}Be(α,γ) ^{11}C(p,γ) ^{12}N(p,γ) ^{13}O(β^+,ν) ^{13}N(p,γ) ^{14}O, ^{7}Be(α,γ) ^{11}C(p,γ) ^{12}N(β^+,ν) ^{12}C(p,γ) ^{13}N(p,γ) ^{14}O and ^{7}Be(α,γ) ^{11}C(α,p) ^{14}N(p,γ) ^{15}O.

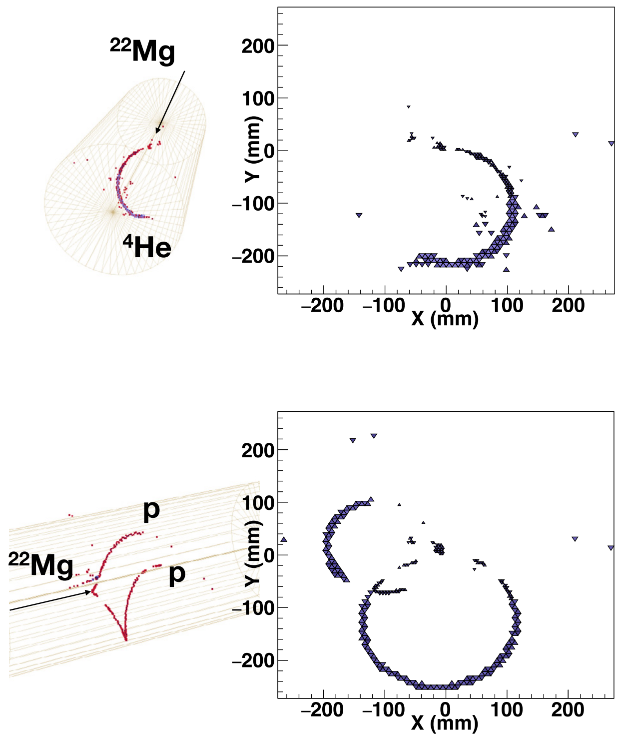

Fig. 2. Upper panels: 3 dimensional hit pattern and projection into the pad plane of an ^{22}Mg(α,α) event. Lower panels: Same as the upper panels but for the ^{22}Mg(α,2p) channels. The particles can be easily distinguished because of the energy loss density along the trajectory.

2. Next-generation experiments with the AT-TPC

AT's provide a potential solution to one of the long-standing technical questions in low-energy nuclear physics: how to perform inelastic scattering reactions in inverse kinematics. The studies of collective nuclear motion [23,24], nucleon–nucleon correlations [25] or exotic clustering modes [26] are usually performed on stable nuclei using proton, deuteron and ^{4}He beams, at energies ranging from 100A to 400A MeV, which are momentum analyzed in magnetic spectrometers capable of providing an outstanding excitation energy resolution [27]. The study of such phenomenon on exotic nuclei requires the use of the inverse kinematics technique. When attempting this type of measurement in inverse kinematics, Coulomb excitation and break-up on high-Z targets is the reaction of choice [28,29]. A promising alternative is proton inelastic scattering at very forward Center-of-Mass (CMS) angles, which allows the extraction of the full dipole strength, taking into account that the nuclear excitation is small and the cross section is dominated by $E1$ transitions. This was demonstrated by in direct kinematics using a proton beam impinging on a ^{208}Pb target [23]. However, attempting this type of measurement in inverse kinematics is extremely challenging due to the very low energy recoil particle. AT's stand as a promising tool to perform such experiments: they provide high luminosity to compensate for the low exotic beam intensity and facilitate the capability of detecting low-energy particles with the required resolution. Several pioneering inelastic scattering experiments were conducted with the MAYA active target [30,31] to extract the isoscalar monopole response on Ni isotopes. The AT-TPC collaboration proposed a campaign of experiments at the NSCL with fast-beams (few hundred A MeV) to measure the isoscalar giant monopole resonance excitation in ^{70}Ni using α scattering, to extract the full electric dipole response of the proton-rich nuclei ^{32}Ar and to establish the (d, ^{2}He) charge-exchange reaction as a surrogate for the (n,p) reaction to extract Gamow–Teller strengths from unstable nucleus [32]. Fig. 8 shows

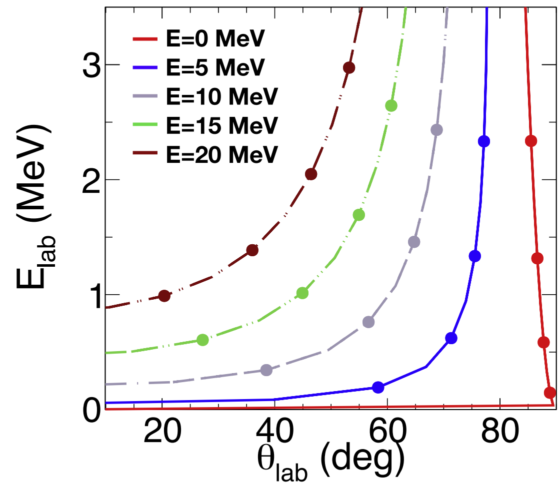

Fig. 3. Kinematics curves for the ^{32}Ar(p,p) reaction at 120A MeV for different excitation energies. Dots refers to CMS angles in steps of 2°. The present experiment aims at measuring below 4° CMS (below 1 MeV of proton kinetic energy).

the kinematics for the ^{32}Ar(p,p') reaction at 120A MeV for different excitation energies relevant for this measurement. As demonstrated, the energy of the proton at very forward CMS angles is around 250 keV for an excitation energy of 10 MeV (see Fig. 3). In order to measure such low-energy particles, the AT-TPC will be filled with pure H_2 at 250 Torr. With this combination of pressure and kinetic energy, proton tracks will have a length of around 7.5 cm, which corresponds to an angular and energy resolution of 1° and 130 keV, respectively [1].

One of the novelties of this experimental campaign will be the use of the S800 spectrograph [33], together with the AT-TPC (see upper panel of Fig. 4), to detect and analyze the heavy recoil particle and provide the identification of the reaction channel. To allow the heavy recoil to reach the focal plane of the S800, a new pad plane featuring a 4 cm diameter hole will be constructed and deployed in the AT-TPC. With a two proton separation energy of S_{2p} = 2.7 MeV, the ^{32}Ar will decay mainly by 2 proton emission to ^{30}S. With an acceptance of ±2.5%, one magnetic rigidity setting of around 3 Tm (see lower Fig. 4) will allow for the analysis of not only the ^{30}S + 2p channel, but also the ^{31}Cl + p channel (direct decays to the ground state). The evaporation protons will be boosted forward and will punch through the detector, making misidentification of the recoil proton unlikely. These experiments leverage the outstanding capabilities of AT's: the low cross section of the reaction channels of interest and the beam intensities are compensated for a very thick pure H_2 target that enables the measurement of very low energy particles. The capabilities of this detection setup will be greatly enhanced with the advent of the SOLARIS project [34] that will allow fast-beam experiments to be performed using a 4 T solenoid magnet.

Other types of experiments that take advantage of the AT's technology are those that involve the decay of charge particles from an unstable nuclei. Implantation-decay experiments using a ^{6}He radioactive beam were successfully performed with an Optical TPC [35], where the β-decay channel into the α + d continuum was measured down to a deuteron energy of 100 keV. One of the main limitations of the method is the mandatory use of a scintillating gas that limits the optimization of the detector. The AT-TPC offers the possibility of using light gases (such as pure H_2) due to the capabilities of the MTHGEM, that would dramatically decrease the straggling suffered by low-energy particles. This possibility allows the AT-TPC to study very exotic decay modes. As an example of such measurement, the AT-TPC collaboration will perform an experiment at ISAC-TRIUMF in which the β^{-}-delayed proton (βp) emission decay will be directly observed for the first time. A high-purity low-energy ^{11}Be beam will be implanted in a low-pressure pure

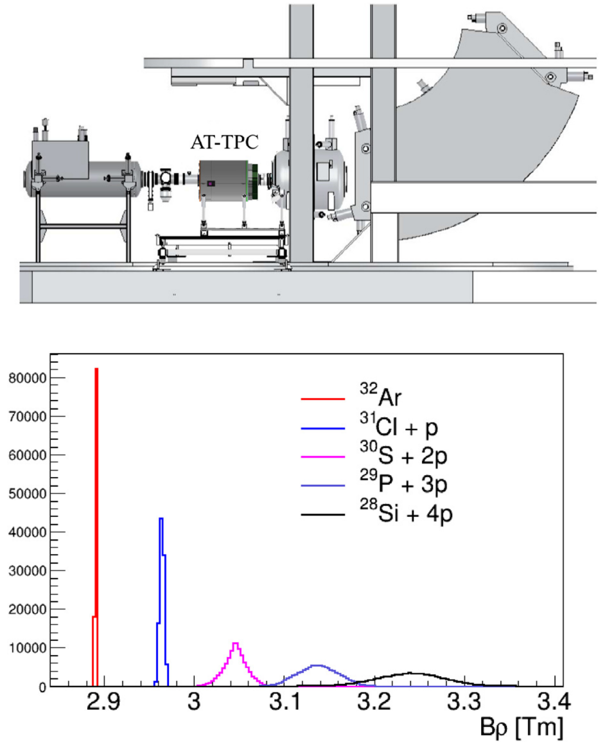

Fig. 4. Upper panel: Illustration of the AT-TPC placed in front of the S800. Right panel: Magnetic rigidities of beam-like particles produced in the decay of excited states in ^{32}Ar.

H_2 gas at the center of the AT-TPC. The high-energy β particles will not be stopped and will only deposit a negligible amount of energy on the thin medium, while the low-energy and much heavier α and p^+ decaying particles will be completely stopped, depositing a characteristic energy pattern. This will allow for a precise measurement of the branching ratio of the βp decay and the continuous spectrum of the proton energy. These values will yield the B(GT) for this decay branch, which is the most direct measurement of how independent the halo neutron is from the core in ^{11}Be [36]. If sufficient precision is obtained, this experiment will also shed light on the hypothesized dark decay of neutrons and thus help clarify the so-called "neutron lifetime anomaly" [37,38].

3. Conceptual design of a TPC with a gas cell

While having a unique tracking medium that acts both as target and detector offers compelling advantages when compared to conventional setups for the majority of applications, there are a few specific scenarios in which decoupling the target from the tracking medium is desirable. This is the case when working with rare and expensive gases or those that may pose a hazard. Our collaboration is designing a detector concept consisting of an isolated cell into which the target gas would be injected, and then deployed into a TPC tracking medium. Under the proper safety conditions, such a design will open exciting opportunities for nuclear structure studies: reactions on a tritium target. The synergistic combination of the most exotic beams provided by the new Facility for Rare Isotope Beams (FRIB) coupled to a thick target to perform two-neutron stripping reactions will allow us to push the limits of the nuclear landscape even further.

Clearly, (t,p) reactions in inverse kinematics stand out as the best tool to study pairing correlations that play a crucial role in determining the properties and structure of atomic nuclei. The evolution of these correlations in exotic nuclei is a subject which has received much attention in recent years, as new accelerator facilities provide unique radioactive beams for study. Of particular interest is the role of neutron–neutron pairing in neutron-rich isotopes, where the effects of weak binding and continuum coupling are important. As an example, recent microscopic calculations based on Skyrme–Hartree–Fock mean field and continuum RPA [39] indicate that for the very neutron-rich Sn ($A >$ 140), a large increase of the pairing gap is expected, which translates to an enhancement of the pair transfer strength. Two-neutron transfer reactions are also of capital importance to investigate shape coexistence near the island of inversions where the balance between single-particle energies, pairing, and quadrupole correlations lead to the development of $2p-2h$ intruder states that compete with spherical $0p-0h$ states [40]. The N=20 centered on ^{32}Mg is a well known case, driven by excitations from the sd to fp shells. Two-neutron transfer reactions are therefore one of the best probes to populate such $2p-2h$ states.

Disregarding required safety considerations for now, the detector concept will be based on the current AT-TPC with major modifications. The most important part is that a self-contained and sealed cell, deployed along the beam axis that would contain the $^3H_2$ gas target. For example, a cell of 5 cm radius and 30 cm length will contain 161 mg of $^3H_2$ at 5 torr of pressure. This amounts to 1.55 Ci of pure tritium providing 10^{19} atoms/cm^2. Although a thorough design of the cell is mandatory to ensure the proper safety conditions, this amount of tritium is relatively small compared to other existing tritium targets such as the Jefferson Lab target that contains 1 kCi of tritium at 10 atm of pressure [41], or the one developed for inclusive electron scattering experiments at the MIT-Bates Linear Accelerator Center containing 1.15×10^5 Ci [42]. A suitable material for the cell would be silicon nitride which is used to construct thin entrance windows to gas ionization detectors [43]. Ideally, the differential pressure between the cell and the tracking volume should be zero in order to minimize the thickness of the cell and avoid structural problems like deformation and bending. Moreover, one has to take into account that the electric field applied in the tracking medium must remain homogeneous along the beam direction after the cell is installed (this could be achieved by using a chain of resistors). The vessel where the TPC and the cell will be installed must be a completely sealed design (except for the beam entrance window) to ensure compliance with the safety regulations. Finally, the cell must couple to a pad plane with a hole in the middle as explained in Section 2, although this is an optional feature. A sketch of a preliminary design is shown in Fig. 5. Like the AT-TPC, this detector will operate inside a magnetic field that will enable the measurement of the magnetic rigidity of the protons and will assist in confining the electrons emitted in the tritium decay (5.7 keV average energy and end-point of around 18.6 keV). One of the greatest assets of using a pure $^3H_2$ target compared to the ones where the tritium is implanted in a titanium foil [40], is the possibility of increasing the beam energy to achieve proper momentum matching (depending on the Q-value) without opening undesired reaction channels on contaminant nuclei. This also increases the energy of the final reaction products, making the identification of the particles and their kinematic observables more straightforward while increasing the acceptance of the detector.

A comprehensive simulation using the ATTPCROOT analysis framework [44] was conducted to evaluate the acceptance of the detector and the expected resolution. The current AT-TPC design, including a cell of 5 μm thickness with 5 torr of tritium gas, was used as detector to simulate the ^{30}Mg(t,p) ^{32}Mg reaction at 5A MeV populating the ^{32}Mg ground state [40]. The magnetic field was set to 2 T. The tracking medium consists of 40 torr of isobutane, although these are not realistic conditions since the differential pressure is relatively large for the cell thickness. The minimum proton energy for this reaction is 2.38 MeV at forward angles (180° in the Laboratory system) and increases rapidly to a maximum of around 31 MeV. The energy loss of a 2.8 MeV proton in the cell wall is around 80 keV.

The simulation uses the Geant4 [45] engine via the Virtual Monte Carlo (VMC) package [46] that allows for a flexible configuration of the simulation parameters without changing the code. The energy loss provided by the simulation output is converted into pulses by simulating the detector behavior: The energy loss in the gas is converted into

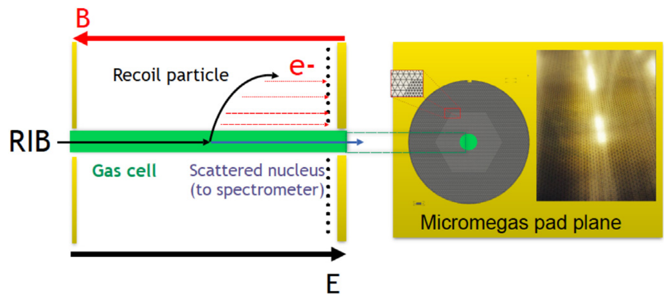

Fig. 5. Conceptual sketch of the TPC with a gas cell. A radioactive beam (RIB) is injected into the gas cell contained within the detector. Recoil particles will be tracked in the outer volume. The detector will operate inside a magnetic field of around 2 T. A Micromegas device with a hole in the middle will be mounted on the anode end of the detector as sensor plane. The concept is adapted from the AT-TPC.

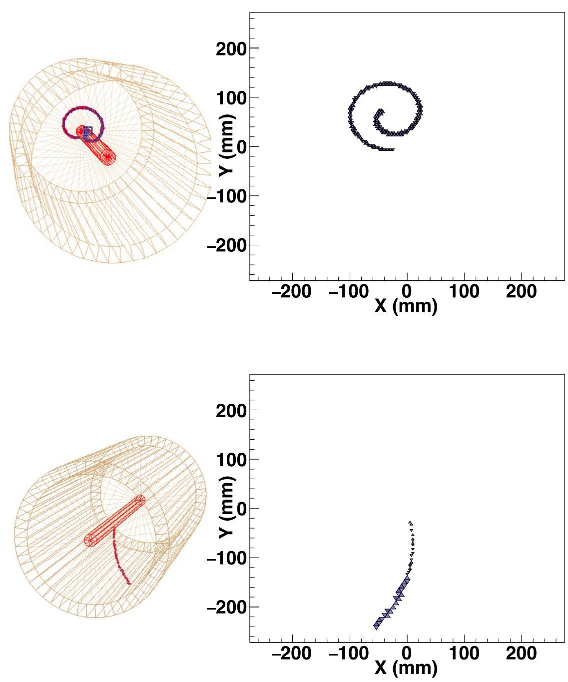

Fig. 6. 3-dimensional hit pattern representation (left panels) and projection into the pad plane (right panels) of two ^{30}Mg(t,p) ^{32}Mg events.

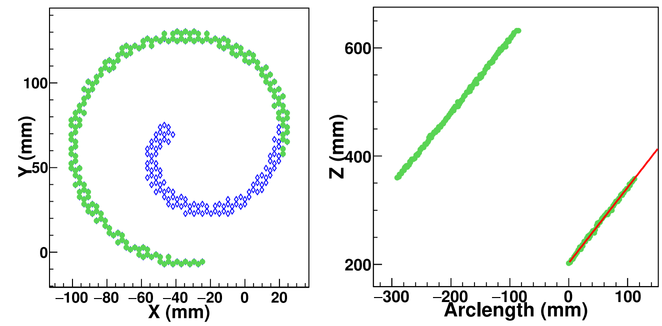

Fig. 7. Left panel: Simulated proton track projected into the TPC pad plane. Open blue diamonds and solid green dots refer to the full hit pattern and the part of the hit pattern used to calculate the radius of curvature, respectively. Right panel: Arc length of each hit pattern point as a function of the z coordinate. The red line is the least-squares fit performed to extract the scattering angle from the slope.

electrons that are drifted to the pad plane. Pulses are generated taking into account the response function of the pad and the electronics [47]. The data is then transformed into a three dimensional hit pattern that represents the position of each simulated interaction point convoluted with the size of the pads and the sampling rate of the electronics. Two simulated ^{30}Mg(t,p) ^{32}Mg events are shown in Fig. 6 where the proton tracks are clearly visible while the ionization electrons released by the beam are fully contained in the cell. The simulated tracks can be analyzed in the same fashion as the experimental data which is injected into a series of pipelined tasks that identify and analyze each track. The first step of the analysis involves the extraction of features from the hit pattern to infer the initial track parameters used in a Monte Carlo fitting that provides better resolution [8]. The ATTPCROOT framework features several pattern recognition algorithms that can be used depending on the topology of the tracks. For this simple study we have used the circle Hough transform [48] combined with the RANdom SAmple Consensus (RANSAC) [49]. The Hough transform allows for the extraction features that are described by a given parameterization (circle in this case) from a collection of points. This method is used to extract the center and the radius of curvature of each track, as well as the angle with respect to the beam direction (scattering angle) and the initial point of the track (more details about the method can be found in Ref. [50]). However, depending on the energy of the proton, the radius of curvature might change dramatically as the proton is traversing the TPC volume, which is particularly critical for protons of low energy as illustrated in the left panel of Fig. 7. In order to determine with better precision the angle and the radius of curvature, we apply the RANSAC algorithm to the first fraction of points of the hit pattern filtered by the Hough transform. RANSAC estimates a mathematical model (circle) from a collection of points. This allows for a better determination of the radius of curvature since the very first part of the spiral can be approximated to a circle (see left panel of Fig. 7).

Once the radius of curvature is determined, the scattering angle can be inferred by parameterizing the position along the z axis as a function of the arc length as shown in the right panel of Fig. 7. From the radius of curvature and the scattering angle, one infers the energy of the proton, considering that the magnetic field is parallel to the beam direction. For example, the track shown in Fig. 7 corresponds to a proton of 3.27 MeV and 137.11° of energy and angle, respectively, that was reconstructed with an energy of 2.99 MeV and angle of 136.47°. In fact, the angular resolution provided by the method is around 0.45° (standard deviation) which greatly constrains the parameter space of the Monte Carlo fit. On the other hand, the energy resolution that this method provides is around 2.5 MeV (standard deviation). The kinematics plot for the ^{30}Mg(t,p) ^{32}Mg reaction populating the ground state and reconstructed using the initial parameters estimated with the Hough transform and RANSAC is shown in Fig. 8. As illustrated, the agreement with the calculation is excellent even taking into account that the proton losses energy on the cell wall. The resolution of this method worsens as the energy increase mainly due to the lower ionization of the proton tracks (i.e. less number of points in the hit pattern). It is also worth mentioning that the angular coverage is limited by the radius of the cell (2.5 cm). In addition, reactions occurring near the edges are more complicated to reconstruct. While this is not a negative result since the purpose of the method is to estimate the initial parameters of the fit, it is desirable to better constrain the energy space that the fit has to explore. The cause of this relatively large deviation is the rapid variation of the energy with the radius of curvature. For a magnetic field of 2 T, a deviation of 2 mm in the radius of curvature causes an energy spread of 100 keV. A more complete simulation is needed to understand if the limits of the resolution are imposed by the geometry of the detector (magnetic field, size of the pads...) or the tracking algorithm. Nonetheless, the Monte Carlo fit provides a resolution of the order of 36.0 keV and 0.316° for the energy and angle, respectively, for protons within the same energy range [8]. The fit makes use of the characteristic energy loss pattern of the particle in the gas to identify it and provides the kinematics with high resolution. It also allows for the reconstruction of the track from the vertex position by extrapolating it back to the beam position.

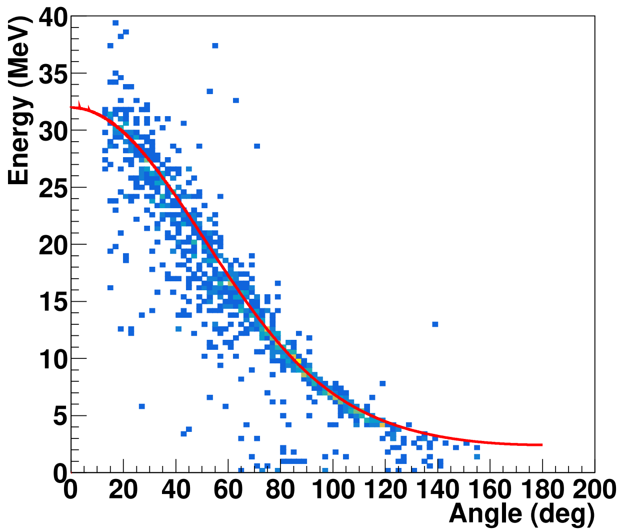

Fig. 8. Kinematics for the ^{30}Mg(t,p) ^{32}Mg reaction reconstructed from the radius of curvature and angle inferred from the Hough transform and RANSAC. The red solid line represents the calculation.

The large acceptance, dynamic range, luminosity and resolution that this type of device provides opens extremely compelling opportunities to conduct long-sought experiments with pure tritium targets and the most exotic radioactive beams that FRIB will deliver.

4. Conclusions

The AT-TPC is a versatile device that enables experiments with very low-intensity radioactive beams in the low-energy nuclear physics domain. In particular, the AT-TPC is one of the most promising options to perform experiments when the energy of the reaction products is very low, including very exotic decay experiments where the radioactive ion is implanted in the gas medium. Recently, the range of application of the AT-TPC was extended to experiments with fast-beams (100A MeV) that will feature an unprecedented experimental setup, eventually providing a full reconstruction of the reaction kinematics by measuring every reaction partner.

The conceptual design of a TPC with a decoupled gas cell that acts as target has been discussed. This design offers several advantages with respect to conventional AT's: pure rare and radioactive gases can be used as a thick target that provides high luminosity while minimizing the total volume and therefore the cost, space-charge effects caused by high beam intensities (one of the main drawbacks of AT's) are greatly diminished in this configuration, the tracking medium of the TPC can be optimized choosing the gases that perform better. We have demonstrated that this device is ideal to perform (t,p) reactions in inverse kinematics in remarkably clean and controlled conditions. In particular, the study of pairing correlations, identified as topic of major importance in the recent NSAC Long-Range Plan [51], will be greatly boosted using this device.

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