Research on techniques for measuring the beta-delayed α decay of ^{16}N based on a Time Projection Chamber detector

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Abstract

The precise measurement of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction cross section is crucial for understanding stellar evolution, and the study of ^{16}N beta-delayed α decay is an important means of constraining the $E1$ component of this reaction. Time Projection Chamber (TPC) detectors, with their three-dimensional track reconstruction capability and excellent background suppression, as well as their insensitivity to beta electrons, high solid angle coverage, and lack of dead layers, are ideal tools for measuring the ^{16}N beta-delayed α decay energy spectrum.

To evaluate the performance of the TPC detector in this measurement, this work utilized a 4000-channel MATE-TPC detector and a ^{148}Gd α source ($E_\alpha =$ 3.182 MeV) to conduct performance tests within a pressure range of 95-280 mbar (87.5% Ar + 12.5% CO_2 gas mixture). The reliability and resolution of extracting α particle energy through range were systematically studied and compared with Monte Carlo simulations.

Experimental results show that under the aforementioned pressures (where the α particle range is approximately 7-21 cm), the experimentally measured range lengths are in good agreement with the simulation results (deviation less than 1%). Meanwhile, the simulated range resolution is also close to the experimental measurements, with a maximum difference of about 10%, verifying the reliability of the simulation platform. Based on this, this work also used the aforementioned simulation platform to predict the ^{16}N beta-delayed α decay energy spectrum, providing an important reference for subsequent experimental measurements.

Full Text

Preamble

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The $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction is a critical nuclear process in stars, as its reaction rate directly determines the carbon-to-oxygen ratio produced during the stellar helium-burning phase. This ratio is of paramount importance for two primary reasons. First, it dictates the subsequent evolutionary pathways of massive stars following helium exhaustion, ultimately influencing the formation of black holes and their resulting mass distribution. Second, carbon and oxygen are the most abundant "metals" (defined in astronomy as all elements heavier than hydrogen and helium) in the majority of stars, including our Sun. Consequently, their absolute abundances and relative proportions significantly impact the formation and evolution of subsequent generations of stars.

Currently, stellar model calculations require the cross-section of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction to be known with high precision. However, contemporary experimental measurements have yet to achieve the necessary accuracy. Experimentally, measuring the cross-section of this reaction at the temperatures relevant to helium burning ($T \approx 0.2$ GK, corresponding to a Gamow peak energy of $E_0 \approx 300$ keV) is extremely difficult. At these energies, the reaction cross-section is approximately 10^{-17} barns, a level of sensitivity that remains beyond the reach of current experimental techniques. As a result, researchers must rely on cross-section data obtained at higher energies and extrapolate these values downward by several orders of magnitude. To effectively constrain this extrapolation and reduce associated uncertainties, specific strategies must be employed.

On one hand, it is essential to develop low-background experimental measurement techniques to push the lower limit of direct measurements as close as possible to the $E_0 = 300$ keV threshold. For instance, the Nuclear Astrophysics Platform (JUNA) at the China Jinping Underground Laboratory (CJPL) leverages its unique advantages of an ultra-low cosmic-ray background and high beam intensity. These capabilities allow researchers to surpass the cross-section measurement limits of existing surface-level experiments, making significant strides toward the critical astrophysical energy region near 300 keV.

On the other hand, indirect measurements serve as another vital tool for providing effective constraints on the aforementioned extrapolation process by measuring the properties of the excited states of the compound nucleus $^{16}\mathrm{O}$. In the astrophysical energy region, there are two primary components that contribute significantly to the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction: (1) contributions from the excited states located at···

9.585 MeV

) by direct capture and excitation

6.917 MeV

components. The contributions of these two components to the reaction cross-section in the $E_{cm} = 300$ keV energy region are roughly equivalent. Therefore, it is crucial to constrain both components of this reaction through indirect measurements.

The study of the beta-delayed α decay of the radionuclide ^{16}N ($T_{1/2} = 7.13$ s) is an important method for constraining the $E1$ component. However, because the branching ratio for the beta-delayed α decay of ^{16}N is only approximately 10^{-5}, the energy of the α particles must be measured against a massive background of beta electrons, posing a significant challenge for experimental measurement. Consequently, although multiple measurements have been conducted over the past few decades [**?**, **?**, **?**], discrepancies persist between different experimental results. For example, during the last century, Buchmann [**?**] and France [**?**] used silicon detectors to measure the beta-delayed α decay energy spectrum of ^{16}N. However, because silicon detectors are sensitive to beta electrons, this introduced systematic uncertainties.

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摘要

Precise measurements of reaction cross-sections are essential for understanding stellar evolution, and β-delayed particle decay studies serve as a critical method for constraining these reaction components. The Time Projection Chamber (TPC) detector is an ideal tool for measuring β-delayed particle decay energy spectra due to its three-dimensional track reconstruction capabilities and excellent background suppression. Furthermore, TPC detectors are characterized by their insensitivity to beta electrons, high solid-angle coverage, and the absence of dead layers.

To evaluate the performance of such detectors for these measurements, this study utilized the MATE-TPC detector to conduct performance tests using an 87.5%Ar + 12.5%CO_2 gas mixture within a pressure range of $P = 3.182$ to 280 mbar. We systematically investigated the reliability and resolution of particle energy reconstruction derived from track ranges and compared these experimental results with Monte Carlo simulations.

The experimental results demonstrate that within the specified pressure range (where α particle ranges span approximately 7–21 cm), the experimentally measured range lengths are in good agreement with simulation results, with a deviation of less than 1%. Additionally, the simulated range resolution closely matches the experimental measurements, with a maximum discrepancy of approximately 10%, thereby validating the reliability of the simulation platform. Based on these findings, this work further utilizes the validated simulation platform to predict the β-delayed particle decay energy spectrum, providing a vital reference for subsequent experimental measurements.

关键词

Time Projection Chamber (TPC); α decay; range resolution; ^{12}C$(\alpha,\gamma)^{16}$O reaction; nuclear astrophysics. CLC number: O571.53; Document code: A; DOI: 10.11804/NuclPhysRev.37.01.40

Mu Huarui et al.: Research on technologies related to the measurement of ^{12}N β-delayed α decay based on a Time Projection Chamber (TPC) detector. Significant discrepancies exist among previous measurement results due to severe background interference at the low-energy end of the α energy spectrum. Although Schürmann et al. re-measured the β-delayed α spectrum of ^{12}N using an ionization chamber—which is insensitive to β electrons and thus yielded a cleaner spectrum—the study was limited by insufficient statistics and failed to resolve the data discrepancies between different measurements. Therefore, it is necessary to conduct a new round of measurements on the ^{12}N β-delayed α decay spectrum to resolve these inconsistencies and provide a more reliable experimental basis for the ^{12}C$(\alpha,\gamma)^{16}$O reaction rate. The Time Projection Chamber (TPC) can perform three-dimensional track measurements of charged particles and possesses exceptional background suppression capabilities. Furthermore, because the TPC is insensitive to β electrons, it serves as an ideal tool for measuring the β-delayed α decay spectrum of ^{12}N. Additionally, performing decay measurements inside a TPC not only provides nearly 4π solid angle coverage but also avoids energy measurement deviations caused by the dead layers of silicon detectors or energy loss in catcher foils encountered in previous experiments. Currently, although TPCs have been widely applied in nuclear physics research, there are no published works utilizing a TPC or other types of tracking detectors to precisely measure the ^{12}N α spectrum. In this work, we utilize a monochromatic α source to test the performance of a TPC detector. Combined with Monte Carlo simulations, we explore the feasibility of using a TPC for ^{12}N α spectrum measurements and estimate key performance indicators, such as the achievable energy resolution, providing an important reference for future experimental measurements.

Figure 2

Figure 1: Figure 2

1 实验测量装置及测试过程

Experimental Setup and the MATE-TPC Detector

The MATE-TPC (Multi-purpose Active-target Time projection chamber for nuclear Experiments) was employed in this work. The detector features an internal sensitive volume with an electron drift length of 200 mm. The anode readout plane consists of 7.0 mm triangular pads, as illustrated in [FIGURE:1]. Signal acquisition and recording are performed using the General Electronics for TPCs (GET) system.

To ensure the α particles from the radioactive source covered an optimal energy range for the experiment, we selected a ^{148}Gd source ($E_\alpha = 3.182$ MeV) and positioned it on the cathode plate of the TPC. To manage the trigger rate, a collimator with a diameter of approximately 1 mm was placed at a distance of 5 mm from the source. A schematic diagram of the complete experimental setup is shown in

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The working gas used during the tests was a mixture of 87.5% Ar and 12.5% CO_2. Testing was conducted at pressures of 280 mbar and 95 mbar, respectively. Under these pressure conditions, the range of the α particles is approximately 7–20 cm. Following the completion of tests at each pressure and electric field setting, we utilized a laser system to measure the electron drift velocity. The measurement precision of this method is better than 1%.

The specific measurement procedure for the drift velocity is as follows: A laser is pulsed through a window reserved on the side of the detector. The laser beam is incident parallel to the readout plane, passes through the TPC, and strikes a silicon detector. Using the signal from the silicon detector as the trigger for the Data Acquisition (DAQ) system, we obtain the time difference Δt_1 between the silicon detector signal and the TPC anode signal. Subsequently, the laser entry position is shifted by a distance ΔL along the direction parallel to the electron drift (Z-axis). The measurement is repeated to obtain a new time difference Δt_2. The electron drift velocity v_d can then be calculated as:

$$v_d = \frac{\Delta L}{\Delta t_1 - \Delta t_2}$$

The primary source of error in this method is the uncertainty in the displacement ΔL, which is approximately 0.1 mm. The uncertainty in the time difference Δt is maintained within 10 ns, thereby ensuring that the measurement accuracy of the electron drift velocity is better than 1%.

[FIGURE:3] displays the projection of an α particle track on the XY plane (the readout plane perpendicular to the electron drift direction) at a gas pressure of 95 mbar. The left panel shows the experimental data, while the right panel shows the results of a Monte Carlo simulation. In these figures, the X and Y axes represent the pad coordinates, and the Z axis (color scale) represents the amount of charge collected by the corresponding pad in arbitrary units.

2 实验数据分析及结果讨论

The detector provides three-dimensional track information for charged particles within its sensitive volume. Consequently, the energy information of these particles can be extracted not only from the total charge collected by the anode plate but also from the range derived from the 3D track data. Generally, extracting energy information via the range provides superior resolution and is the most commonly employed method; it is also the approach adopted in this work. In a typical nuclear reaction or decay event, multiple tracks often appear simultaneously. A core task of the data analysis is the accurate identification and separation of these individual tracks. Common tracking algorithms include the Hough transform, Kalman filtering, point cloud segmentation, and neural networks. Currently, we primarily utilize the Hough transform or RANSAC-based methods for track selection. Once selection is complete, the tracks are fitted to determine key parameters such as the specific angle, length, and starting position, which in turn yield critical information regarding the particle’ s momentum, energy, and reaction vertex. Presently, our standard track fitting method is charge-weighted.

In this work, we utilize the MATE-TPC linear fitting method and the rigid-body principal axis method. In the principal axis method, the charge $i = 1, 2, \ldots$ is treated as mass to construct the moment of inertia matrix for the track, from which the unit vector of the central principal axis is derived. The track length is generally extracted by calculating the distance between the initial and final points of the track. However, due to factors such as diffusion, the coordinates of these points may not lie exactly on the fitted line. Therefore, we project the initial and final points onto the fitted line to obtain the “true start and end points” on the track axis; the distance between these two points is defined as the track length. The definition of the α particle track length (L) is shown in [FIGURE:N]. It can be observed that as the angle decreases to a certain threshold, L decreases significantly. This is primarily because when the primary ionization electrons received by a triggered channel on the anode plate have a certain width in their time distribution along the z-direction, the signal waveform undergoes broadening (as shown in [FIGURE:N]). In our data analysis, the peak of the waveform is taken as the trigger time for that channel (which, combined with the electron drift velocity, determines the z-position). This leads to a deviation in the experimentally determined length of the α particle track in the z-direction. Consequently, in this work, we have discarded data where $\theta < 20^\circ$. In practice, for experimental data at small angles, the drift time in the z-direction could be extracted by analyzing the Bragg curve of the signal (rather than the time difference between different trigger signals used here), which, combined with the electron drift velocity, would yield the track length in the z-direction. The length perpendicular to the z-direction is still determined by the dependence of the experimentally extracted α particle track length at 120 mbar on the incident angle; the additional straight line represents the average track length.

The fitting results and specific analytical methods will be published in subsequent work. In the present study, we also attempted to use this method to extract track lengths for $\theta < 20^\circ$, while maintaining the previously described data processing method for $\theta > 20^\circ$. We found that the track lengths obtained by these two methods agree well, with a difference of only approximately 1%. This indicates that the proposed method can accurately extract α particle track lengths for $\theta < 20^\circ$ in future processing. In this work, however, the data for $\theta > 20^\circ$ still exhibit a weak correlation (with a maximum variation in L of about 2–3 mm). This may be caused by variations in the distance the α particles travel through the collimation hole before entering the TPC as the angle changes, as illustrated in [FIGURE:N]. Therefore, when analyzing the range resolution, we considered the following two cases: (1) all data where $\theta > 20^\circ$, corresponding to [TABLE:N]; and (2) data restricted to $\theta > 35^\circ$ and $30^\circ < \phi < 150^\circ$, corresponding to [TABLE:N]. Naturally, case (2) yields better range resolution.

To better understand the detector' s response to monoenergetic α particles, we input the experimentally determined emission positions and angles for each α particle track, along with the energy (3.182 MeV), into a Monte Carlo simulation to generate an equivalent volume of simulated data.

The simulation results for various parameters are summarized as follows: (keV) 20.81(1), 20.65(1), 3.97(4), 3.77(4), 3.54(7), 3.09(7), 44(0.5), 42(0.5), 40(0.8), 35(1); 16.39(1), 16.43(1), 3.45(4), 2.91(6), 2.90(4), 2.52(4), 50(0.6), 42(0.9), 42(0.6), 36(1); 12.31(1), 12.33(1), 2.92(3), 2.48(3), 2.24(4), 1.87(4), 56(0.6), 48(0.6), 43(0.8), 36(1); 9.02(1), 8.919(5), 2.52(2), 2.33(4), 1.79(3), 1.36(3), 66(0.5), 61(1), 47(0.8), 35(1); 7.04(1), 6.97(1), 2.17(4), 2.04(5), 1.70(4), 1.04(4), 72(1.3), 68(1.7), 57(1.3), 35(1). These values represent the normal signals on the anode plate versus the broadened waveforms caused by small angles. The simulation package we used, "MateRoot," is a software platform designed for processing and analyzing experimental data, as well as conducting real-time simulations for detectors and physical experiments.

MateRoot is developed using object-oriented C++ and is supported by the ROOT framework at its base. The simulation component relies on the Geant4 Monte Carlo toolkit [**?**] and is designed for multi-user access.

We have developed a library of models including fusion reactions, two-body reactions, beta decay, and multi-body decay, enabling the simulation of a wide range of nuclear physics processes. The software provides users with convenient input cards using C++ syntax. Simulated data are packaged in the same format as experimental data, allowing both to share the same analysis pipeline and providing immediate feedback for physical experiments. Using identical data analysis methods, we processed the simulated data and extracted the α range and resolution, as shown in [TABLE:N]. The experimentally extracted range resolution primarily comprises two contributions: first, the intrinsic range straggling of charged particles moving through matter; and second, the additional broadening of the track length caused by the finite resolution of the TPC detector and the data analysis methods. The former is the intrinsic fluctuation of the range, independent of the detector response, and represents the theoretical limit of the range resolution achievable by the detector. The latter is closely related to the detector' s construction, response, and analysis methods—such as the granularity of the anode plate—and can potentially be minimized by optimizing the detector design or analysis algorithms. To estimate these two contributions, we used Geant4 to simulate the range of α particles with fixed energy in the gas. In the simulation, we tracked the position of the α particle at every step and defined the range as the maximum distance from the emission point. The range resolution extracted this way can be roughly considered as the first contribution mentioned above, labeled as "limit" in [TABLE:N]. For comparison with the energy resolution of other types of charged particle detectors, we converted the range resolution into energy resolution using the simulated energy-range relationship, as shown in [TABLE:N]. It can be seen that the experimentally extracted ranges for α particles at different pressures agree well with the simulation results, with differences generally within 1-2 mm, corresponding to an energy difference of approximately 20 keV. This indicates that in this energy region, we can use simulations to calibrate the energy of the experimentally extracted ranges with an accuracy of about 20 keV. The range resolution (defined as FWHM in this work unless otherwise specified) gradually decreases with increasing gas pressure, from 3.97(4) mm at 95 mbar to 2.17(4) mm at 280 mbar. However, the corresponding energy resolution increases with pressure, from 44(0.5) keV at 95 mbar to 72(1.3) keV at 280 mbar. As previously noted, because the extracted range has a weak dependence on the emission angle, further restricting the α emission angle improves the range resolution by approximately 10%. In fact, the range resolutions in [TABLE:N] are very close to the simulated results denoted by "limit," with differences of only 10%-20%. Furthermore, if the emission angle is restricted to an even narrower range, the resolution can be further optimized. For instance, at 220 mbar and 280 mbar, further restricting the angle can reduce the range resolution by about 0.5 mm, bringing the experimental and simulated results closer together, with differences of less than 5% across the 95-280 mbar range (corresponding to track lengths of 7-21 cm). This demonstrates that simulations can reliably estimate the achievable range or energy resolution in actual experiments. As shown in [TABLE:N], the simulated energy resolution ranges from 40(0.8) keV at 95 mbar to 57(1.3) keV at 280 mbar.

The limit resolution (intrinsic range straggling) shown in [TABLE:N] remains essentially constant at 35-36 keV regardless of gas pressure. This indicates that for longer ranges (above 10 cm), the energy resolution of our TPC is dominated by intrinsic range straggling; further optimization of the detector structure (such as the granularity or shape of the readout pads) will not significantly improve energy resolution (with a maximum improvement of about 10%). Conversely, at higher pressures where the range is shorter (below 10 cm), the simulated energy resolution is significantly higher than the intrinsic straggling contribution. In such cases, optimizing the detector structure can lead to substantial improvements in energy resolution.

We performed energy loss curve measurements and corresponding simulations for $E = 3.182$ MeV α particles in the MATE-TPC. The pressures analyzed were 95 mbar, 120 mbar, 160 mbar, 220 mbar, and 280 mbar. To further analyze the intrinsic range straggling of α particles in the gas, we also simulated the angular deviations caused by Rutherford scattering. In the simulation, we fixed the emission angle and energy ($\theta = 46.48^\circ, \phi = 124.78^\circ, E = 3.182$ MeV) and analyzed the resulting track angles. The results showed a certain degree of broadening in both θ and ϕ. At 95 mbar, the distributions of θ and ϕ were centered at the input angles and followed Gaussian distributions with standard deviations of $\sigma(\theta) = 2.2^\circ$ and $\sigma(\phi) = 2.4^\circ$, respectively. To confirm that this broadening was due to Rutherford scattering in the gas rather than the detector’ s intrinsic response, we repeated the analysis with the Rutherford scattering process disabled in the simulation. In this case, almost no broadening was observed (as shown in [FIGURE:N]). This indicates that angular changes caused by Rutherford scattering will affect the precision of our emission angle measurements. [FIGURE:N] compares the angular distributions at 95 mbar with scattering enabled and disabled for a fixed initial angle of $\theta = 46.48^\circ, \phi = 124.78^\circ$. To further validate the reliability of the simulation, we compared the experimental and simulated energy loss curves (energy deposition per unit distance). The extraction method was as follows: first, the 3D tracks within the TPC were fitted using the method described earlier.

Then, the 3D coordinates of each triggered pad were projected onto the fitted line. The distance from this projection to the track starting point (as defined in the range extraction section) serves as the horizontal axis of the histogram shown in [FIGURE:N], while the vertical axis represents the charge (energy deposition) of the corresponding pad at that distance. Since the energy loss curves of individual α particle tracks exhibit significant fluctuations, we averaged multiple tracks to obtain the results shown in [FIGURE:N].

As seen in the figure, the simulated energy loss curves agree well with the experimental results, further validating the reliability of the MATE-TPC simulation platform. However, the experimental energy loss curve shows a noticeable dip near the starting point, a feature absent in the simulation. This is primarily because the radioactive source is mounted on the cathode plate, which distorts the local electric field and leads to incomplete electron collection—a factor not accounted for in the simulation. Additionally, at the end of the energy loss curve, while the shapes are very similar, there is an offset of approximately 1-2 mm between the simulation and experiment, which accounts for the corresponding difference in the extracted ranges.

Before and after measurements at each pressure, we used a laser to measure the electron drift velocity. We found that for a given pressure, the two measurements were consistent, with a maximum difference of approximately 0.5%. To estimate the impact of slow variations in drift velocity on the range, we applied the following correction: we assumed the drift velocity changed linearly over time between the two laser measurements. Based on the timestamp of each event, we interpolated the drift velocity and used this new value to reconstruct the 3D tracks and extract the range. We found that after this correction, the central value of the range changed by less than 0.1%, and the resolution changed by less than 1%. This suggests that the observed variations in electron drift velocity do not significantly affect the experimental range or its resolution.

3 使用

Feasibility Analysis of MATE-TPC

Based on the discussions in the previous section, the current MATE-TPC simulation platform effectively reproduces experimental measurements, including the range length, range resolution, and energy loss curves for α particles at $E_\alpha = 3.182$ MeV. Building upon this foundation, we conducted simulations in the lower energy region corresponding to β-delayed α decay ($E_\alpha = 0.5 - 2.0$ MeV) to estimate experimental feasibility and key performance indicators, such as the expected energy resolution.

To balance energy resolution and detection efficiency, it is necessary to select an appropriate gas pressure that maintains the α particle range within a 10–20 cm interval. Consequently, we selected two specific gas pressures, 40 mbar and 80 mbar, to cover the $E_\alpha = 0.5 - 2.0$ MeV energy range. The simulation results are summarized in . As shown in the table, the energy resolution achievable under these pressures remains nearly independent of the α particle energy, stabilizing at approximately 40 keV (with a maximum variation of about 10%). Furthermore, this resolution is almost entirely determined by the intrinsic fluctuations of the range, denoted as σ_{limit}.

Therefore, the aforementioned energy resolution represents the theoretical limit for extracting energy information via range measurements within this energy region. It is essentially impossible to further improve this resolution by optimizing the TPC detector hardware itself. Considering that our actual range resolution may be approximately 10% worse than the simulated values (as discussed in the previous section), we conservatively estimate that the energy resolution achievable in actual β-delayed α decay measurements will be around 45 keV (with a maximum variation of approximately 10%).

Clearly, this energy resolution is significantly inferior to that obtained in previous experimental measurements using silicon detectors or ionization chambers. For example, in the measurements by Bhattacharya et al., the resolution achieved using an ionization chamber near $E_\alpha = 1.5$ MeV was approximately 17 keV, which is several times better than the resolution expected in this work. To evaluate the feasibility of β-delayed α decay measurements under the expected resolution of $\sigma = 45$ keV, we applied Gaussian broadening to the theoretical calculations.

[FIGURE:1]

[FIGURE:1] compares the theoretical α spectrum before and after broadening. As seen in the figure, while the expected energy spectrum in this work can still clearly identify the peak shape near $E_\alpha = 1.75$ MeV, the "dip" structure near $E_\alpha = 1.0$ MeV is significantly obscured. This dip near 1.0 MeV is precisely one of the primary points of contention in existing experimental data. To resolve the discrepancies in current data, further improvements in energy resolution are required. For instance, by using TopMetal sensors to directly collect primary ionization electrons and determining the energy of charged particles through total charge collection—rather than the current range-energy calibration method—it is expected that the energy resolution can be significantly enhanced.

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The $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction is a critical nuclear process in astrophysics. Precise measurements of its reaction rate are of great significance for understanding stellar evolution and the origin of elements in the universe. The $E2$ component of this reaction can be effectively constrained through measurements of the ^{16}N β-delayed α decay energy spectrum. Among various detection methods, the Time Projection Chamber (TPC) is an ideal tool for such measurements due to its superior background suppression capabilities, high solid angle coverage, and lack of dead layers. In this work, we utilized the MATE-TPC detector and a gas mixture of $P10$ ($87.5\%\mathrm{Ar} + 12.5\%\mathrm{CH_4}$) at various pressures (ranging from 95 to 280 mbar) to conduct performance tests.

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The α energy spectrum and the spectrum obtained after broadening with $\sigma = 45$ keV.

Performance tests were conducted to systematically investigate the reliability and resolution of the detector in extracting particle energy via range measurements. The experimental results were subsequently compared with Monte Carlo simulations.

The experimental results demonstrate that within the pressure range of 95–280 mbar (corresponding to α particle ranges of 7–21 cm), the measured range lengths are in good agreement with the simulation results, with a discrepancy of only approximately 1–2 mm, which translates to an energy difference of about 20 keV. This indicates that Monte Carlo simulations can reliably extract α particle energies in experimental measurements. The experimental energy resolution degrades slowly as the range decreases above 10 cm (from 42 keV at 21 cm to 55 keV at 12 cm), whereas the resolution degrades more rapidly when the range is less than 10 cm.

This degradation is primarily due to the increasing contribution of the MATE-TPC readout pad granularity (equilateral triangles with 5 mm sides) to the range resolution as the range shortens. Therefore, to achieve optimal energy resolution, the α particle range should be maintained above 10 cm. Furthermore, our Monte Carlo simulations, based on the energy loss curves of α particles, successfully reproduced the experimental energy resolution (with a discrepancy of less than 5 keV for ranges above 10 cm). This suggests that simulations can be used to reliably estimate the energy resolution achievable in experiments.

Based on the aforementioned validation, we performed simulation predictions for the ^{16}N β-delayed α decay ($E_\alpha \approx 2.4$ MeV). The results indicate that at gas pressures of 80 mbar and 150 mbar, the $E_\alpha \approx 2.4$ MeV energy region can be covered while maintaining α particle ranges within the 10–20 cm interval. Under these conditions, the detector can achieve an energy resolution of 40–50 keV. Although this resolution is 2–3 times worse than previous results using silicon detectors or ionization chambers, simulations show that this resolution is primarily determined by the intrinsic straggling of the range and is difficult to improve by further optimizing the range readout method. Consequently, to further enhance the energy resolution, alternative energy readout methods are required. For instance, replacing traditional readout pads with TopMetal sensors to determine energy by collecting primary ionization electrons could eliminate the impact of range and gain fluctuations, thereby significantly improving energy resolution.

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Study on Techniques for Measuring β-delayed Decay using a Time Projection Chamber

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Abstract

The study of β-delayed particle emission is a crucial method for investigating the structure of nuclei far from the stability line. This paper presents a detailed study of the techniques involved in measuring β-delayed decay using a Time Projection Chamber (TPC). We discuss the experimental setup, signal processing, and track reconstruction algorithms specifically optimized for low-energy decay events. By utilizing the three-dimensional tracking capabilities of the TPC, we demonstrate improved efficiency and resolution in identifying decay products and determining branching ratios. These technical developments provide a robust foundation for future experiments targeting exotic nuclei at radioactive ion beam facilities.

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1. Introduction

The study of nuclei far from the line of β-stability is one of the frontiers in modern nuclear physics. As we move toward the drip lines, the separation energy of nucleons decreases significantly, leading to the phenomenon of β-delayed particle emission. In these processes, a precursor nucleus undergoes β-decay to an excited state of the daughter nucleus, which subsequently decays by emitting one or more nucleons (protons, neutrons, or alpha particles). Measuring the energy spectra, branching ratios, and angular correlations of these emitted particles provides essential information regarding the shell structure, deformation, and astrophysical nucleosynthesis paths (such as the *rp*-process and *r*-process).

Traditionally, silicon detector arrays have been used for such measurements. However, they face limitations when dealing with low-energy particles due to dead layers and the difficulty of distinguishing between different types of particles in a high-background environment. The Time Projection Chamber (TPC) offers a compelling alternative. As an active target detector, the TPC allows the gas medium to serve as both the detection volume and the reaction target. This configuration enables the reconstruction of three-dimensional tracks, providing high detection efficiency even for low-energy particles and excellent particle identification (PID) capabilities through dE/dx measurements

Abstract

Precise measurement of the O reaction cross section is crucial for understanding stellar evolution, and the study of N beta-delayed decay is an important way to constrain the E1 component of this reaction. Time Projection Chamber (TPC) detectors have three-dimensional track reconstruction capability and excellent background suppression ability. Meanwhile, TPC detectors are insensitive to beta electrons, have high solid angle coverage and no dead layers, which makes them an ideal tool for measuring the N beta-delayed decay spectrum. To evaluate the performance of TPC detectors in such measurements, we conducted

Figure 4

Figure 2: Figure 4

performance tests using the MATE-TPC detector with 4000 channels and a source (= 3.182 MeV) over a pressure range of 95-280 mbar (87.5% Ar + 12.5% mixed gas). We systematically investigated the reliability of particle energy determination from the measured range and its resolution, and compared them with Monte Carlo simulations. The experimental results show that under the aforementioned pressures (where the particle ranges are approximately 7-21 cm), the measured ranges agree well with simulation results (differences are less than 1%). Meanwhile, the simulated range resolution is also in close agreement with experimental measurements, with a maximum difference of about 10%, which validates the reliability of our simulation platform. Based on this, we also used the simulation platform to predict the N beta-delayed decay spectrum, providing an important reference for future experimental measurements.

Key words: time projection chamber; N beta-delayed decay; range resolution; O reaction; nuclear astrophysics Gao Bingshui, E-mail:

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Figures