Experimental Study of Detector Working Gas Properties Using Laser and Radioactive Sources

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Abstract

Properties such as the average ionization energy, Fano factor, and drift velocity of the working gas in gas detectors have significant impacts on the preliminary simulation, parameter design, and even track reconstruction of the detector. SeF6 serves as the target working gas in domestic neutrinoless double beta decay experiments, with its relevant parameters unknown and requiring investigation. To investigate the relevant parameters of this gas, a measurement scheme was designed, and the measurement precision and reliability of this experimental scheme were verified using Ar/CH4=90/10 (P10) working gas. In the experiment, measurements of an alpha source using a grid ionization chamber yielded an average ionization energy of $27.10\pm0.04 eV for P10; when the energy resolution reached 0.91\pm$0.001 after electronics calibration and noise subtraction. Simultaneously, the drift velocity was measured using a 266 nm laser and a Time Projection Chamber, with results consistent with Garifield++ simulation results. The experimental results demonstrate that this measurement scheme is feasible and the measurement results are highly reliable, paving the way for subsequent research on the properties of SeF6.

Full Text

Experimental Study of Working Gas Properties in Detectors Using Laser and Radiation Sources

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Abstract

The properties of working gases in gas detectors, such as average ionization energy, Fano factor, and drift velocity, have significant impacts on detector simulation, parameter design, and track reconstruction. SeF_6 serves as the target working gas in domestic neutrinoless double-beta decay experiments, yet its relevant parameters remain unknown and require investigation. To study these gas parameters, we designed a comprehensive measurement scheme and validated its accuracy and reliability using Ar/CH_4=90/10 (P10) as the working gas. In our experiments, we measured the average ionization energy of P10 to be 27.10$±$0.04 eV using a grid ionization chamber with an α source. When the energy resolution reached 0.91%, we determined the Fano factor to be 0.175$±$0.001$after calibrating the electronics and subtracting noise contributions. Additionally, we measured the
$+simulations. These experimental results demonstrate the feasibility of our measurement scheme and the high re$
properties.

Keywords: Grid ionization chamber; Energy resolution; Average ionization energy; Fano factor; Time projection chamber; Drift velocity

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Introduction

The Standard Model of particle physics represents a cornerstone of modern physics and natural science, having withstood experimental verification for over half a century. While the model predicts massless neutrinos, neutrino oscillation phenomena have definitively established their non-zero mass, representing the only solid experimental evidence beyond the Standard Model. Consequently, neutrino research may serve as a breakthrough into a new era of particle physics, with neutrinoless double-beta decay experiments providing an ideal observational window for neutrino properties [**?**]. Due to the extremely long half-lives of neutrinoless double-beta decay (typically exceeding 10^{23} years), constructing massive detectors is essential. Simultaneously, selecting nuclides

with high Q-values is necessary to effectively distinguish reaction events from natural backgrounds. In response, the Institute of Modern Physics of the Chinese Academy of Sciences and Central China Normal University have jointly proposed the "No neutrino Double-beta-decay-Experiment (NvDEx)" [**?**], planning to conduct a neutrinoless double-beta decay experiment with ^{82}Se at the Jinping Underground Laboratory. This experiment will employ $^{82}SeF_6$ gas at 10 atmospheres as the detection medium, utilizing a time projection chamber (TPC) read out by a top metal detector to study neutrinoless double-beta decay of ^{82}Se [**?**]. The advantages of this approach include the ease of constructing large-volume gas detectors and the ability to exploit the 3D track reconstruction capability of TPCs to record the trajectory characteristics of the two back-to-back β particles produced in ^{82}Se decay, along with their energy loss profiles along the tracks. These features serve as primary parameters for particle identification. Furthermore, the Q-value of ^{82}Se decay is 2.996 MeV, higher than most natural radioactive backgrounds, providing experimental advantages [**?**].

However, SeF_6 is a highly toxic electronegative gas rarely used as a working gas in nuclear radiation detectors. Unlike conventional working gases, when SeF_6 serves as a TPC working gas, primary ionization electrons are rapidly captured by SeF_6 molecules to form negative ions. The drift velocity of these negative ions, along with the average ionization energy and Fano factor of SeF_6 gas, constitute crucial parameters for TPC simulation and design, while the negative ion drift velocity also represents a key parameter for track reconstruction in experiments. Currently, most gas property studies focus on conventional gases [**?**][**?**][**?**], with no reported research on SeF_6 parameters. Therefore, we have initiated experimental investigations of ion drift velocity, average ionization energy, and Fano factor for SeF_6 gas. This paper focuses on the development and performance calibration of the grid ionization chamber for measuring average ionization energy and Fano factor, as well as the small time projection chamber (TPC) for measuring electron/ion drift velocity. To validate our methodology, we conducted measurements using conventional working gases as test subjects. Nuclear radiation gas detectors typically employ mixtures of noble gases and polyatomic molecular gases, among which Ar/CH_4=90/10 (P10) is a commonly used working gas with well-documented average ionization energy, Fano factor, and electron drift velocity [**?**][**?**][**?**], facilitating comparison with our experimental results. This paper presents the detector calibration using P10 as the working gas, along with optimization procedures. Our measurements agree well with existing experimental results and theoretical simulations, establishing a reliable foundation for direct measurement of SeF_6 gas parameters.

1. Measurement Principles and Detector Design

1.1 Average Ionization Energy and Fano Factor

The average ionization energy of a gas refers to the mean energy required to transform gas molecules from a neutral state to positive ions and electrons during an ionization event. This property is influenced by factors such as tem-

perature and pressure, and under constant temperature and pressure follows the relationship [**?**]:

$$W_i = \frac{E}{n}$$

where E represents the energy loss of the incident particle and n is the average number of electron-ion pairs produced by gas molecule ionization. Equation (1) indicates that we must measure the number of ionized electron-ion pairs under known particle energy loss conditions. In the laboratory, α radioactive sources emit particles with fixed energies and short ranges, providing known ionization energy losses. In gas detectors, the signal amplitude from a grid ionization chamber is proportional to the number of electrons ionized and collected in the drift region, enabling electron number measurement and making the grid ionization chamber method effective for determining working gas average ionization energy.

The Fano factor is a crucial parameter in gas detectors describing statistical fluctuations in energy deposition processes, specifically fluctuations in primary ionization. For gas mixtures, typical values range from $0.1 \leq \text{Fano} \leq 0.3$ [**?**]. The Fano factor is calculated as follows [**?**]:

$$Fano = 2.352\frac{W_i}{E}\Delta E_i$$

In equation (2), ΔE_i represents the intrinsic full-width-at-half-maximum (FWHM) resolution of the detector, W_i is the gas average ionization energy, and E is the particle' s ionization energy loss. While W_i and E can be obtained through the average ionization energy measurement scheme, the intrinsic resolution must be calculated through equation (3). Here, ΔE_t denotes the FWHM resolution of the detector, and ΔE_n represents the FWHM resolution obtained by feeding a pulse generator signal simulating the detector into the electronics system under identical electronic conditions, which can be regarded as noise contributed by the electronics. ΔE_o accounts for other effects such as rise time effects, but these contributions are minor and can be neglected. Therefore, this measurement scheme requires determining both the detector resolution and the pulse generator resolution under the same electronics. As evident from equations (2) and (3), the measurement demands excellent energy resolution. Compared with proportional counters [**?**] and pulse ionization chamber methods [**?**], grid ionization chambers exhibit no gain fluctuations and feature lower background noise and superior energy resolution due to their structure, making them suitable for this measurement.

1.2 Drift Velocity

Drift velocity refers to the motion speed of electrons or ions in a gas under electric field influence, depending on gas properties, electric field strength, and

temperature. Drift velocity is measured through the following scheme:

$$v = \frac{\Delta H}{\Delta t} = \frac{H_2 - H_1}{t_{H2} - t_{H1}}$$

where ΔH is the drift distance difference and Δt is the drift time difference for different incident positions in the field cage. ΔH requires a stable linear particle event penetrating the field cage to ensure parallelism between the two incident tracks and prevent effects from inclined events. A UV laser combined with an LX-axis precision optical translation stage satisfies these requirements: the laser is fixed on the translation stage, and adjusting the stage' s micrometer enables parallel laser movement. The TPC field cage is fixed to the target chamber endcap via a support frame to maintain stability. After aligning the laser perpendicular to the field cage plane and fixing both on the optical platform, adjusting the stage micrometer allows measurement experiments. UV lasers have been widely applied to simulate charged particle tracks in gas detectors [**?**][**?**][**?**][**?**], producing stable linear tracks with adjustable positions. This experiment employs a 266 nm laser developed by Changchun Institute of Optics, with an average power of 10 mW and single-pulse energy ranging from 0.1 to 3 µJ depending on frequency. For each laser event, the laser signal generation time serves as time zero (t_0), and the detector signal generation time as the endpoint (t_H). The drift time difference Δt between different incident positions yields the drift velocity [**?**].

Regarding detector selection, grid ionization chambers must consider electron transmission efficiency and operate without gain. At low electric fields, increased attachment and recombination effects produce relatively small signals that are difficult to measure. Therefore, we adopted a time projection chamber with signal gain. Like ionization chambers, TPCs feature simple fabrication and uniform, controllable drift region electric fields, with signal generation times correlating to particle incident positions in the field cage, making them suitable for drift velocity measurements [**?**]. The TPC-plus-laser measurement scheme is illustrated in [Figure 2: see original paper]. Compared with fixed-source and fixed-distance measurement schemes [**?**][**?**], this combination allows flexible adjustment of the drift distance range to accommodate different electronics dynamic ranges, facilitating measurements of unknown gases. Furthermore, as an electronegative gas, SeF_6 captures numerous primary ionization electrons, converting them to negative ions for drift. Although negative ions differ from electrons, they can still undergo avalanche gain and be collected to produce signals [**?**][**?**][**?**], making this method applicable to SeF_6 as well.

1.3.1 Grid Ionization Chamber

The physical grid ionization chamber is shown in [Figure 3: see original paper]. The experimental chamber is cylindrical, consisting from top to bottom of a cathode, field cage, grid, and anode. The cathode comprises a wire mesh elec-

trode with 0.05 mm wire diameter and 150 mm ring diameter. The field cage consists of 17 copper ring electrodes, each 2 mm thick, assembled with 4 mm spacing between rings. Adjacent rings use 10 MΩ resistors for voltage division to create a uniform electric field. The total field cage height is 114 mm, with the top connected to ground through a first-order RC filter circuit. The grid is constructed from wire electrodes with 0.05 mm wire diameter, 0.5 mm spacing between adjacent wires, and 2 mm grid thickness. The anode is a PCB copper electrode with 6 mm separation from the grid.

1.3.2 Time Projection Chamber

The time projection chamber is shown in [Figure 4: see original paper]. Its field cage comprises four double-sided copper-clad electrode strip PCBs with slits. The electrode strips are 2 mm wide with 1 mm hollow slits between strips to provide laser incident conditions. The strip period is 3 mm with 17 strips total. The field cage height is 51 mm, with 1 MΩ resistors soldered between adjacent strips for uniform drift electric field. The cathode is a planar electrode at the field cage top. The multiplication region employs three layers of THGEM with 2 mm spacing between layers and 3 mm distance from the field cage bottom. Voltage is applied to the three THGEM layers through a voltage divider resistor string. Since only drift velocity is measured, the readout electrode uses an entire planar electrode with 2.5 mm spacing from the THGEM.

1.4 Experimental and Electronics Setup

Before measuring average ionization energy and Fano factor, to calculate particle energy deposition, the experimental α source was attached to a 1 mm thick collimator with a 0.5 mm aperture and fixed at the center of the grid ionization chamber' s mesh cathode (as shown in [Figure 3: see original paper]). LISE++ calculations confirmed that the experimental α source could not penetrate the collimator, entering the detector only through the aperture. For drift velocity measurements, a 266 nm laser was used with the laser signal serving as the data acquisition trigger. Both sides of the TPC target chamber were machined with quartz glass windows to provide incident conditions. To prevent gas contamination, both the grid ionization chamber and TPC were placed in high-vacuum target chambers, with pressure controlled slightly above Lanzhou atmospheric pressure (approximately 840 mbar) to reduce air exchange between the sealed chamber and external environment. All measurements were conducted in a closed-gas mode. After detector assembly, the chambers were flushed 2–3 times with a vacuum pump before gas filling to prevent residual air impurities from affecting results.

High voltage for the grid ionization chamber and TPC was supplied by an iseg Germany high-voltage control system. The TPC drift region electric field strength was controlled by adjusting the external resistor string values and field cage voltage. Grid ionization chamber signals were initially filtered and amplified by a 142PC preamplifier, with timing signals fed to a CF8000 discriminator

for constant-fraction timing discrimination, then widened by a CO4020 logic module to provide DAQ GATE and Trigger signals. Energy signals were passed through a 572A main amplifier before entering an ADC for measurement. TPC signals were preliminarily amplified by a 142B preamplifier, then passed through a 474A amplifier, and together with the laser trigger signal, processed through a CF8000 discriminator. The laser signal, after CO4020 processing, also provided DAQ GATE and Trigger, while the discriminated TPC signal was collected by a TDC.

2. Experimental Results

2.1 P10 Average Ionization Energy Measurement

As described above, an α source provided incident particles, requiring measurement of the number of electron-ion pairs produced by primary ionization to calculate average ionization energy. This necessitated first calibrating the relationship between ADC channel number and electron-ion pair number, followed by α source energy spectrum measurement in P10 gas using the grid ionization chamber. In this experiment, we used a silicon detector for the first step. With silicon' s known average ionization energy of 3.6 eV [**?**], a triple-component α source (^{239}Pu at 5.16 MeV, ^{241}Am at 5.48 MeV, and ^{244}Cm at 5.80 MeV) was placed on the silicon detector surface inside a vacuum chamber to ensure complete particle energy deposition in silicon. Using equation (1), the electron-ion pair number was determined for calibration. The silicon detector voltage was set to 25 V, where signal amplitude no longer depended on voltage, with the 572A main amplifier gain at 20×. The resulting silicon detector spectrum is shown in [Figure 6: see original paper], with ROOT-fitted peak data presented in .

Based on the mean values of the three peaks, the relationship between ADC channel number and energy was fitted as:

$$channel = 329.69 \times E - 1.35$$

where *channel* is the ADC channel number and E is the particle ionization energy loss, which according to equation (1) also equals $3.6 \times 10^{-6} \times n$ (MeV), with n being the electron number. Thus, the relationship between energy E and channel number can be converted to a relationship between channel number and electron number n:

$$n = \frac{channel + 1.35}{329.69 \times 3.6 \times 10^{-6}}$$

Subsequently, α source energy spectrum measurement was performed with the grid ionization chamber in P10 gas. Due to small signals in the current electronics configuration, the 572A main amplifier gain was adjusted to 200×. However,

electronics parameter changes required testing the linear relationship between different 572A gain settings using a pulse generator. The results are shown in , demonstrating excellent linearity across different gains. This yielded the conversion relationship between electron number and ADC channel number at 200× gain:

$$n = \frac{channel/10 + 1.35}{329.69 \times 3.6 \times 10^{-6}}$$

After flushing and filling the target chamber with P10 gas, ^{241}Am α source experiments were conducted as described. Due to the 1 mm collimator aperture, α particles lost energy passing through it. LISE++ calculations indicated an energy loss of 0.07 MeV, leaving 5.41 MeV for the remaining particle with a range of 56.67 mm. The detector' s sensitive region was sufficiently large, with 110 mm height along the particle incident direction and an effective radius of 65 mm in the perpendicular plane, ensuring complete deposition of the α particle' s remaining energy. Grid ionization chambers face electron grid transmission issues; when the ratio of collection region to drift region electric fields $E_t/E_d >$ 2.5, electron transmission efficiency at the grid approaches 100%, with higher ratios bringing transmission closer to 100% [**?**]. Therefore, the grid ionization chamber anode voltage was set to 2000 V, grid voltage to 1300 V, and cathode grounded, making E_t/E_d much greater than 3. The resulting energy spectrum is shown in [Figure 7: see original paper].

Under these conditions, the measured mean value of the ^{241}Am α source spectrum was 2355 channels. Substituting this into equation (7) yielded an electron-ion pair number $n = 1.996 \times 10^5$. Combining this electron number with the corresponding deposited energy of 5.41 MeV in equation (1) gave an experimental average ionization energy for P10 gas of 27.10$±$0.04 eV. Published experimental results typically range from 26–28 eV [**?**][**?**][**?**], confirming the feasibility of our average ionization energy measurement scheme.

2.2 P10 Gas Fano Factor Measurement

According to equations (2) and (3), Fano factor calculation requires determining the detector' s intrinsic resolution from the detector resolution and electronic noise resolution. To reduce noise and improve energy resolution, the anode readout preamplifier was replaced with a lower-noise A250CF CoolFET, while the grid was switched to 142PC filter power supply. Limited by the A250CF CoolFET' s voltage supply maximum, detector anode voltage was adjusted to 1200 V and grid voltage to 800 V. Energy resolution was measured under these conditions, with results shown in [Figure 8: see original paper].

ROOT fitting yielded standard deviations σ and mean values for the three peaks, providing the grid ionization chamber resolution shown in . In the current electronics configuration, the ADC channel width was 1.5 keV/channel. LISE++ calculations indicated energy losses of 70 keV, 67 keV, and 64 keV for the three

source components passing through the small aperture. Experimental data are as follows:

Subsequently, a pulse generator signal was injected into the preamplifier' s Test input, feeding it through the same electronics as the detector signal. The pulse generator signal amplitude was adjusted according to the ADC spectrum until it matched the α source peak position, as shown in [Figure 9: see original paper]. The first peak in [Figure 9: see original paper] formed from the superposition of the ^{239}Pu signal from the triple-component source and the pulse generator signal. Fitting yielded a standard deviation σ of 13.71, representing the electronic noise standard deviation. Since the radioactive source event rate is extremely low compared to the pulse generator, its contribution to the signal peak can be neglected. This gave detector and electronic noise standard deviations of 14.12 and 13.71, respectively, corresponding to FWHM resolutions ΔE_t and ΔE_n. Substituting into equation (3) yielded an intrinsic detector resolution ΔE_i = 11.91 keV. Combining the experimental ΔE_i and W_{P10} in equation (2) gave a Fano factor of 0.175$±$0.001, consistent with Kase's results [**?**]. Additionally, an empirical relationship exists between Fano factor and average ionization energy for gas mixtures [**?**]:

$$Fano = (0.188 \pm 0.006)W - (0.15 \pm 0.02)$$

where W is the average ionization energy and I is the gas' s first ionization potential. For P10 gas, we adopted the experimental value W_{P10} = 27.10 eV and calculated a weighted first ionization energy I_{P10} = 15.44 eV, yielding $Fano = 0.179 \pm 0.031$. This experimental result agrees with the empirical formula calculation, confirming the feasibility of our experimental scheme.

2.3 P10 Drift Velocity Measurement

Prior to experiments, Garfield++ simulations were completed for P10 gas drift velocity at 300 K and 845 mbar to verify experimental results. In experiments, the field cage and THGEM were connected to negative high voltage, with electric field strength varied by changing the external resistor string values and field cage voltage. An optical translation stage controlled movement distance via a micrometer screw with 0.01 mm precision, making its error negligible compared to millimeter-scale movements. The laser spot intensity follows a Gaussian distribution with 1 mm diameter (6σ). Allowing the laser to penetrate the field cage introduces a real drift distance deviation of $\pm\sigma$ mm. After aligning the laser with the slits, the laser signal served as the trigger to acquire TPC timing signals. The laser was then moved to penetrate the next slit and TPC timing signals were acquired again. The drift distance difference ΔH error was $\pm\sqrt{2}\sigma$ mm, or $±$0.24 mm. [Figure 10: see original paper] shows the time spectrum at 60 V/cm electric field strength, where the two peaks correspond to laser incident signals from different field cage heights.

From the micrometer screw changes, the drift height difference was $\Delta H = 2.90\$\pm0.24 mm. Fitting yielded peak mean values of 923.4 and 1215.1, with corresponding fitting errors of 0.1 and 0.$ $58.34\pm0.14 ns. Substituting into equation (4) yielded a drift velocity of v = 4.97\pm\$0.42$ cm/μs at 60 V/cm electric field strength. Repeating this process at different electric fields produced electron drift velocities from 0-700 V/cm, shown in [Figure 11: see original paper], which agree well with Garfield++ simulation results, confirming the validity of our drift velocity measurement scheme.

Conclusion

Using P10 gas as our experimental subject, we validated the feasibility of a comprehensive research scheme for measuring gas properties including average ionization energy, Fano factor, and drift velocity, preparing for subsequent SeF_6 gas measurements. After calibrating the electronics with a silicon detector, we measured P10' s average ionization energy as $27.10\$\pm\$0.04$ eV using a grid ionization chamber and triple-component α source. The grid ionization chamber achieved an energy resolution of approximately 1%, with the best resolution reaching 0.91%. Using a pulse generator to simulate detector signals, we eliminated electronic noise and determined the intrinsic detector resolution of 11.91 keV, yielding a P10 gas Fano factor of $0.175\$\pm0.001 when substituted into equation (2). Applying the empirical relationship between average ionization ener$ with both methods producing consistent results. Additionally, TPC combined with laser measurements yielded P10 gas electron drift velocities that agreed well with Garfield++ simulations and other experimental results. These P10 gas measurements validate the feasibility of our comprehensive scheme for gas property characterization, which can serve as a general methodology for studying different gases. With improved experimental conditions and equipment, we will extend this measurement scheme and detector apparatus to investigate $^{82}SeF_6$ gas properties.

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