Properties of thick GEM in low-pressure deuterium

C.S. Lee, S. Ota, H. Tokieda, R. Kojima, Y.N. Watanabe and T. Uesaka

Center for Nuclear Study, University of Tokyo,
2-1 Hirosawa, Wako, Saitama 351-0198, Japan
Nishina Center for Accelerator-based Science, RIKEN,
2-1 Hirosawa, Wako, Saitama 351-0198, Japan
Department of Physics, University of Tokyo,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

E-mail: cslee@cns.s.u-tokyo.ac.jp

ABSTRACT: Deuteron inelastic scattering (d, d') provides a promising spectroscopic tool to study nuclear incompressibility. In studies of deuteron inelastic scattering of unstable nuclei, measurements of low-energy recoiled particles is very important. In order to perform these measurements, we are developing a GEM-TPC based gaseous active target, called CAT (Center for nuclear study Active Target), operated with pure deuterium gas. The CAT has been tested with deuterium gas at 1 atm and 100-µm-thick GEMs. The low-pressure operation of CAT is planned in order to improve the detection capability for lower-energy recoil particles. A 400 µm-thick gas electron multiplier (THGEM) was chosen for the low-pressure operation of CAT. However, the properties of THGEM in low-pressure deuterium are currently undocumented. In this work, the performance of THGEM with low-pressure pure deuterium gas has been investigated. The effective gas gain of THGEM has been measured in various conditions using a 5.5-MeV \(^{241}\)Am alpha source. The effective gas gain was measured for 0.2-, 0.3- and 0.4-atm deuterium gas and a gas gain of about 10\(^3\) was achieved by a double THGEM structure at 0.2 atm. The maximum achieved gain decreased with increasing gas pressure. The dependences of the effective gas gain on the electric field strengths of the drift, transfer and induction regions were investigated. The gain stability as a function of time in hydrogen gas was also tested and a relaxation time of THGEM of about 60 hours was observed with a continuous irradiation of alpha particles, which is significantly longer than previous studies have reported. We have tried to evaluate the gas gain of THGEM in deuterium gas by considering only the Townsend ionization process; however, it turned out that more phenomenological aspects,
such as transfer efficiency, should be included in the evaluation. The basic properties of THGEM in low-pressure deuterium have been investigated for the first time.

**KEYWORDS:** Electron multipliers (gas); Time projection Chambers (TPC); Time projection chambers
1 Introduction

Isoscalar-type inelastic scattering on unstable medium-to-heavy nuclei such as Ni and Sn isotopes can provide important information on the equation of state (EoS) of nuclear matter. In measurements of scattering off stable nuclei, scattering in the center-of-mass frame at forward angles around $0^\circ$ has been measured, which is essential to extract information on the EoS since a fixed target of stable nuclei and a light isoscalar-type probe such as deuterium or alpha particles can be used in combination with a high-resolution spectrometer. On the other hand, it is experimentally infeasible to apply “normal” kinematics to unstable nuclei, because it is very difficult to make fixed targets of short-lived nuclei. However, there is another way to measure the inelastic scattering off unstable nuclei: the so-called inverse kinematics, where a fixed light target of isoscalar-type probes (deuterium or alpha particles, for example) is bombarded with unstable nuclei. In inverse kinematics, the forward-angle scattering in the center-of-mass frame corresponds to a very low recoil energy of the probe in the laboratory frame. For the (d, d$'$) reaction with a 100 MeV/u $^{132}$Sn beam, for example, a scattering angle of 1$^\circ$ in the center-of-mass frame corresponds to a deuteron total kinetic energy of 500 keV. To extract such low-energy recoiling probes from the reaction point, a gas target is required.

Active target systems enable us to deduce the trajectories of such low-energy recoiling particles, where the gas is used not only as a target but also as an amplification gas. A GEM-TPC-based (Gas Electron Multiplier and Time Projection Chamber) active target system is reported in refs. [1, 2] where a He+CO$_2$ gas was used. We are developing a GEM-TPC-based gaseous active target with a pure deuterium gas, called the Center for Nuclear Study Active Target (CAT), for the purpose of measuring deuteron inelastic scattering off unstable nuclei. To achieve the required gain, some GEMs can be stacked. The readout region can be mechanically independent from the...
amplification part using GEMs. The requirements for the CAT are an angular resolution in the center-of-mass frame \( \delta \theta_{\text{CM}} \), of 1° and a total kinetic energy resolution, \( \delta E/E \), of 10%.

The minimum energy deposition of our interest is 5 keV/cm, the energy deposition of recoiling deuterons to 9° in the center-of-mass frame from \(^{132}\)Sn(d, d') reaction at 100 MeV/nucleon with 0.4-atm deuterium and the range of such a deuteron is 4.4 m. The readout pad of our TPC has a shape of an equilateral triangle and each side is 5 mm long. The conversion gain of our preamplifier is 400 mV/pC. If an effective gas gain of \( 10^4 \) is achieved, the resulting pulse height is 20 mV for the energy deposition along a flight length of 2.5 mm which is considered as an average flight length on the single readout pad. With this pulse height, the pulse is able to be well discriminated from a typical noise level of 5 mV. Although the balance between the effective gas gain and the conversion gain can be optimized, an effective gas gain of \( 10^4 \) is required for the current setup. On the other hand, the maximum energy deposition of recoiling deuterons is 50 keV/cm and the dynamic range of our readout circuit also covers this energy deposition. In a previous study (ref. [3]), we assembled a 100-\( \mu \)m-thick GEM-based CAT prototype. It has been successfully tested in experiment using deuterium under atmospheric conditions (room temperature, 1 atm pressure). In the present work, we discuss the next phase of development in which the CAT is operated with low-pressure deuterium gas (0.2–0.4 atm) in order to measure scattering at angles closer to zero degrees.

In such a low-pressure gas, we need more GEMs to achieve a gain of \( 10^4 \). C.K. Shalem et al. investigated the performance of a THGEM for the first time (refs. [4, 5]) and they showed that THGEMs provide a maximum gain that is a factor of 10 higher than that achieved from a standard GEM under low-pressure conditions. THGEM is chosen for the CAT to have a gas gain of \( 10^4 \) in low-pressure deuterium gas. However, there are currently no references outlining the properties of THGEM in low-pressure deuterium. Therefore, as a first step, the simplest configuration of a double THGEM structure was studied (the signal was not observed when only a single THGEM was used). In the present study, we studied the performance of THGEM in hydrogen/deuterium gas: the effective gain of a double THGEM configuration with various gas pressures and its dependences on the drift, transfer and induction fields using an \(^{241}\)Am alpha source were studied. The long-term stability of the effective gas gain was also investigated.

2 Experimental setup

THGEM has an area of \( 10 \times 10 \text{cm}^2 \), a hole diameter of 300-\( \mu \)m and 700-\( \mu \)m pitch. The holes of THGEM were created by a mechanical drilling. Figure 1 provides a schematic view of the setup. The lengths of the transfer region between two THGEMs and the drift region of the alpha particles from the \(^{241}\)Am source are 2 mm and 20 mm, respectively. The length of the induction region between the board of readout pads and the lower THGEM (THGEM1) is 2 mm. Each readout pad has an area of \( 1.5 \times 1.5 \text{cm}^2 \) and there are 6×6 pads on the board. The 6 pads are connected in series to collect enough charge even with a low gain. The range of an alpha particle in low-pressure deuterium gas is long enough to reach the opposite side of the drift region (30 cm) from the source point. For example, the range in 0.2-atm deuterium is about 95 cm. Figure 2 shows an image of the readout pads with the alpha source. The charge on the readout pads was integrated with a charge-sensitive preamplifier RPA-211, manufactured by REPIC Co. Ltd., Japan. The preamplifier has a conversion gain of 400 mV/pC and a time-constant of 80 ns. The output signal from the
preamplifier was treated by a shaping amplifier (ORTEC 571) and the pulse height of the shaped signal was recorded by a multi-channel analyzer (MCA) (Kromek 102).

A schematic view of the gas supply system used in the present work is displaced in figure 3. For an adequate gas supply, a gas regulator for low-pressure conditions was employed. The oxygen contamination in the chamber and the leakage of hydrogen/deuterium are monitored continuously. For the oxygen contamination, an oxygen concentration sensor JKO-25LJII (from JIKCO Ltd.) unit was employed at the outlet pipe of the vacuum pump. Gasman M07630 (from CROWCON Detection Instruments Ltd.) unit was used as a hydrogen leak monitor (no alarm was triggered during the measurements). The procedure of the gas operation before starting the measurement is as following. Once we pump the chamber and achieve a gas pressure $\leq 0.4$ kPa, the hydrogen/deuterium gas is filled. After filling the gas, the gas flow becomes purer ($O_2$ level under 0.1%) with respect to the concentration of deuterium inside the chamber while monitoring the oxygen contamination level and the gas leak rate. Because the flammability limits based on the volume percentage of hydrogen in oxygen at 1 atm are 4.0 and 94.0, we had to keep the oxygen concentration inside the chamber less than 6%. Low oxygen concentration is very important not only for safety but also for avoiding electron attachment by oxygen molecules in the gas. The oxygen concentration level was always kept less than 0.1% through out the entire measurement. Guided by GARFIELD++ simulations of electron attachment, a transverse diffusion with oxygen concentration levels lower than 0.1% and a drift field strength higher than 1 kV/cm/atm, the recombination during the drift is assumed to be negligible in our measurement.

3 Measurement

In order to evaluate the performance of THGEM, the effective gas gain, $G_{\text{eff}}$, was derived. The effective gas gain is defined by the following relation, which is the amount of charge collected on the readout pad divided by the primary charge:

$$ G_{\text{eff}} = \frac{Q_{\text{pads}}}{q_e \cdot \Delta E/W_1}, $$

(3.1)
where $\Delta E$ is the energy loss of alpha particle, $W_i$ is the average energy for ion-electron pair creation of the gas, $q_e$ is the elementary charge and $Q_{\text{pads}}$ is the total charge collected on the readout pads. All generated charges are expected to be collected since the size of each single readout pad is large enough to cover the diffusion of the electron avalanche. The $W_i$ value of hydrogen, 36.4 eV (ref. [6]), is adopted for deuterium by assuming that the gases have the same chemical properties. The methodology in the present work is similar with ref. [7]. The energy loss $\Delta E$ of an alpha particle in the gas can be obtained from the LISE++ (ref. [8]) physical calculator by considering the distance between the source point and the start/end of the readout pad. $G_{\text{eff}}$ was measured as a function of $E_{\text{THGEM}}/P$, $E_D$, $E_T$ and $E_I$, where $E_{\text{THGEM}}$, $E_D$, $E_T$ and $E_I$ are the electric fields of holes of GEM, drift region, transfer region and induction region, respectively. The gain stability over a long time period in hydrogen gas was also investigated.
Figure 4 shows a typical spectrum for alpha particles in deuterium gas. The peak around 2800 ch corresponds to the energy deposition by the alpha particles that pass directly through the regions between the connected pads. Alpha particles emitted from the source at non-zero angles are responsible for the background component that is fitted with the dashed green line. The energy spectrum was fitted with the sum of the Gaussian and exponential functions. The mean of the Gaussian function is used to derive the effective gas gain of THGEM.

4 Results and discussion

4.1 Gain curves for 0.2-, 0.3- and 0.4- atm D\textsubscript{2}

We recorded the gain curves of a double THGEM structure from the least condition to be able to record a spectrum until measurements became hindered by sparks caused by electrical breakdown of the gas. Figures 5, 6 and 7 show the gain curves for 0.2-, 0.3- and 0.4- atm deuterium, respectively. For these measurements the electric fields of the drift, transfer and induction regions were all fixed to 1 kV/cm/atm.

As indicated by figures 5, 6 and 7, the THGEMs need more bias voltage $\Delta V_{\text{THGEM}}$ to achieve the same gain in higher pressure conditions because the gas gains reduce at higher pressures. To see the contribution of a single THGEM from a double THGEM configuration, we have taken an asymmetric bias for two THGEMs: keeping the voltage of one THGEM fixed while varying the voltage applied to the other. When we changed the bias of THGEM2 to +50 V and fixed that of THGEM1, the total gain becomes nearly double. The maximum gain achieved for a double THGEM structure was about $10^3$, which is an order of magnitude lower than our goal of $10^4$. However, if we employ a triple THGEM structure, an additional gain factor of 10 should be achievable, considering the difference of the gas gains between double and triple THGEM structure (ref. [9]).
4.2 Dependence on the electric fields of the drift, transfer and induction regions

The dependence of the effective gas gain on each electric field was also measured. In these measurements, the strength of the electric fields, with the exception of the field of interest, were fixed to 1 kV/cm/atm and each bias voltage $\Delta V_{\text{THGEM1}}$ and $\Delta V_{\text{THGEM2}}$ was fixed to 500 V. Figure 8 shows the dependence of $G_{\text{eff}}$ on the drift field strength $E_D$. $G_{\text{eff}}$ increases with the $E_D$ until
1.25 kV/cm/atm and then decreases gradually. According to ref. [10], all field lines from the drift region enter the holes, and it could be inferred that the collection efficiency is close to 100% at a moderate field strength, while a field-dependent fraction of the electron and ion charge is collected by the bottom and top GEM electrodes, respectively, at a stronger field. The tendency in our result seems to be the same as that in reference ref. [10], although the plateau could not be seen. The measurements were stopped at a field strength of 3 kV/cm/atm, since sparking becomes a problem above this value.

As already mentioned, a strong electric field above the THGEM foil can cause the gas gain to decrease. If the transfer field strength is too strong, it will cause the same effect as the drift field. However, we did not observe a gradual decrease of gas gain in strong transfer fields, but a plateau of the gas gain instead. $G_{\text{eff}}$ increases almost linearly with $E_T$ for weak electric fields (below 2 kV/cm/atm). After the maximum gain for this setup was reached, a plateau was observed (figure 9). This plateau can be interpreted as the maximum transfer efficiency of gas electrons between two THGEMs. The measurement was stopped at a field strength of 6 kV/cm/atm owing to the spark problem.

The effect of the induction field is that $G_{\text{eff}}$ increases almost linearly with $E_I$ up to $E_I = 10$ kV/cm/atm (figure 10). The measurement was stopped at a field strength of 12.5 kV/cm/atm, because of the sparking problem. The extra increase at around 10 kV/cm/atm is due to a parallel plate multiplication between the bottom electrode of THGEM and the readout pad as described in ref. [10]. This parallel plate multiplication may benefit charge collection, but worsen the angular resolution. However, the reason for the difference between the slopes at $\leq 3$ kV/cm/atm and 3–10 kV/cm/atm is not fully understood.
Figure 9. Transfer-field dependence of effective gas gain $G_{\text{eff}}$ in 0.2-atm $D_2$.

Figure 10. Induction-field dependence of effective gas gain $G_{\text{eff}}$ in 0.2-atm $D_2$.

4.3 Dependence of the electric field-to-pressure ratio, $E_{\text{THGEM}}/P$

In this subsection, we compare the measured effective gains with the highest voltage configurations at each pressure and discuss their tendencies from the point of view of Townsend coefficient. Figure 11 shows the compilation of $E_{\text{THGEM}}/P$ dependences of $G_{\text{eff}}$ at pressures of 0.2, 0.3, and 0.4 atm, as well as calculated gas gains.
Assuming the amplification process originates from only the Townsend ionization process, the intrinsic gas gain with THGEM is expressed by

$$G_{\text{calc.}} = e^{(\alpha_{GEM1} + \alpha_{GEM2})d},$$  \hspace{1cm} (4.1)

where $\alpha_{GEM1(2)}$ is the first Townsend coefficient for the bias voltage to each GEM and $d$ is the distance between parallel plates (metal foils for GEM). The $\alpha$ of hydrogen is described (ref. [11]) as

$$\alpha_n/P_0 = 5.1 \times \exp\left[(-138.8 \pm 0.4)P_0/E\right],$$  \hspace{1cm} (4.2)

where $P_0$ is the gas pressure at 0°C. In the region of $E/P_0 \geq 200$, $\alpha_n$ of deuterium can be also described by the formula above. Because the avalanche of GEM holes is different from that of parallel plates, especially the distribution of the electric field strength, an adequate electric field of GEM holes should be accounted for by the calculation. In the present work, 80% of the applied electric field was taken to be the average strength of GEM hole (see figure 12), as a tentative assumption.

Each curve is scaled by different factors (see table 1). The differences in the scale factor may be understood by considering the efficiencies of transmission and collection in the drift, transfer and induction regions for each different setup. The scaling factor for the 0.2-atm case is the smallest, which means that the transfer or collection efficiency is also the smallest. On the other hand, that for the 0.4 atm case is the largest. Further quantitative studies to evaluate the transfer or collection efficiency are required.
Figure 12. Calculated $E_{\text{hole}}$ along the central hole axis.

Table 1. Scale factors $G_{\text{eff}}/G_{\text{calc}}$ for each gas pressure.

| Pressure (atm) | Scale factor |
|---------------|--------------|
| 0.2           | 0.0548       |
| 0.3           | 0.0987       |
| 0.4           | 0.1581       |

4.4 Gain stability

The fluctuation of the effective gas gain of THGEMs with time was investigated for gain stability with hydrogen gas, because there are only few chemical differences between hydrogen and deuterium. The $G_{\text{eff}}$ in 0.2-atm hydrogen gas for a double THGEM structure was measured for 90 hours with a continuous alpha source irradiation. The result is shown in figure 13.

The high voltage to the THGEMs was supplied 4 hours before the start of the measurement and maintained stably until the end. The bias voltage to the THGEMs was 550 V and each electric field was $E_D = 1 \text{ kV/cm/atm}$ and $E_T = E_I = 1.5 \text{ kV/cm/atm}$. In order to keep the temperature inside the chamber constant, the ambient room temperature was kept fixed with a standard air conditioning unit during the measurement. The oxygen concentration level was kept consistently under 0.1%. The result shows that it takes about 60 hours for $G_{\text{eff}}$ to stabilize. After 60 hours, $G_{\text{eff}}$ varies only about 1%. Because only small changes of gas pressure $P$ and temperature $T$ were observed, the $P/T$ correlation of $G_{\text{eff}}$ could not be derived and, therefore, $P/T$ correction was not necessary for this measurement. Our result, a relaxation time of 60 hours, is relatively long compared to refs. [12, 13]. There is presently no clear understanding for such a long relaxation time. It might be come from the feature of hydrogen gas or that of an individual THGEM. This phenomenon will be investigated further in the future. Moreover, a stability test with a medium-mass ion beam ($Z \sim 50$) condition will also be performed in the near future.
Figure 13. Time dependence of effective gas gain $G_{\text{eff}}$ in 0.2 atm pressure $\text{H}_2$.

Figure 14. The gain deviation after 60 hours.

5 Summary

We are developing a low-pressure deuterium GEM-TPC-based active target, called CAT. The basic properties of THGEMs with pure deuterium gas were investigated for the first time. To avoid an explosion of deuterium gas and an attachment problem, we continuously monitored and maintained the oxygen concentration level so that it was less than 0.1% during measurements. The maximum effective gas gain achieved was about $10^3$ at 0.2-atm with $E_D = E_T = E_I = 1 \text{kV/cm/atm}$, which is a factor of 10 lower than our goal of $10^4$. However, if we employ a triple THGEM structure, an additional factor of 10 can easily be achieved, based on considerations of the difference of the gas gain between double and triple THGEM structure. With a gain of $10^4$, the CAT can cover an angular range up to around 9° deduced with an angular resolution of 1° and a kinetic energy resolution of 10%. We have deduced the most suitable electric field strengths for the drift and transfer regions for the highest achieved gas gain of THGEMs in low-pressure deuterium. For the drift region, 1 kV/cm/atm provided the maximum collection efficiency and gas gain. The transfer field strength of 2 kV/cm/atm provided the maximum transfer efficiency between two THGEMs and a higher field strength made only negligible change and a higher spark probability. Basically, a stronger induction field strength provided a higher gas gain. Understanding of the effective gas gain of THGEM was approached by the dependence of $E_{\text{THGEM}}/P$ and a simple theoretical model considering only the Townsend ionization process. However, a more detailed description of the amplification in the entire system is needed to understand the results. We measured the long-term stability with controlled gas pressure and temperature and the relaxation time of about 60 hours in 0.2-atm deuterium gas was obtained. There is currently no clear understanding for such a long relaxation time. A continuous development of CAT is in progress and a triple THGEM configuration with pure deuterium gas will be studied in the near future.
Acknowledgments

This work was partially supported by Grants-in-aid 60548840 from the Ministry of Education, Culture, Sports, Science and Technology (MEXT).

References

[1] K. Yamaguchi et al., Development of the GEM-MSTPC for measurements of low-energy nuclear reactions, Nucl. Instrum. Meth. A 623 (2010) 135.

[2] H. Ishiyama et al., GEM-MSTPC: an active-target type detector in low-pressure He/CO₂ mixed gas, 2012 JINST 7 C03036.

[3] S. Ota et al., Modification of Active Target for the forward angle scattering and measurement of deuteron induced reaction on ⁵⁶Fe, CNS Annual Report 2011, CNS-REP-90, Tokyo Japan (2013), pg. 70, site: http://www.cns.s.u-tokyo.ac.jp/archive/annual/ann11.pdf.

[4] C. Shalem et al., Advances in Thick GEM-like gaseous electron multipliers - Part I: atmospheric pressure operation, Nucl. Instrum. Meth. A 558 (2006) 475.

[5] C.K. Shalem et al., Advances in Thick GEM-like gaseous electron multipliers - Part II: Low-pressure operation, Nucl. Instrum. Meth. A 558 (2006) 468.

[6] Average Energy Required to Produce an Ion Pair, ICRU Report 31 (1979).

[7] S.K. Das et al., Gas-gain study of standard CERN GEM and 400-μm-thick Thick GEM in low-pressure He/CO₂ mixed gas, Nucl. Instrum. Meth. A 625 (2011) 39.

[8] O.B. Tarasov and D. Bazin, LISE++: Radioactive beam production with in-flight separators, Nucl. Instrum. Meth. B 266 (2008) 4657.

[9] V. Peskov et al., Further evaluation of a THGEM UV-photon detector for RICH-comparison with MWPC, arXiv:1008.0151.

[10] S. Bachmann et al., Charge amplification and transfer processes in the gas electron multiplier, Nucl. Instrum. Meth. A 438 (1999) 376.

[11] D.J. Rose, Townsend Ionization Coefficient for Hydrogen and Deuterium, Phys. Rev. 104 (1956) 273.

[12] R. Chechik et al., Thick GEM-like (THGEM) detectors and their possible applications, physics/0606162.

[13] M. Alexeev et al., Development of THGEM-based photon detectors for Cherenkov Imaging Counters, 2010 JINST 5 P03009.

[14] F. Sauli, GEM: A new concept for electron amplification in gas detectors, Nucl. Instrum. Meth. A 386 (1997) 531.

[15] A. Breskin et al., Thick GEM-like hole multipliers: properties and possible applications, Nucl. Instrum. Meth. A 535 (2004) 303.

[16] A. Breskin et al., GEM photomultiplier operation in CF₄, Nucl. Instrum. Meth. A 483 (2002) 670.

[17] V. Tikhonov and R. Veenhof, GEM simulation methods development, Nucl. Instrum. Meth. A 478 (2002) 452.