Performance of a micro-TPC for a
time-resolved neutron PSD

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Abstract

We report on the performance of a micro-TPC with a micro pixel chamber (µPIC) readout for a time-resolved neutron position-sensitive detector (PSD). Three-dimensional tracks and the Bragg curves of protons with energies of around 1 MeV were clearly detected by the micro-TPC. More than 95% of gamma-rays of 511 keV were found to be discriminated by simple analysis. Simulation studies showed that the total track length of proton and triton emitted from the \(^{3}\text{He}(n,p(573 \text{ keV}))^{3}\text{H}(191\text{ keV})\) reaction is about 1.2 cm, and that both particles have large energy losses (> 200 keV/cm) in 1 atm Ar+\(\text{C}_2\text{H}_6(10\%)+^{3}\text{He}(<1\%)\). These values suit the current performance of the micro-TPC, and we conclude that a time-resolved neutron PSD with spatial resolution of sub-millimeters shall be developed as an application of the micro-TPC.

Key words: Gaseous detector; Time projection chamber; Micro-pattern detector; \(^{3}\text{He}\) neutron detector; Position sensitive neutron detector; Time-resolved neutron detector
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1 Introduction

Micro-TPC, a time projection chamber with a micro pixel chamber ($\mu$-PIC) readout was recently developed for the detection of charged particles[1]. The results of a fundamental measurement indicate that some improvements are still required for detecting the minimum ionizing particles (MIPs)[2]. Nevertheless, the results also indicate that low-energy charged particles, which have a large energy loss ($dE/dx$), are already detectable by the micro-TPC with dense samplings.

Neutron position-sensitive detectors (PSDs) with a large detection area and a capacity for high-rate operation are indispensable for use at neutron beams of the next generation[3]. Since the neutron energy is resolved by a measurement of the time-of-flight (TOF), a timing measurement on the order of $\mu$s is strictly required. Gaseous neutron detectors filled with $^3$He have been keenly developed and used because of large cross section to thermal neutrons of about 25 meV. Because the energy losses of both the proton and the triton emitted from the $^3$He (n, p (573 keV)) $^3$H(191keV) reaction are large, we expect to detect the fine tracks of both particles by the micro-TPC. We can thus determine the incident position from the detected tracks with a resolution of sub-millimeters. Since gamma-rays are thought to make a large background when used at neutron beams, discrimination between the neutrons and gamma-rays is also important, which should be realized by the measured values, such as the energy losses ($dE/dx$).

In this paper, we present the tracking performance of the micro-TPC with energies of around 1 MeV. We then report on the discrimination between the electron tracks (gamma-ray events) and the proton tracks (neutron events). Finally, we discuss the development of time-resolved thermal neutron ($\sim 25$ meV) PSD as an application of the micro-TPC while taking account of the experimental results and simulation studies.

2 Micro-TPC

A micro-TPC, a time projection chamber with a micro pixel chamber ($\mu$-PIC[4]) readout, was recently developed for the detection of charged particles[1,2]. $\mu$-PIC is a gaseous two-dimensional PSD manufactured by printed circuit board (PCB) technology. A schematic of the $\mu$-PIC structure is shown in Fig. 1. We developed a $\mu$-PIC with a detection area of $10 \times 10$ cm$^2$ and a pixel pitch of 400 $\mu$m. Cathode strips are formed on one side of a polyimide substrate (100 $\mu$m thick), while anode strips are orthogonally formed on the other side.
The results of a fundamental measurement have already been reported in a previous paper[2]. Here, we briefly mention the essential features of the micro-TPC[1]. The detection volume of the micro-TPC is $10 \times 10 \times 8 \text{cm}^3$ with a drift field of 0.4kV/cm. The micro-TPC can be stably operated at a gas gain of 3000 with Ar-$\text{C}_2\text{H}_6$(10%) flow. We are optimizing the geometrical structure of the pixels using a three-dimensional simulator[5,6] in order to realize a stable operation with a gas gain of $10^4$. The signal from each strip is fed to an amplifier-shaper-discriminator (ASD[7]) chip, which outputs both an amplified analog signal and a discriminated digital (LVDS) signal. LVDS signals are in turn read by a position encoding module (PEM), which works at a clock rate of 20 MHz. PEM calculates the two-dimensional incident position while taking the anode-cathode coincidence within one clock pulse. When at least one anode-cathode coincidence is found within the maximum drift time (2 $\mu$s) from the external trigger, or the "$t = 0$" time, the two-dimensional position and the elapsed time from the trigger are recorded. For the energy measurement, every 32 analog outputs of the cathode ASD chips are summed and digitized by an 8-channel 100 MHz flash ADC (FADC). In this way, we can realize three-dimensional tracking and spectroscopy of the charged particles with the micro-TPC.

3 Measurements

3.1 Proton tracking

We irradiated the micro-TPC with fast neutrons from a radioactive $^{252}\text{Cf}(\sim 2\text{MBq})$ source, the neutron energy of which peaks between 500 keV and 1 MeV. Protons arise from elastic neutron scattering by hydrogen nuclei in $\text{C}_2\text{H}_6$. Part of the neutron kinetic energy is transferred to the hydrogen nucleus, i.e. the proton. The radioactive source was placed 8.5 cm from the aluminum window of the micro-TPC, and an Yttrium Aluminum Perovskite (YAP) scintillator[8](1” $\times$ 1” $\phi$) was set 3 cm from the radioactive source at the opposite side of the micro-TPC. The set-up is shown in Fig. 2. One fission decay of $^{252}\text{Cf}$ emits 3.8 neutrons and 9.7 photons on average, therefore, the micro-TPC was triggered by gamma-rays detected by the YAP scintillator. The three-dimensional tracking performance for protons of around 1 MeV and a gamma-ray background of several hundred keV were thus measured in this "n/$\gamma$-run".

From all of the measured data, we selected data with a length $>$1cm and $N_{\text{hit}} \geq 4$ as the track data. Here, length is the track length calculated by simply connecting the detected points, and $N_{\text{hit}}$ is the number of detected points.
Several proton tracks with energies between 500 keV and 1 MeV are shown in Fig. 3. The hardware threshold level at the ASD chip was 50 keV/cm, which was low enough to detect sub-MeV protons having energy losses larger than 200 keV/cm. Therefore, the detection efficiency was estimated to be almost 100%. In Fig. 4, FADC waveforms of the proton tracks are shown. Here, the same events are shown in Fig. 3 and Fig. 4. Since the elapsed time from the trigger represents the drift length, these waveforms are regarded as the Bragg curves. The directions of the tracks are obviously known from the shape of the Bragg curves.

From measurements with $^{252}$Cf, the micro-TPC was found to possess sufficient performance to detect the tracks and Bragg curves of protons with energies of around 1 MeV.

### 3.2 Particle discrimination

Since gamma-rays are thought to make a large background when used at neutron beams, discrimination between the neutrons and gamma-rays is important. We measured the particle discrimination power by irradiating the micro-TPC with gamma-rays from a radioactive source of $^{22}$Na. Annihilated back-to-back gamma-rays of 511 keV were emitted from the source. The micro-TPC was triggered by one of the gamma-rays detected by a YAP scintillator, while the other scattered the electrons in the micro-TPC. This radioactive source was chosen because the gamma-ray energy is close to the $Q$ value (764 keV) of the $^3$He (n, p) $^3$H reaction. Thus, the particle discrimination of the 511 keV gamma-rays was measured in this ”γ-run”. Since the $dE/dx$ of electrons scattered by the gamma-rays were much smaller than those of the neutrons, analog signals were amplified by the gain amplifier((gain = 8) before being digitized by the FADC in the γ-run.

The typical three-dimensional track of the electron (gamma-ray event) is shown in Fig. 5. Comparing the tracks in Fig. 3 and Fig. 5, one finds that the proton tracks are more dense and straight than those of the electrons. Consequently, one can assume that the discrimination of the proton tracks and the electron tracks are realized by the energy loss and the fitting results with straight lines. We defined the energy loss by $dE/dx = E/\text{length}$ and $\chi^2$ by

$$\chi^2 = \sum_{i=1,2,n-1,n} \frac{\Delta_i}{\sigma},$$

where $E$ is the detected energy, $n$ is the number of detected points, $\Delta_i$ is the distance between the $i$th detected point and the best-fit straight line, and $\sigma =$
270μm is the measured three-dimensional spatial resolution of the micro-TPC. The degree of freedom (d.o.f) was three for all of the tracks, since we used the first two and the last two points to calculate $\chi^2$. The $dE/dx$ distributions of the n/γ-run and the γ-run are shown in Fig. 6. In the data of the γ-run, most events are distributed below 50 keV/cm. On the other hand, neutron events with $dE/dx > 50$ keV/cm can be seen in the n/γ-run as well as the gamma-ray peak below 50 keV/cm. The $\chi^2$/d.o.f distributions are shown in Fig. 7. $\chi^2$/d.o.f distribution of the n/γ-run peaks below 3, because the proton tracks are fitted with the straight lines very well. We thus define the ”neutron region” by $dE/dx \geq 50$ keV/cm and $\chi^2$/d.o.f $< 3$. When we consider the selection efficiency of the neutrons, the lower limit for the energy loss ($dE/dx = 50$ keV/cm) is reasonably low compared to the energy losses ($> 200$ keV/cm) of the protons and tritons from the $^3$He(n,p)$^3$H reaction. It is apparent that the $\chi^2$ cut has a very high efficiency from the steep peak in Fig. 7. Therefore, the selection efficiency for the neutron is thought to be very close to 100%.

Fig. 8 shows $\chi^2$/d.o.f. vs $dE/dx$ plots of the n/γ-run. Neutron events can be seen in the neutron region, while the gamma-ray events are seen out of the neutron region. The result of the γ-run is shown in Fig. 9. Only less than 5% of the total events (14 of 500 events) are seen in the neutron region, which indicates that more than 95% of the gamma-rays are discriminated by this analysis.

In this measurement with a $^{22}$Na radioactive source, more than 95% of the 511 keV gamma-ray background is known to be discriminated by the $dE/dx$ and the $\chi^2$.

4 Time-resolved neutron PSD with the micro-TPC

4.1 Time-resolved neutron PSD with the micro-TPC

Neutron position-sensitive detectors (PSDs) with a large detection area and a capacity for high-rate operation are indispensable for use at neutron beams of the next generation[3]. Since the neutron energy is resolved by a measurement of a time-of-flight (TOF), the timing measurement on the order of μs is strictly required. Gaseous neutron detectors filled with $^3$He have been keenly developed and used because of the large cross section to thermal neutrons of about 25 meV. Recently, a CCD-GEM based $^3$He detector was developed, and the performance was studied[9]. Nice images of the tracks of the proton and triton were obtained, which indicates the potential for the thermal-neutron PSD. However, making a large-area detector and high-rate operation could be problematic for practical use at neutron beams. In addition, the CCD readout
is too slow for the TPC; hence, only two-dimensional tracks are achieved in this readout system. This feature would deteriorate the quality of the neutron images.

On the other hand, the micro-TPC with a large detection area is easily manufactured and high-rate operation up to 7.7 MHz with the $\mu$-PIC was actually realized[2]. Three-dimensional trackings help to determine the incident position with a spatial resolution of sub-millimeters. Fine spatial resolution is strictly required for the neutron diffraction imaging, because the incident angle is determined by the incident position. Therefore, the micro-TPC is an appropriate detector for time-resolved neutron PSD with $^3\text{He}$. The principle of the $^3\text{He}$ neutron detector is $^3\text{He} (\text{n, p (573 keV)}) ^3\text{H(191keV)}$. We have already shown that the micro-TPC possess sufficient performance to detect the tracks and Bragg curves of the proton emitted from this reaction. We subsequently studied the tracks of both particles by a simulation, and evaluated the development of the time-resolved thermal neutron ($\sim 25$ meV) PSD as an application of the micro-TPC.

We calculated the energy depositions of protons and tritons along the tracks by Geant4 (ver 5.0 patch-01)[10]. A gas mixture of Ar-C$_2$H$_6$(10%)-$^3$He($< 1\%$) at 1 atm was used for the calculation. We did not take account of the ionization of $^3\text{He}$ for the energy deposition because its amount is vary small. The result is shown in Fig. 10. The track length (1.2cm) and the $dE/dx$ of both particles ($> 200$ keV/cm) are reasonable for detection by the micro-TPC. The protons and the tritons are easily distinguished from the Bragg curves. As a result, the incident position is determined with a spatial resolution of sub-millimeters.

From a measurement with a $^{22}\text{Na}$ source, more than 95% of the 511 keV gamma-ray background was known to be discriminated by $dE/dx$ and $\chi^2$. For practical use, the total energy deposition ($E$) is also used to discriminate the low energy gamma-rays that have large $dE/dx$. With this total energy cut, almost complete gamma-ray rejection will be realized. In this way, we reject the gamma-ray background almost completely, which is another appropriate feature of the neutron PSD as an application of the micro-TPC.

This neutron PSD is operated with the gas at normal pressure. We can thus reduce the materials needed for the high-pressure gas enclosure, which is useful for a better image of the neutrons.

From simulation studies and the experimental results, we conclude that a time-resolved neutron PSD with a spatial resolution of sub-millimeters shall be developed as an application of the micro-TPC.
4.2 Future plans

We are developing a $\mu$-PIC with a detection area of $30 \times 30$ cm$^2$. We will soon increase the clock rate of the encoding system from 20 MHz to 100 MHz, because the current spatial resolution is dominated by this clock rate. With these improvements, we are quite sure that we can develop a time-resolved neutron PSD as an application of the micro-TPC.

The parallax error could be problematic for a non-pressurized 8cm-thick TPC. One solution to avoid it is to build a curved detector so that one of the two parallax errors will not be observed. Because the $\mu$-PIC is a thin (~100$\mu$m) polyimide sheet, curved detectors can, in principle, be manufactured. Another solution is to determine the start timing of the drift by detecting the gas scintillation light so that the interaction position would be determined three-dimensionally with a resolution of sub-millimeters. The study on the gas scintillation seems to be one of the most important tasks of ours in the near future development. CF$_4$ gas, which is a common gas for the $^3$He neutron detector because of its large stopping power (for shorter tracks) and small Z (for less gamma-ray background), would also be useful for this purpose, because its scintillation wavelength fits the detection by the photomultipliers[11]. Total light yield from the CF$_4$ gas by the neutron capture reaction of $^3$He is estimated to be $O(10^3)$ photons, which seems to be enough to trigger the TPC with a timing resolution of ~10ns even with a photomultiplier coverage of a few % and its quantum efficiency of ~ 10% at 600nm. In this way, we think the parallax error could be avoided with some more improvements of the micro-TPC.

The results on the tracking performance and the particle discrimination indicate a strong possibility the application of the micro-TPC as a dark matter detector. Actually, our results are comparable to those shown in Ref. [12] concerning the points of tracking performance and discrimination. We are going to study the detector response to low-energy nuclear recoils in order to estimate the feasibility for a dark matter detector.

5 Conclusions

Three-dimensional tracks and the Bragg curves of the protons with energies of around 1 MeV were clearly detected by the micro-TPC. We also showed that more than 95% gamma-rays of the 511 keV were discriminated, while the efficiency to the neutrons of the same energy range was retained at ~100%. Simulation studies showed that the total track length of the proton and the triton emitted from the $^3$He(n,p(573 keV))$^3$H(191keV) reaction is about 1.2
cm, and that both particles have sufficient energy losses (> 200keV/cm) in 1 atm Ar+C\textsubscript{2}H\textsubscript{6}(10%)+\textsuperscript{3}He(< 1%). These values suit the current performance of the micro-TPC, and we conclude that a time-resolved neutron PSD with a spatial resolution of sub-millimeters shall be developed as an application of the micro-TPC.

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Fig. 1. Schematic structure of the $\mu$-PIC. Cathode strips are formed on one side of the polyimide substrate of 100 $\mu$m thick, while anode strips are orthogonally formed on the other side.

Fig. 2. Schematic drawing of the experimental set-up. $^{252}$Cf is placed at the "R.I. source" position in the neutron-run, while $^{22}$Na is used in the $\gamma$-run.
Fig. 3. Several three-dimensional proton tracks (500 keV - 1 MeV) detected in the n/γ-run.

Fig. 4. Energy loss of the protons. Each track has its counterpart in Fig. 3. The directions of the tracks are recognized from the shape of the Bragg curves.
Fig. 5. Typical three-dimensional track of an electron detected in the γ-run. Projections are also shown in the gray points.

Fig. 6. $dE/dx$ distributions of the n/γ-run (hatched) and γ-run (non-hatched.) Neutron events are seen in >50 keV/cm in the n/γ-run.
Fig. 7. $\chi^2$/d.o.f. distributions of the n/γ-run (hatched) and γ-run (non-hatched.) Neutron events make the peak below 3.

Fig. 8. $\chi^2$/d.o.f vs $dE/dx$ plots of the n/γ-run. The neutron region is superimposed.
Fig. 9. $\chi^2$/d.o.f. vs $dE/dx$ plots of the $\gamma$-run. Less than 5% of the detected events (14 of 500 events) are seen in the superimposed neutron region.

Fig. 10. Calculated energy loss along the proton and triton track in 1 atm Ar+$C_2H_6(10\%)+^3He(<1\%)$. The total track length is about 1.2 cm.