



Development of a low-background micro pattern gaseous detector for a directional dark matter search

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Doctoral Dissertation

Development of a low-background micro pattern
gaseous detector for a directional dark matter search

(方向感度を持つ暗黒物質探索実験のための
低バックグラウンドマイクロパターンガス検出器開発)

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Abstract

Dark matter is thought to be a particle that can account for about 27 % of the composition of the universe but has yet to be discovered despite many experiments that have been conducted to search for it. The expected amplitude of the seasonal variation with the conventional direct search observation methods, which detect the recoil energy from the nucleus, is only a few percent. It is difficult to derive a highly reliable evidence from the annual modulation signatures. On the other hand, a directional method, which captures the “dark matter wind” on the Earth caused by the movement of the solar system through the galaxy, is expected to provide a more reliable evidence from the anisotropy of the recoil direction of atomic nuclei. NEWAGE (NEw generation WIMP search with an Advanced Gaseous tracker Experiment) is a directional dark matter search using a three-dimensional gaseous tracking detector. It has the world’s best sensitivity as a directional method, but its sensitivity is not as high as that of conventional dark matter search experiments, and further improvements in sensitivity are required. The main background was alpha-rays from radioactive impurities contained in the readout detector, μ -PIC. The removal of this background was an urgent issue. In the previous study, reducing the alpha-ray emission from the surface of LA μ -PIC by changing the materials used for the surface was succeeded. In this study, to reduce not only the alpha-rays emitted from the detector surface but also the radon emitted from the detector material, we screened and selected the materials to be used for the detector and fabricated a new detector, Low background μ -PIC (LBG μ -PIC). As a result, the radon emission was reduced by more than one order of magnitude and the sensitivity for dark matter search can be improved by one-order of magnitude.

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1 Introduction

Various observations of the universe have shown that an undiscovered particle called dark matter account for about 27% of the energy composition of the universe. Another unknown, dark energy, accounts for about 68% and known baryons account for only about 5%. The energy composition of the universe is shown in Figure 1.1.

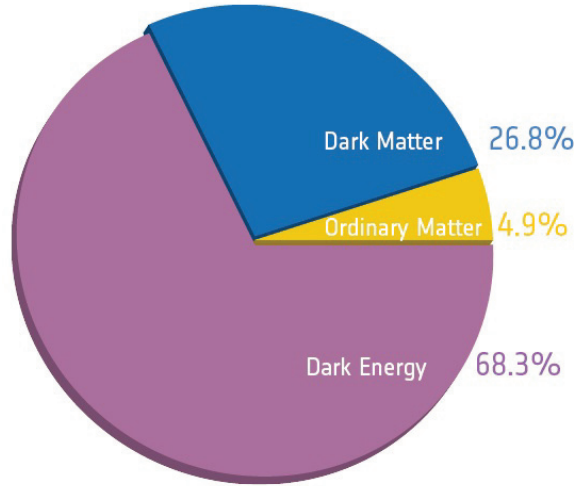


Figure 1.1: Energy composition of the universe from the Planck results[1].

While the existence of dark matter has been confirmed by various observations, most of its properties are still unknown. Since there is no particle that satisfies these properties in the framework of the Standard Model, it is considered to be a set of new particles that is yet to be discovered. In order to discover the dark matter, direct search experiments searching for the recoil between the dark matter and nucleus, indirect search experiments searching for the annihilation signals of the dark matters, collider experiments searching for the dark matter production are being conducted.

A great number of dark matter search experiments have been running aiming for the direct detection of the dark matter. NEWAGE is one of these experiments using a gaseous time projection chamber (TPC) to detect the dark matter with directional sensitivities.

This thesis consists of following chapters.

In Chapter 2, dark matter properties and search methods are reviewed. Principles of gaseous detectors and low radioactivity measurement methods will be described in Chapter 3 and Chapter 4, respectively. Chapter 5 summarizes the current NEWAGE status. In Chapter 6, a development of a low background micro pixel chamber (LBG μ -PIC) is described. Sensitivity improvement of NEWAGE with the LBG μ -PIC will be discussed in Chapter 7. This thesis is concluded in Chapter 8.

2 Dark matter

Observational results showing the existence of the dark matter and its natures are reviewed in this chapter.

2.1 Dark matter evidences

Galaxy rotation curve F. Zwicky observed in 1930s[2] (Figure 2.1) the motions of galaxies in the Coma cluster and claimed that the cluster contained 100 times more unobserved mass than the total mass of galaxies optically observed. This is the case where the dark matter was proposed for the first time. V. Rubin observed the rotation velocities of galaxies with the 21cm line of hydrogen atoms and found that the velocities did not decrease even in the outer regions of galaxies in 1970s[3].

The rotational velocity $v_{\text{rot}}(r)$ at a distance r from the galactic center can be expressed as Eq.(1) according to Kepler's law,

$$\frac{v_{\text{rot}}^2(r)}{r} = G_N \frac{M(r)}{r^2} \quad (1)$$

where $M(r)$ is the mass within the radius r and G_N is the Gravitational constant. If only the optically observable mass exists in the galaxy, the majority of the galaxy's mass is expected to be concentrated in the bulge at the center. In this case, the rotation velocity is expected to decrease in proportion to $r^{-1/2}$ at the outer part of the galaxy. However, observed rotational velocity curves of the galaxies do not fall as much as expected from the mass inferred from optical observations even in the outer regions of the galaxy (Figure 2.1). This discrepancy indicated the existence of mass that cannot be observed optically.

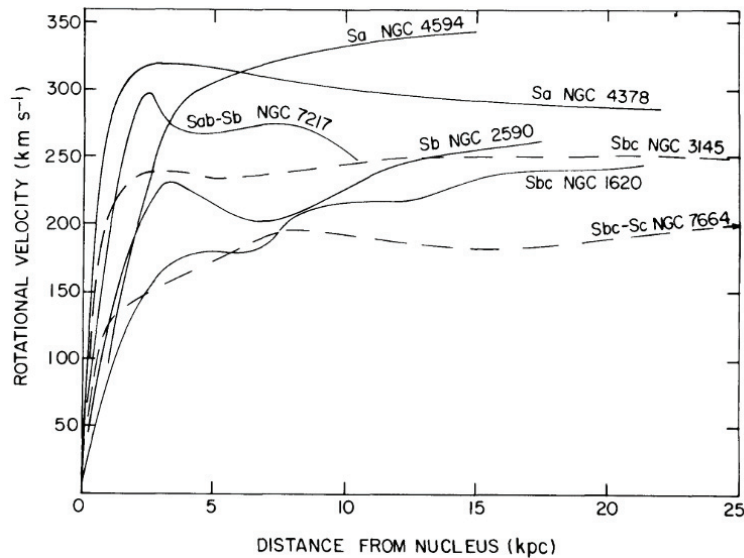


Figure 2.1: Rotation velocity curves for seven galaxies. Rotation velocities of these galaxies show no decreases even in the outer regions of galaxies[3].

Cosmic microwave background(CMB) A cosmological model that assumes the existence of Cold Dark Matter (CDM) and includes the cosmological term Λ is known as the Λ -CDM model, which is the current standard model in cosmology. The scale factor a for the size of the universe and its derivative in the Λ -CDM model are expressed as Eq.(2).

$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2 \left(\frac{\Omega_m}{a^3} + \frac{\Omega_r}{a^4} + \Omega_\Lambda - \frac{\Omega_k}{a^2} \right), \quad (2)$$

where H_0 is the Hubble constant, Ω_k is the curvature of the universe, and Ω_m , Ω_r , and Ω_Λ are the matter, radiation, and dark energy densities, respectively. Here dimensionless parameters Ω_m , Ω_r , and Ω_Λ are defined by dividing the corresponding energy densities by the critical density ρ_c . From the solution of this differential equation including the cosmological parameters, we can determine whether the universe is contracting or expanding, whether the universe is flat or not, and whether there was a Big Bang or not. Therefore, we can see that the evolution of the universe is determined by the cosmological parameters. These parameters can be determined by observing the Cosmic Microwave Background (CMB), the electromagnetic waves coming from the early universe when the universe cooled down after the Big Bang and became electrically neutral. WMAP (Wilkinson Microwave Anisotropy Probe) [4], and Planck satellite[5] observed CMB and found a temperature fluctuation in the CMB which can be expressed as

$$\delta T/T(\theta, \phi) = \sum_{lm} a_{lm} Y_{lm}(\theta, \phi), \quad (3)$$

where $T(\theta, \phi)$ is the spatial distribution of temperature, Y_{lm} is spherical harmonics, θ and ϕ are angles between two directions. The first peak of the obtained angular power spectrum of CMB temperature fluctuations (Figure 2.2) gives the total baryon abundance, while other peaks are related to the amount of non-baryonic matter. By fitting the data from the Planck satellite with the Λ CDM model, total and baryon matter densities of $\Omega_m h^2 = 0.1430 \pm 0.0011$, $\Omega_b h^2 = 0.02237 \pm 0.00015$ were obtained, respectively. The matter density was found to be about five times larger than that of baryons[5]. The rest part of the matter is considered to be the dark matter.

Gravitational lensing Gravitational lensing is an effect in which a heavy gravitational source such as an astronomical object bends the light from astronomical objects behind by gravity. There are two types of gravitational lensing effects: the strong and the weak gravitational lensings. The strong gravitational lensing is observed as a distortion of each background object and the weak one is detected as a statistical deformation of the background galaxies. Observations of the weak gravitational lensing effect in the Bullet cluster ([6], Figure 2.3) has shown that the mass distribution obtained from the weak gravitational lensing effect is different from the baryon distribution obtained by X-ray observations. This result suggested that, in a collision of clusters of galaxies, interstellar matter such as plasma did not pass through due to the Coulomb interaction, while the ‘matter’ with mass and interaction smaller than the Coulomb interaction did pass through. Since such ‘matter’ does not exist in the Standard Model, this matter could be the dark matter.

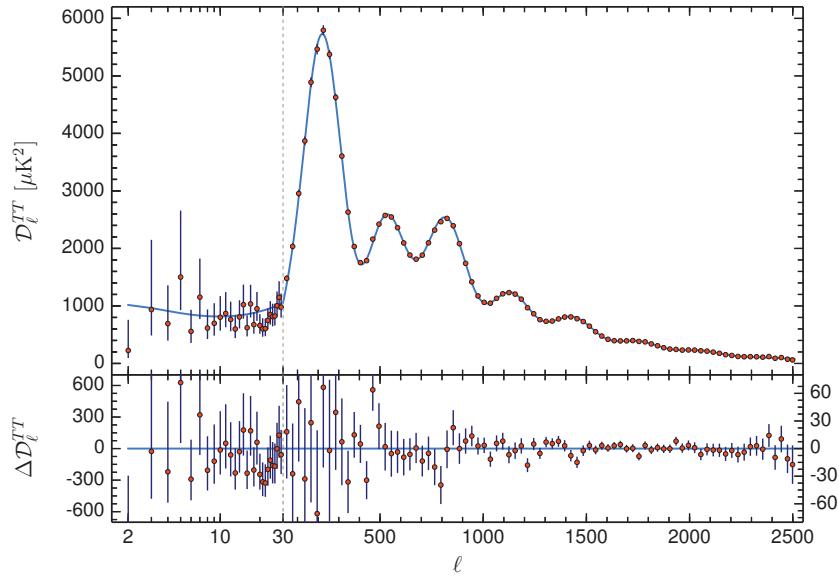


Figure 2.2: Temperature power spectrum from Planck2018 results[5].

Ia Supernovae The observations of Type Ia supernovae by the SuperNova Legacy Survey and the Sloan Digital Sky Survey[7] set a limit on the dark energy of the universe ($\Omega_\Lambda = \Lambda/(3H_0^2)$), and together with the Λ -CDM model ($\Omega_m + \Omega = 1$) provided $\Omega_m = 0.295 \pm 0.034$.

2.2 Dark matter candidates

It is generally believed that dark matter was created in the early universe and decoupled from the ordinary matter as its density decreased with the expansion of the universe. The dark matter is called Hot Dark Matter (HDM) if its velocity was relativistic, and Cold Dark Matter (CDM) if its velocity was non-relativistic at the “clear up of the universe” when the cosmic temperature decreased due to the expansion of the universe and photons became to move freely. Numerical simulations of the universe’s large-scale structure suggest that cold dark matter is the most likely candidate. As described in the previous section, observations strongly support the existence of the dark matter at various scales of the universe. In this section, we will review some promising candidates for the dark matter currently considered.

WIMPs Weakly Interacting Massive Particles (WIMPs) are massive particles that are not in the Standard Model and interact only weakly with each other and with the particles in the Standard Model. Supersymmetry (SUSY) model and the Universal extra dimension (UED) model contain WIMPs as forms of neutralinos and Kaluza-Klein particle, respectively. SUSY model introduces particles with a different spin from the Standard Model (SM) partners by 1/2, called super-partners. In the SUSY model, the lightest SUSY particle (LSP) is thought to be stable and thus it can be the dark matter. In the UED model, the lightest Kaluza-Klein particle (LKP) can be the dark matter[8].

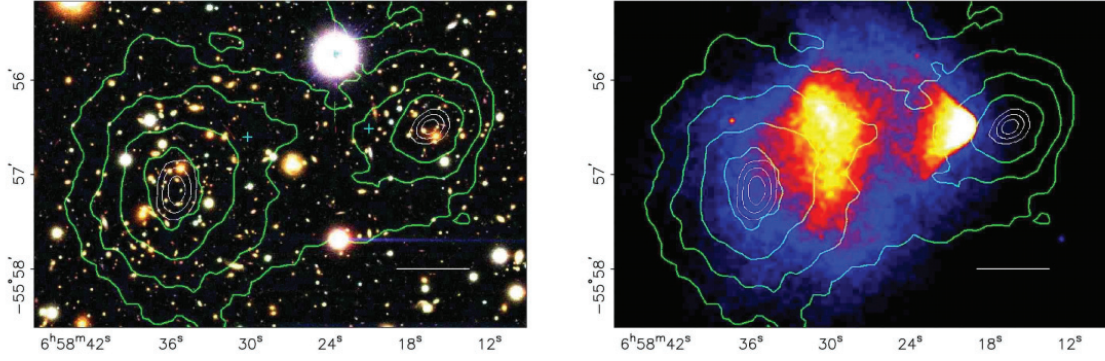


Figure 2.3: Merging Bullet cluster 1E0657-558 (Taken from: [6]) The green contours in both figure show the mass distribution known from the weak lensing effect. The color gradation in the right figure shows the distribution of X-ray emission intensity. The blue cross points, +, show the location of the centers of the plasma clouds.

Axion In quantum chromodynamics, the CP symmetry of the strong interaction is broken, while the CP symmetry is strictly preserved within experimental limits. This discrepancy is called the “strong CP problem”. To deal with this problem, a spontaneous breaking of the symmetry was introduced by Peccei and Quinn [9]. A particle derived from the symmetry breaking is the axion. Limits on the axion mass was set by observing neutrinos from supernova explosions[10]. The interaction between the axion and matter is thought to be very weak. Primakov effect, in which axions are converted into photons in a strong magnetic field, is one of the most powerful ways to observe the axion[11].

Sterile neutrino There are three type of neutrinos ν_e , ν_μ and ν_τ in the Standard Model. From the neutrino oscillation, which was observed with solar neutrinos, atmospheric neutrinos and accelerator neutrinos, these neutrinos were known to have non-zero finite mass and are mixed between themselves. Forth neutrino, called sterile neutrino, is proposed to explain LSND experiment results[12] if this neutrino has a keV-mass, sterile neutrino can be a candidate of the dark matter.

2.3 Dark matter search methods

The candidates of dark matter were reviewed in the previous section. This section describes methods to search for WIMPs, one of the most promising candidates for the dark matter. WIMPs search methods are classified into three types: direct search experiments, indirect search experiments and accelerator experiments. A diagram for these experiments is shown in Figure 2.4. χ represents a WIMP, q represents a particle in the Standard Model, and Q represents a mediator of the interaction. The reaction evolving in time is expressed as the arrow in the Feynman diagram for each method.

2.3.1 Direct dark matter searches

Direct dark matter search experiment is a method to detect interactions in which nuclei or electrons in a detector are recoiled by the dark matter. Since dark matter-derived events are considered to be very rare, it is necessary to perform these experiments in an

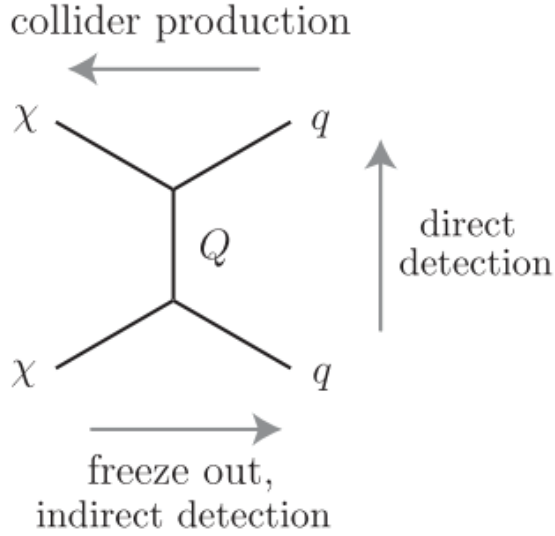


Figure 2.4: Feynman diagram of dark matter searches. χ and q represent the dark matter and a particle in the Standard Model, respectively. The arrows represent the time evolution direction of the interactions.

environment where the backgrounds, or non-dark matter events, are suppressed. Many experiments are carried in underground experiment facilities such as Kamioka Observatory in Japan, Sudbury in Canada, and Gran Sasso in Italy to avoid the effect of cosmic rays. The rock above the experiment facilities absorb the cosmic rays. The energy deposition to nuclei or electrons in the interaction with the dark matter can be detected as ionization, heat, light, and nuclear tracks. Direct dark matter search experiments aim to detect the dark matter by these signals. Some experiments are designed to distinguish the dark matter events from the background events by detecting more than one of these signals. Details on the direct search method is discussed in Section 2.4.

2.3.2 Indirect dark matter searches

The dark matter is known to form a high density region in the galactic centers and the centers of stars by gravity. Gamma-rays, neutrinos, and antiparticles may be emitted as a result of the annihilation of the dark matter in such regions. Therefore, if the dark matter annihilation occurs, there is a possibility that some particular types of cosmic ray flux shows some excess. In 2008, the Fermi satellite observed gamma-rays excess from galactic Center around 130 GeV[13] which was interpreted as a signal from the dark matter. Latest results[14], however, showed that the excess was within statistical variations; there is no evidence for the discovery of the dark matter with gamma-rays.

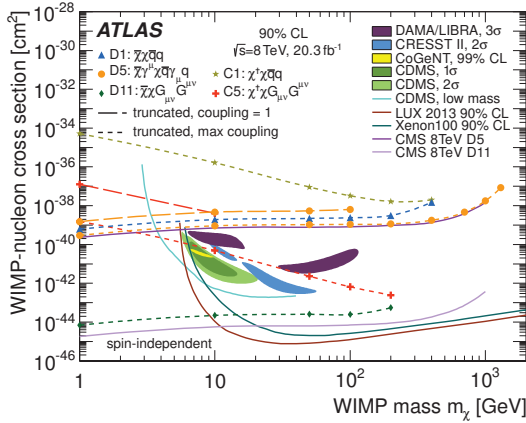
Alpha Magnetic Spectrometer (AMS-02) on the International Space Station (ISS) is an experiment that can measure the ratio of electrons to positrons using a strong magnetic field. AMS-02 observed a decrease in flux above a few hundred GeV[15] which is consistent with the dark matter model with a mass of about 1 TeV. However, this result can also be interpreted as positrons originating from pulsars and observations are being continued.

Neutrinos with an energy of about half the mass of dark matter can be produced in the final state of the dark matter annihilations. Cross section limits were set by IceCube[16]

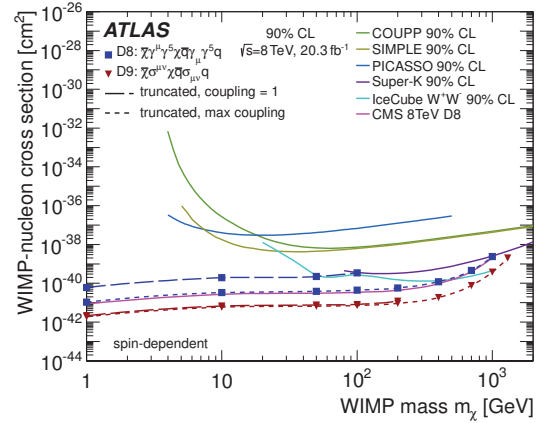
and Super-Kamiokande[17] by searching neutrinos from the Sun.

2.3.3 Collider dark matter searches

Searches for the dark matter in accelerators is performed by identifying the missing transverse energy. Dark matter searches are carried out with the Large Hadron Collider (LHC) at CERN (European Organization for Nuclear Research), by events with large missing in momentum balance of the observed final-state particles, which is an indication for production of a weakly-interacting particle. The limits of the scattering cross sections between the dark matter and nucleons obtained from ATLAS[18] and CMS[19] are shown in Figs.2.5 and 2.6, respectively.



(a) Spin-independent case



(b) Spin-dependent case

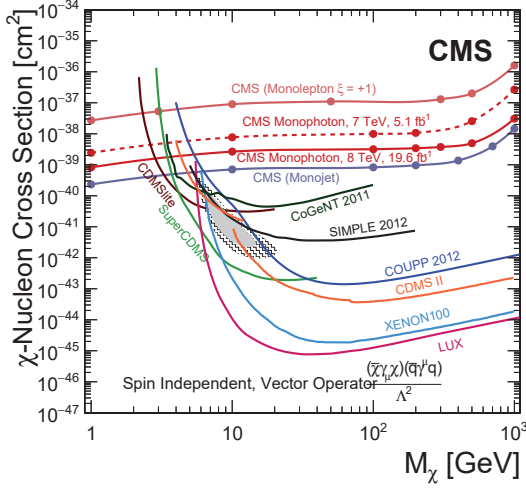
Figure 2.5: 90% C.L. limits on the (a) spin-independent and (b) spin-dependent WIMP–nucleon scattering cross section as a function of the dark matter mass m_χ from ATLAS result [18].

2.4 Direct dark matter searches

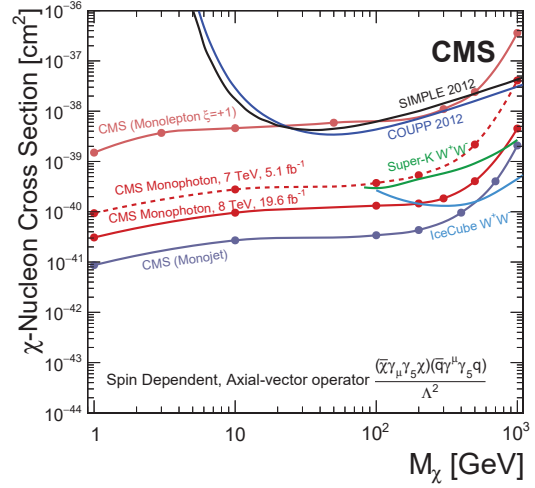
A theoretical framework and experimental approaches of the direct dark matter searches are reviewed in this section.

2.4.1 Direct dark matter search principle

The energy spectrum of the nuclear recoils by the halo dark matter can be calculated by considering the relative motion of the galactic halo and the Earth[20]. We assume WIMPs as the galactic dark matter halo. Since our solar system is moving in the galactic halo and the earth is orbiting the sun, the relative velocity of the Earth to the galactic halo varies seasonally (Figure 2.7). The energy spectrum from the interaction with the dark matter, which is expected to be observable with detectors on the earth, is also expected to have annual modulations. The relative velocity of the earth to the galactic halo can be expressed by the following:



(a) Spin-independent case



(b) Spin-dependent case

Figure 2.6: 90% upper C.L. limits on (a) the spin-independent and (b) spin-dependent χ -nucleon scattering cross section as a function of the dark matter mass M_χ from CMS result[19].

$$v_E = v_{\text{sun}} + v_{\text{orb}} \cos \theta_{\text{orb}} \sin(2\pi y) \quad (4)$$

$$\simeq 244 + 15 \sin(2\pi y) [\text{km/sec}], \quad (5)$$

where v_{sun} is the velocity of the sun relative to the galactic halo, v_{orb} is the orbital velocity of the earth orbiting the sun, $\cos \theta_{\text{orb}}$ is the cosine of the angle of the earth's orbital plane relative to the galactic plane, and y is the time in units of one year elapsed since March 2nd. In June, the direction of the solar system and the Earth's orbit are same, so that the relative velocity is maximum, while in December, the direction of the solar system and the Earth's orbit are opposite, so that the relative velocity becomes minimum.

As for determination of the energy spectrum from WIMP-nucleon interaction, the differential number density of WIMPs dn is expressed using v_E ,

$$dn = \frac{n_0}{k} f(\mathbf{v}, \mathbf{v}_E) d^3v, \quad (6)$$

$$n_0 \equiv \int_0^{v_{\text{esc}}} dn, \quad k = \int_0^{2\pi} d\phi \int_{-1}^{+1} d(\cos \theta) \int_0^{v_{\text{esc}}} f(\mathbf{v}, \mathbf{v}_E) v^2 dv,$$

where k is the normalization constant, n_0 is the mean number density of WIMPs, v_{esc} is the escape velocity of the galaxy, θ is the angle between v_E and velocity of WIMP, and ϕ is the azimuth angle from the WIMPs velocity vector.

Here, we assume that the velocity distribution of the WIMPs $f(\mathbf{v}, \mathbf{v}_E)$ follows the Boltzmann distribution in the galaxy.

$$f(\mathbf{v}, \mathbf{v}_E) = e^{-(\mathbf{v} + \mathbf{v}_E)^2 / v_0^2}, \quad (7)$$

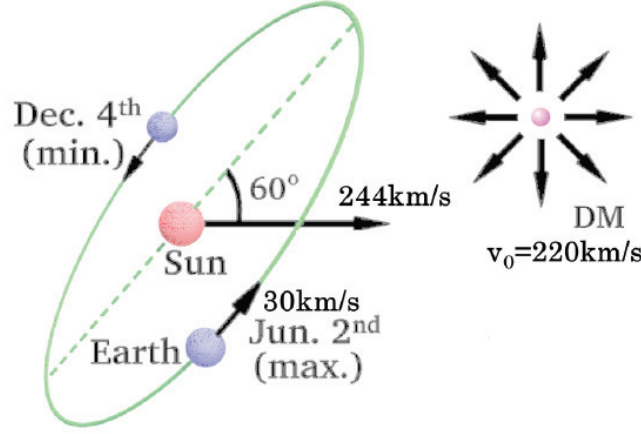


Figure 2.7: Schematic diagram of the solar system. Movements of the solar system, the Earth and DM (dark matter) are shown. The relative velocity of the Earth to the galactic halo is at its maximum on Jun. 2nd and is at its minimum on Dec. 4th.

where v_0 is the velocity dispersion of our galaxy. The normalization constant k for the case v_{esc} is infinite (k_0) and finite (k_1), respectively, are derived as,

$$k = k_0 = (\pi v_0^2)^{3/2} \quad (v_{\text{esc}} = \infty) \quad (8)$$

$$k = k_1 = k_0 \left\{ \text{erf} \left(\frac{v_{\text{esc}}}{v_0} \right) - \frac{2}{\pi^{1/2}} \frac{v_{\text{esc}}}{v_0} e^{-v_{\text{esc}}^2/v_0^2} \right\} \quad (v_{\text{esc}} \neq \infty), \quad (9)$$

where $\text{erf}(x) \equiv \frac{2}{\pi^{1/2}} \int_0^x e^{-t^2} dt$ is the error function.

When $v_E = 0$ and $v_{\text{esc}} = \infty$, the event number R_0 [$\text{kg}^{-1}\text{day}^{-1}$] is

$$R_0 = \frac{2}{\pi^{12}} \frac{N_A}{A} \frac{\rho_D}{M_D} \sigma_0 v_0 \quad (10)$$

$$= \frac{361}{M_D} M_N \left(\frac{\sigma_0}{1\text{pb}} \right) \left(\frac{\rho_0}{0.3 \text{ GeV}/c^2/\text{cm}^3} \right) \left(\frac{v_0}{220 \text{ kms}} \right), \quad (11)$$

where σ_D is the dark matter mass density, M_D is the dark matter mass, and M_N is the target nucleus mass and N_A is the Avogadro's number. The rate in Eq.(11) is normalized to $\sigma_0 = 1 \text{ pb}$, $v_0 = 220 \text{ km/s}$, and $\rho_D = 0.3 \text{ GeV}/c^2/\text{cm}^3$.

The energy spectrum of dark matter events, dR/dE_R , can be written as,

$$\begin{aligned} \frac{dR}{dE_R} &= \int_{E_{\min}}^{E_{\max}} \frac{1}{Er} dR(E) \\ &= \frac{1}{E_0 r} \int_{v_{\min}}^{v_{\max}} \frac{v_0^2}{v^2} dR(v), \end{aligned}$$

where $r = 4M_D M_N / (M_D + M_N)^2$ and $E_{\min} = E_R/r$ is the minimum WIMP kinetic energy to give the recoil energy E_R . $E_{\max}$ is the maximum kinetic energy of WIMP in the laboratory frame determined by v_{esc} and v_E . $v_{\min}, v_{\max}(=v_{\text{esc}}, \text{ here})$, are the corresponding velocities and E_0 is defined as $E_0 = \frac{1}{2} m_D v_0^2$.

The energy spectrum is obtained using Eq.(6), (7) as,

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} \frac{k_0}{k} \frac{1}{2\pi v_0^2} \int_{v_{\min}}^{v_{\max}} \frac{1}{v} f(\mathbf{v}, \mathbf{v}_E) d^3v. \quad (12)$$

From the integration of Eq.(12), the formula of energy spectra of WIMP signal are obtained as

$$\frac{dR(0, \infty)}{dE_R} = \frac{R_0}{E_0 r} e^{-E_R/E_0 r}, \quad (13)$$

$$\frac{dR(0, v_{\text{esc}})}{dE_R} = \frac{k_0}{k_1} \left[\frac{dR(0, \infty)}{dE_R} e^{-E_R/E_0 r} - \frac{R_0}{E_0 r} e^{-v_{\text{esc}}^2/v_0^2} \right], \quad (14)$$

$$\frac{dR(v_E, \infty)}{dE_R} = \frac{R_0}{E_0 r} \frac{\pi^{1/2}}{4} \frac{v_0}{v_E} \left[\text{erf} \left(\frac{v_{\text{min}} + v_E}{v_0} \right) - \text{erf} \left(\frac{v_{\text{min}} - v_E}{v_0} \right) \right], \quad (15)$$

$$\frac{dR(v_E, v_{\text{esc}})}{dE_R} = \frac{k_0}{k_1} \left[\frac{dR(v_E, \infty)}{dE_R} - \frac{R_0}{E_0 r} e^{-v_{\text{esc}}^2/v_0^2} \right]. \quad (16)$$

Scattering cross sections for dark matter and nucleus

WIMPs are thought to react with a nucleon in a nuclei in a Spin-Independent (SI) and Spin-dependent (SD) interaction, and the scattering cross section between WIMPs and nuclei is expressed as Eq.17.

$$\sigma_{\chi-N} = \sigma_{\chi-N}^{SI} + \sigma_{\chi-N}^{SD} \quad (17)$$

Spin-Independent(SI) reaction

The scattering cross section reaction is written as follows.

$$\sigma_{\chi-N}^{SI} = \frac{4\mu_{\chi-N}^2}{\pi} [Zf_p + (A-Z)f_n]^2, \quad (18)$$

where Z is the atomic number, A is the mass number, f_p and f_n are the SI couplings of the WIMP-proton and WIMP-neutron, respectively, $\mu_{\chi-N}$ is the reduced mass of the WIMP mass M_D and the nuclear mass M_N , expressed as :

$$\mu_{\chi-N} = \frac{M_D M_N}{M_D + M_N}. \quad (19)$$

In case $f_p = f_n$, we get :

$$\sigma_{\chi-N}^{SI} = \sigma_{\chi-p}^{SI} \frac{\mu_{\chi-N}^2}{\mu_{\chi-p}^2} A^2. \quad (20)$$

As can be seen in Eq.(20), nuclei with larger A are more advantageous in SI reactions.

Spin-Dependent (SD) reaction

The scattering cross section in Spin-Dependent interactions is expressed as Eq.(21).

$$\sigma_{\chi-N}^{SD} = \frac{32}{\pi} G_F^2 \mu_{\chi-N}^2 (a_p \langle S_p \rangle + a_n \langle S_n \rangle) \frac{J+1}{J} \quad (21)$$

Table 2.1: Spin J and abundance in nature for isotopes for the dark matter detectors.

Isotope	J	Abundance(%)	$\lambda^2 J(J+1)$	Unpaired nucleon
^1H	1/2	100	0.750	proton
^7Li	3/2	92.5	0.244	proton
^{11}B	3/2	80.1	0.112	proton
^{15}N	1/2	0.4	0.087	proton
^{19}F	1/2	100	0.647	proton
^{23}Na	3/2	100	0.041	proton
^{127}I	5/2	100	0.007	proton
^{133}Cs	7/2	100	0.052	proton
^3He	1/2	1.0×10^{-4}	0.928	neutron
^{17}O	5/2	0.0	0.342	neutron
^{29}Si	1/2	4.7	0.063	neutron
^{73}Ge	9/2	7.8	0.065	neutron
^{129}Xe	1/2	26.4	0.124	neutron
^{131}Xe	3/2	21.2	0.055	neutron
^{183}W	1/2	14.3	0.003	neutron

Here, G_F is the Fermi coupling constant, $\langle S_p \rangle$ and $\langle S_n \rangle$ are the spins of the proton and neutron in the nucleus, respectively, J is the total spin in the nucleus, a_p and a_n are the SD couplings of dark matter and the respective nucleons written as :

$$a_p = \sum_{q=u,d,s} \frac{\alpha_{2q}}{\sqrt{2}G_F} \Delta_q^{(p)} \quad (22)$$

$$a_n = \sum_{q=u,d,s} \frac{\alpha_{2q}}{\sqrt{2}G_F} \Delta_q^{(n)} \quad (23)$$

where $\Delta_q^{(p)}$ and $\Delta_q^{(n)}$ are the quark spins. They are calculated as $\Delta_u^{(p)} = \Delta_d^{(n)} = 0.78 \pm 0.02$, $\Delta_d^{(p)} = \Delta_u^{(n)} = -0.48 \pm 0.02$ and $\Delta_s^{(p)} = \Delta_s^{(n)} = 0.15 \pm 0.02$. Using the Lande factor $\lambda = a_p \langle S_p \rangle + a_n \langle S_n \rangle$, the scattering cross section of SD can be expressed as

$$\sigma_{\chi-N}^{\text{SD}} = \sigma_{\chi-p}^{\text{SD}} \frac{\mu_{\chi-N}^2}{\mu_{\chi-p}^2} \frac{\lambda^2 J(J+1)}{0.75} \quad (24)$$

The SD reaction occurs only with nuclei that have spin, and target nuclei with a large $\lambda^2 J(J+1)$ have large scattering cross sections in the SD reaction.

Quenching Factor

It is impossible to detect all the energy of nuclear recoil caused by the interaction of the dark matter and the nucleus. This is because even if the energy received by the nuclear recoil with the dark matter ionizes the molecules in the detector, not all of the electrons can be detected because the electrons can recombine with ions or be captured

by molecules. This effect is called “the quenching effect”. The relation between nuclear recoil energy and detected energy is expressed as follows,

$$F_q = \frac{E_{det}}{E_{tot}}, \quad (25)$$

where E_{tot} is the total nuclear recoil energy and E_{det} is the detected energy. F_q is called “Quenching Factor”. This value varies with E_{tot} and nucleus types.

Nuclear Form Factor

Nuclear Form Factor is the factor introduced to describe the spatial extent of the nucleus. The effective cross section between nucleus and the dark matter can be calculated with this factor. In the first Born approximation, the form factor is given as using Fourier transformation,

$$\begin{aligned} F(qr_n) &= \int \rho(r) \exp(i\mathbf{q} \cdot \mathbf{r}) dr \\ &= \frac{4\pi}{q} \int_0^\infty r \sin(qr) \rho(r) dr, \end{aligned}$$

where $\rho(r)$ is the density distribution of the scattering center. In the case of SI interaction, the form factor is written as

$$F(qr_n) = 3 \frac{j_1(qr_n)}{qr_n} \exp\left(-\frac{(qs)^2}{2}\right), \quad (26)$$

where $j_1(x)$ is the Bessel function $j_1(x) = (\sin x - x \cos x)/x^2$, $r_n \simeq 1.14A^{1/3}$ fm is the effective nuclear radius for this interaction and $s = 0.9$ fm is the nuclear skin thickness.

In the case of SD interaction, the form factor is written as

$$F(qr_n) = j_0(qr_n), \quad (27)$$

where $j_0(x)$ is the Bessel function $j_0(x) = \sin x/x$, $r_n \simeq 1.0A^{1/3}$ fm. There are several calculation model which can obtain the nuclear form factor, such as the Helm form or Hartree-Fock, but the differences between them are small.

Expected energy spectrum

By integrating Eq. (12), expected energy spectra can be obtained. Figure 2.8 illustrates energy spectra for some WIMP mass cases, 50, 100 and 200 GeV/c². Here, ¹⁹F is assumed as the target nuclei. WIMP-proton SD cross section with $\sigma_{\chi-N}^{SD} = 1$ pb was assumed.

As seen from Figure 2.8, because of momentum transfer between the dark matter and target nucleus when the dark matter mass is heavier the expected event rate of high energy is increased. On the other hand, when the dark matter mass is lighter the expected event rate of low energy is increased.

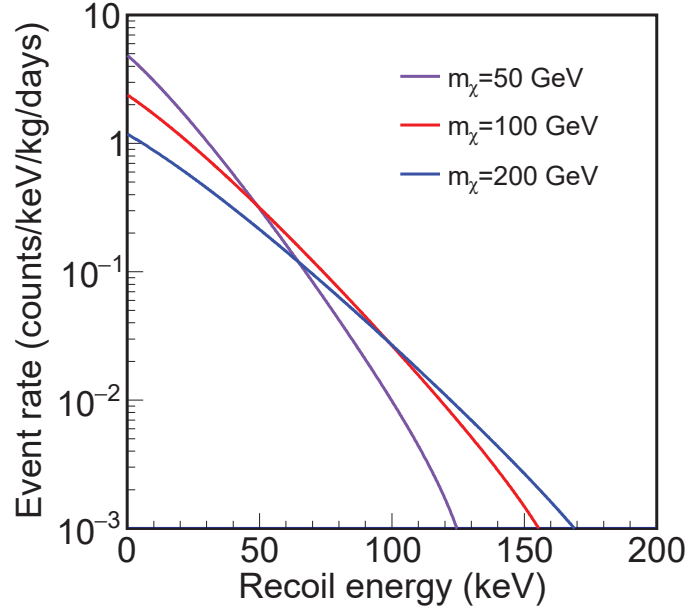


Figure 2.8: Expected energy spectrum for target ^{19}F . For the cases WIMP mass $m_\chi = 50, 100$ and $200 \text{ GeV}/c^2$ and assuming that WIMP-proton SD cross section $\sigma_{\chi-N}^{SD}$ is 1 pb.

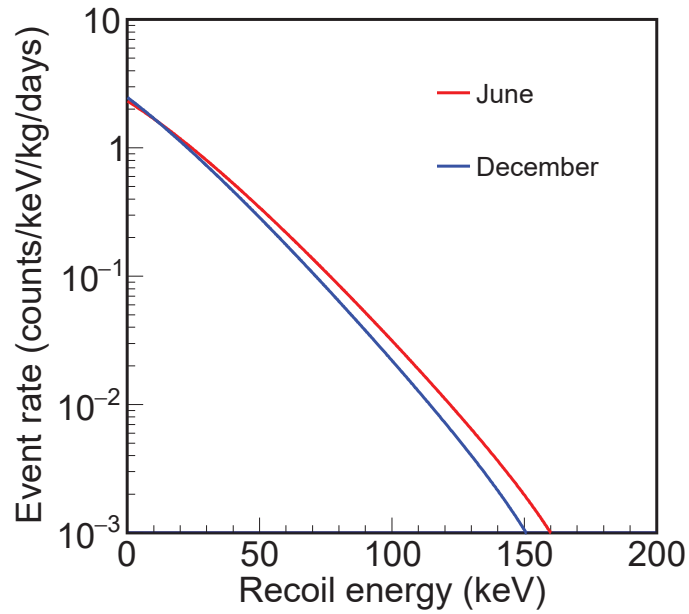


Figure 2.9: Expected energy spectrum on June and December. The target is ^{19}F , WIMP mass $m_\chi = 100 \text{ GeV}/c^2$ and WIMP-proton SD cross section $\sigma_{\chi-N}^{SD}$ is 1 pb.

2.4.2 Direct dark matter search results

Because of the Earth’s orbital motion around the sun (Figure 2.7), the velocity of the Earth to dark matter Halo in the galaxy modulates. Due to this modulation, the expected spectrum with the dark matter also modulates. This modulation signature is called “annual modulation”. The rate in a particular energy range due to this modulation is maximum on June 2nd and is minimum on December 4th. Expected energy spectra for the maximum (June) and the minimum (December) are shown in Figure 2.9. The difference between these two spectra is approximately 5 % at the maximum.

As an annual modulation dark matter search experiment, DAMA/LIBRA experiment using NaI scintillator claims the evidence of annual modulation of the dark matter[21]. With a total exposure 2.46 ton-year, an annual modulation was observed in the energy region of 2-6 keV with a confidence level of 12.9σ . On the other hand, other direct search experiments with NaI scintillator, COSINE[22] and ANAIS[23], has not found any positive signal of the dark matter in this region.

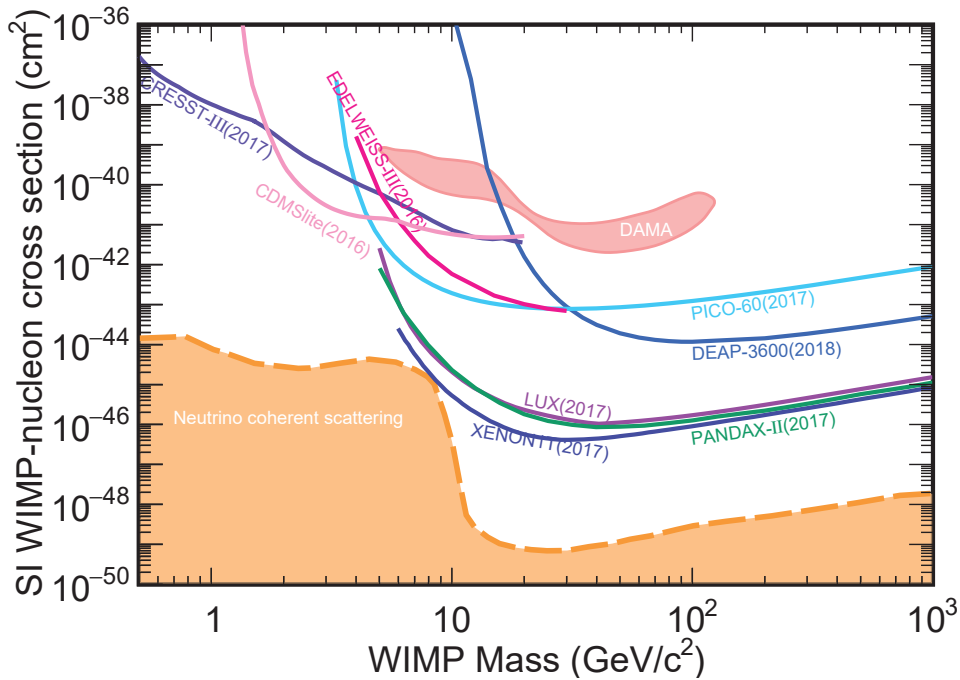


Figure 2.10: 90% C.L. upper limits of WIMP-nucleon SI cross section for some experiments[24].

For the sensitivity to the SI cross section, experiments using a dual-phase liquid xenon detector(LXe) record world leading limits, XENON1T[25], LUX[26], PANDAX-II[27] (Figure 2.10, [24]). LXe is used for sensitive material for the dark matter search for these detectors. This is because that its large atomic number and high density provides a large target mass and self-shielding from ambient backgrounds. In addition, LXe can be circulated and purified to achieve radiopurity even during the measurement. For the sensitivity of the SD (Spin-dependent) cross section, experiments using nucleus which has large $\lambda^2 J(J+1)$, for example fluorine ^{19}F has advantages. Among fluorine ^{19}F riched

detectors, PICO-60, using super heated liquid detector, set the best sensitivity limit on WIMP-proton SD cross section[28]. In the view of low mass dark matter, below 10 GeV/c², the highest sensitivity was set by experiments using bolometers. The main good feature of bolometers is the low threshold, which set best sensitivity limits on SI-WIMP cross section for low mass WIMPs. (CRESST[29], CDMS[30])

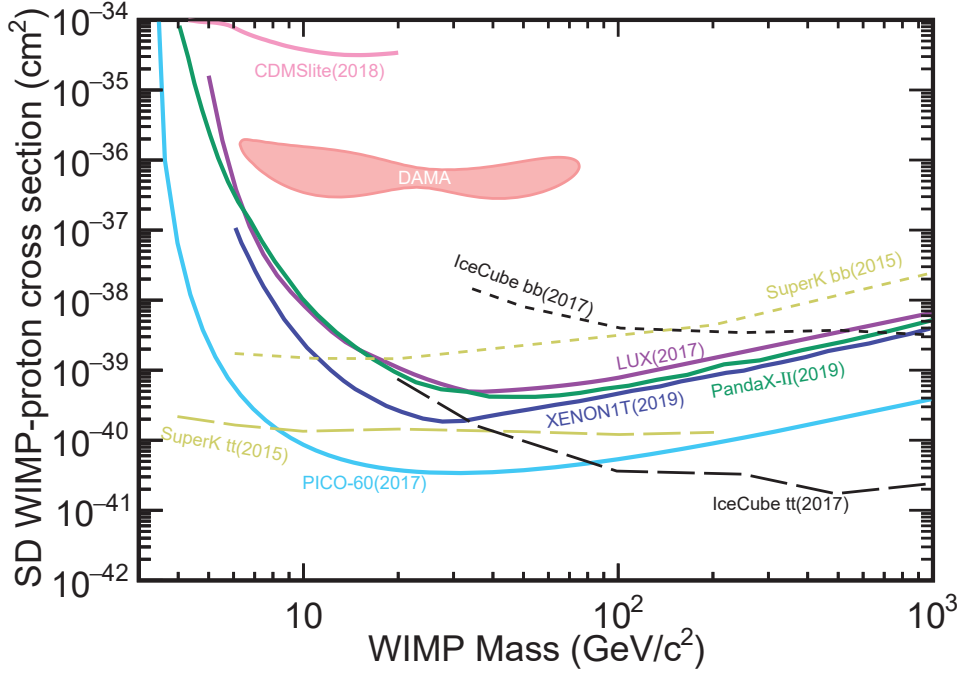


Figure 2.11: 90% C.L. upper limits of WIMP-proton Spin-dependent cross section for some experiments.[24]

2.4.3 Directional dark matter search

Our solar system moves in the direction of the Cygnus constellation. Therefore, “dark matter wind” can be seen as if they were blowing towards us from the direction of the Cygnus. The direction of Cygnus seen from detectors on the Earth varies day and night and seasonally due to the Earth’s rotation and revolution. Therefore the dark matter blowing from the Cygnus should be distinguished from the background on the Earth. While conventional dark matter search experiments have been trying to capture annual modulation of a few percent or so, directional dark matter search experiments may have enhanced sensitivity through the directional signals. This could be a more reliable evidence of direct detection of the dark matter. The angle-dependent spectrum of nuclear recoils is calculated as follows.

$$\frac{d^2 R}{dE_R d\cos\theta} \simeq \frac{1}{2} \frac{R_0}{E_0 r} \exp \left[-\frac{(v_E \cos\theta - v_{min})^2}{v_0^2} \right], \quad (28)$$

where θ is the supplementary angle between nuclear recoil direction and Cygnus direction. Dependence of the expected event rate on the angle θ and recoil energy is shown in

Figure 2.12.

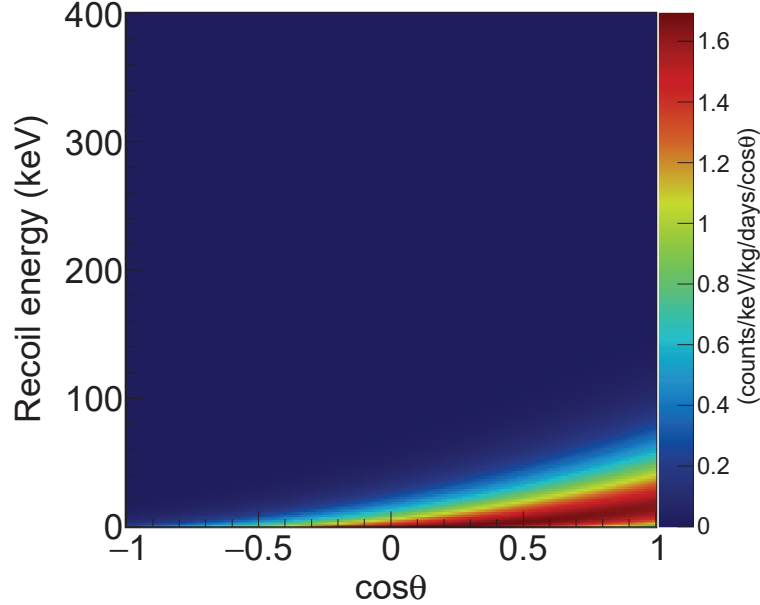


Figure 2.12: Expected energy and angular distribution from nuclear recoil with dark matter. In this plot, θ is the angle between the direction of Cygnus constellation and the incoming direction of nuclear track. The target is ^{19}F , WIMP mass $m_\chi = 100 \text{ GeV}/c^2$ and WIMP-proton SD cross section $\sigma_{\chi-N}^{SD}$ is 1 pb.

Gaseous and emulsion detectors are used as detectors for directional dark matter search experiments. The length of the nuclear recoil track caused by the dark matter is expected to be very short, *i.e.* in the gaseous detector the track will be about 1 mm for the 50 keV nuclear recoil events. DRIFT[31] and NEWAGE[32] are gaseous detector experiments. Here only DRIFT will be introduced here and the detail of NEWAGE, which this thesis is covering, will be introduced in Section 5.1. Details on the gaseous detector principle will be reviewed in Section 3.

The DRIFT experiment, at Boulby mine in UK, is the pioneer of the directional dark matter search with a large gaseous detector at low pressure and low background operation. DRIFT experiment uses MWPC (Multi-Wire Proportional Counters, reviewed in Chapter 3) with 2 mm pitch, as a readout device. Negative ion TPC, which enables to determine the z-position along the drift direction with negative ion gas, allow DRIFT to reject near-detector events. They achieved 0.28 pb at $100 \text{ GeV}/c^2$ [31] sensitivity without directional information of nuclear recoil tracks.

NEWSdm is a dark matter search experiment using newly developed emulsion detector, Nano Imaging Tracker (NIT). Since this detector has sub-micron position resolution and the target mass for dark matter can be increased. This experiment is under research and development[33].

3 Gaseous detector and TPC

We introduced gaseous detectors as one of the tracking detectors for the directional dark matter search experiments in the previous chapter. The principle and variations of gaseous detectors is described in this chapter. The principle of Time-Projection Chamber (TPC) is also described.

3.1 Physical processes

When a charged particle passes through a gas medium, it deposits the kinetic energy and creates ion-electron pairs along its trajectory. This process is called “ionization”. The number of ion-electron pairs produced by this ionization process, n , is written as follows.

$$n = \frac{E_d}{W}, \quad (29)$$

where E_d is the total energy deposition of the charged particle in the gas, W is called “W-value”, an average energy needed to make an ion-electron pair. This W-value is intrinsic to gas species; the W-values of the gases often used for gaseous detectors are summarized in Table 3.1.

Gas	Density [kg/m ³]	W-value [eV]
He	0.179	41.3
Ne	0.839	37
Ar	1.66	26
Xe	5.50	22
CH ₄	0.667	30
CF ₄	3.78	34

Table 3.1: Properties of the gases used as gaseous detector media.

The number of electrons produced by the ionization is sometimes in the order of only tens per a readout channel and they do not provide a sufficient signal to noise ratio when they are readout. Gas amplification, caused by the strong electric field formed with the fine-structured electrodes, is used to readout this small charge. This gas amplification process, called “electron avalanche”, is as follows. Electrons are accelerated by the strong electric field and collide with molecules. When the collision energy exceeds the ionization energy of the molecule, the molecule is ionized and another ion-electron pairs is created. This newly produced electron is also accelerated and ionizes other molecules. Repetitions of this process gives an exponential increase to the number of electrons. The total number of electrons $N(x)$ and increased number of electrons $dN(x)$ after passing a certain length dx can be written as

$$dN(x) = N(x)\alpha dx, \quad (30)$$

where α is the first Townsend coefficient, the numbers of ion-electron pairs generated per a unit length, expressed as a function of the electric field and gas pressure as follows:

$$\alpha = A \exp\left(-\frac{B}{E/p}\right), \quad (31)$$

where p is the gas pressure, E is the electric field and A and B are gas specific parameters. From Eq.(30), the number of electrons is known to increase exponentially along their paths and the total number of electrons can be described as follows:

$$N(x) = n_0 \exp \left(\int \alpha(x) dx \right), \quad (32)$$

where n_0 is the initial number of electrons and $\alpha(x)$ is the Townsend coefficient as a function of the electron position x . Eq.(32) can be simplified as Eq.(33) in a specific case where α is constant,

$$N(x) = n_0 \exp(\alpha x). \quad (33)$$

The number of multiplication factor M , or the gas gain, is known from Eq.(32).

$$M \equiv N(x)/n_0 = \exp \left(\int \alpha(x) dx \right). \quad (34)$$

The gas gain, expressed as Eq.(34), is one of the most important parameters that characterizes gaseous detectors. As can be inferred from Eq.(31) and Eq.(34), the gas gain depends on the electric field, the gas pressure and the gas properties (parameters A and B in Eq.(31)). Gaseous detectors are designed to form a strong electric field to obtain sufficient gas gains through the gas avalanche. A pair of anode and cathode electrodes, where in most of the cases the anode electrode has a fine structure of $O(10 \mu m)$, forms a strong electric field. The electron avalanche will occur in the strong electric field. After the electron avalanche, electrons will be collected to the anode electrodes.

3.2 Gaseous detectors

Gaseous detectors make use of electron avalanche, as described in the previous subsection. As examples of gaseous detectors, Multi Wire Proportional Counters (MWPC) and Micro Pattern Gaseous Detector (MPGDs) will be introduced in the following subsections.

3.2.1 Multi Wire Proportional Counter (MWPC)

Proportional Counter is one of the gaseous detectors composed of a cylindrical chamber and a thin anode wire. The cylindrical chamber is made of metal, such as aluminium, and this chamber is filled with noble gas, such as argon and xenon-based gas. Higher voltage, typically about 1 kV to 2 kV, than potential of the cylindrical chamber is applied to the anode wire. The electrons produced by the ionization, called primary electrons, are collected by the electric field in the chamber and multiplied by the strong electric field near the anode wire. The induced charge from this multiplied electrons can be detected by the anode wire and readout. There are two modes for this detector, proportional and Geiger mode. In the proportional mode, a moderate high voltage is applied and the number of multiplied electrons is proportional to the energy deposition. When a higher voltage than that of the proportional mode is applied, the number of electrons multiplied by the strong electric field is no longer proportional to the energy deposition, but fixed amount of charge is readout regardless of the primary number of electrons.

Multi Wire Proportional Counter (MWPC) invented by Georges Charpak[34] is a gaseous detector with multi anode wires sandwiched between two cathode. Multi anode wires are arranged in a row with few millimeter pitch (Figure 3.1). Thanks to this multi-wires arrangement, the closest wire to the track of the particle can detect the ionization when charged particle passes through the chamber and ionization occurs. From the coordinate of the wire, the position where the charged particle passed through can be determined. From this MWPC, one dimensional information of the particle can be obtained. The position resolution of MWPC is $O(1 \text{ mm})$ because the pitch of anode wires is usually $O(1 \text{ mm})$.

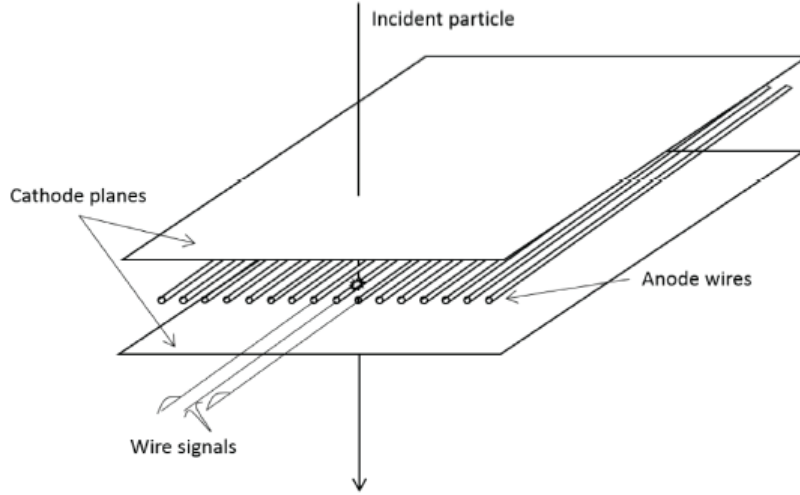


Figure 3.1: Schematic diagram of the first design of the MWPC[35]. There is a gap between two cathode and anodes wires are sandwiched. Electrons from ionization by incident particle are multiplied and readout by anode wires.

3.2.2 Micro Pattern Gaseous Detector (MPGD)

MPGD is one type of gaseous detectors produced with the micro patterning technology, such as photo-lithography and laser drilling. MPGD has fine-pitched readout ($O(100 \mu\text{m})$) in contrast to conventional gas detectors like MWPCs, $O(1 \text{ mm})$. This feature makes the detection of shorter tracks possible. MPGDs give advantages in the use as the directional dark matter search detectors in which the recoil nucleus has a track length of shorter than a few mm.

GEM (Gas Electron Multiplier) is an MPGD developed by F. Sauli[36]. Copper electrodes are formed on both sides of a thin insulator. Polyimide or liquid crystal polymer are often used as the insulator material and the thickness of the insulator varies between $50 \mu\text{m}$ to 1 mm . A number of holes with a diameter of about $70 \mu\text{m}$ to a few hundreds μm are drilled, etched or laser drilled on the GEM at regular intervals from $140 \mu\text{m}$ (shown in Figure 3.2) to 1 mm . A strong electric field is formed in the GEM hole by applying a high voltage between the electrodes as shown in Figure 3.3. An electron entering the hole undergoes a gas avalanche. Because of their hole structure, the GEMs can be stacked in multiple stages, which relax the gain per GEM layer to suppress discharge probabilities and ensure a stable operation. GEM can also be used as a pre-amplifier for other MPGDs.

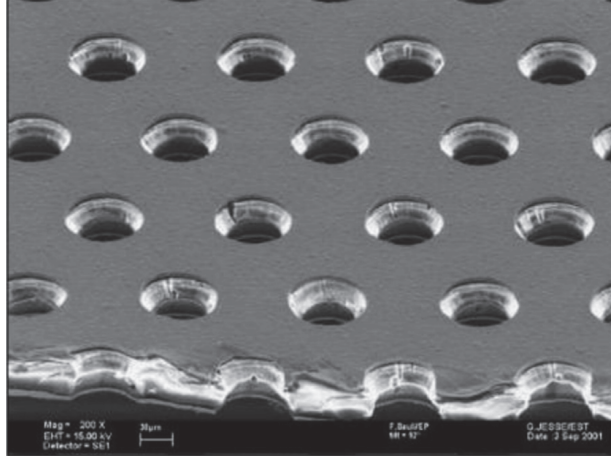


Figure 3.2: Microscope photo of a GEM [37]. The hole diameter of this GEM is $70\ \mu\text{m}$ and the pitch between holes is $140\ \mu\text{m}$.

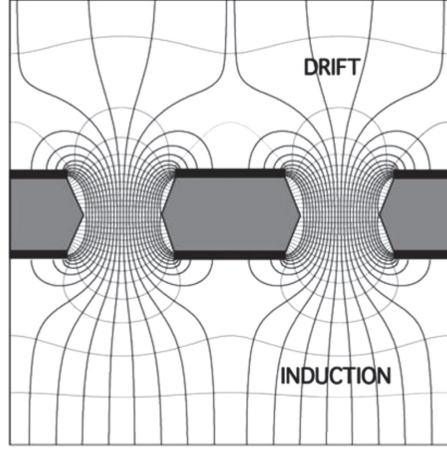


Figure 3.3: Cross section image of a GEM, electric force lines, and electric field lines in GEM[37]

Micro-mesh gaseous structure (MicroMegas) was developed by Y. Giomataris[38]. It consists of a readout electrode, a metal micromesh located 50 to $150\ \mu\text{m}$ above the electrode, and pillars supporting the mesh (Figure 3.4). The principle is that primary electrons are amplified by the strong electric field between the mesh and the electrode, and the electrons are readout by the electrode.

Micro Pixel Chamber (μ -PIC) was developed by A. Ochi and T. Tanimori.[39]. A schematic view of the μ -PIC is shown in Figure 3.5. A μ -PIC has a number of circular-shaped anode electrodes with a diameter of tens of μm . Each anode electrode is surrounded by a circular-shaped cathode electrode. Anode and cathode electrodes are connected to anode and cathode strips, respectively. Anode strips and cathode ones are built orthogonally to each other on the back-side and top-side of the insulator, respectively. Figure 3.5 shows standard dimensions of the μ -PIC; the diameter of the anode electrodes is $50\ \mu\text{m}$ and the diameter of the cathodes is $250\ \mu\text{m}$. The pitch between anodes is $400\ \mu\text{m}$. Primary electrons undergo electron avalanche amplification by the strong electric

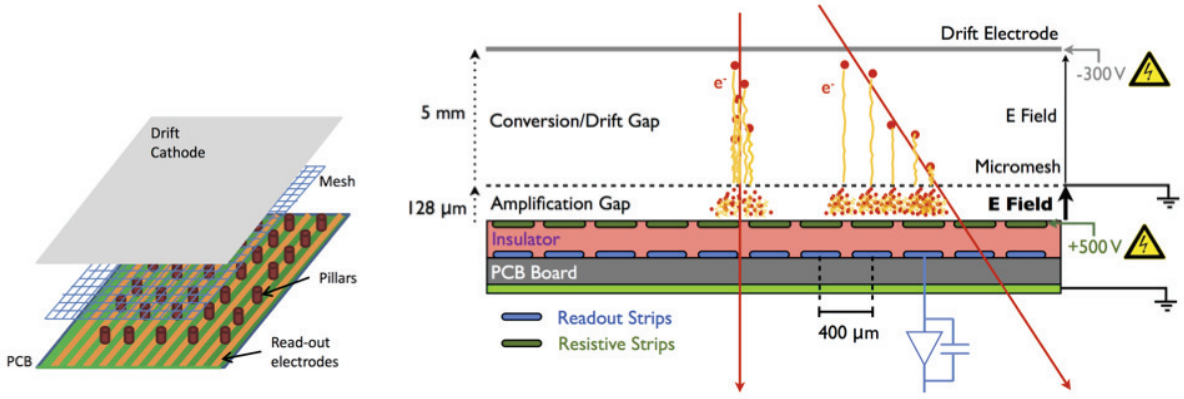


Figure 3.4: MicroMegas schematic diagram[37]

field in the vicinity of the anodes. Induced electric charge is readout by anode and cathode as forms of electrons. A position of each event on the detector can be reconstructed by taking the coincidence of the anode and cathode signals at the same time.

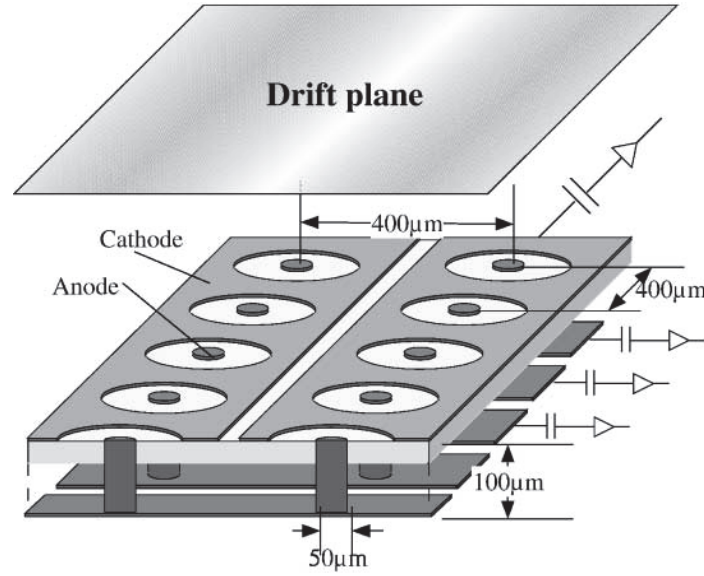


Figure 3.5: Schematic diagram of a μ -PIC [39]

3.3 Gaseous Time Projection Chambers (TPCs)

Time Projection Chamber (TPC) is an instrument that can detect three-dimensional tracks of charged particles. This concept was invented by David Nygren[40]. TPC consists of rectangular or cylindrical field cage filed with gas or liquid and a two-dimensional readout detector in general. An electric field is formed by the field cage and electrons or ions move (“drift”) toward the readout detector following the electric field. When the charged particles passes though the TPC, these particles produce tracks of electrons from ionization and these electrons are drifted toward readout detector. The drifted electrons

are multiplied and readout by the detector and the two-dimensional track of the charged particle can be obtained. The other coordinate of the event can be calculated from the arrival time and drift velocity of the electrons. The typical schematic diagram of the gaseous TPC is shown in Figure 3.6. If there is an external trigger and the time when the event occurred can be determined, the absolute coordinate of the event from the readout detector can be determined. But if there is no external trigger, relative time and coordinate deference within the track can be obtained. For high energy physics experiments, gaseous TPC with a magnetic field is often used. In this configuration, particle can be identified with the combination of dE/dX (energy deposit per track length) and momentum from curvature radius.

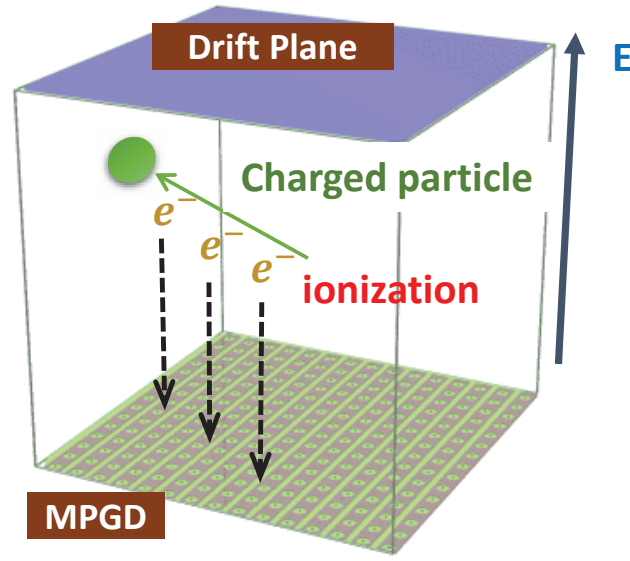


Figure 3.6: Schematic diagram of a TPC. When a charged particle pass though, electrons-ions pairs are created (ionization). The electrons are drifted by electric field towards the readout detector.

Gaseous TPC is used for directional dark matter searches, such as NEWAGE[32]. This is because that the TPC can detect three-dimensional tracks of the charged particles, or nuclear recoils by the dark matter. Detail on the NEWAGE will be described in Section 5.1. Gaseous TPCs have advantages of obtaining the event time information in contrast to nuclear emulsions which accumulate events and have no time information to individual events. By these features, the combined analysis with the direction of obtained track event and the moving direction of the Earth can be performed for directional dark matter search, introduced in Section 2.4.3.

3.4 Low background MPGDs

Low radioactivity is one of the most important requirements for the detector to be used in rare event search experiments, such as dark matter searches. Radioactive isotopes in uranium and thorium chains shown in Figure.9.1 are well-known background sources.

The half-lives of ^{238}U and ^{232}Th are 4.468×10^9 years and 1.405×10^{10} years, respectively. These half-lives are so long that isotopes and their progenies can be background sources over a long period once contaminate in the detector materials. Isotopes in these chains decay with emissions of alpha-rays, beta-rays and gamma-rays. These radiations can be the sources of background events. Not only direct emission of radiation, radon emanation as a form of gas from the detector material is also one of the serious background sources. Radon isotopes of ^{222}Rn and ^{220}Rn are the progenies of ^{238}U and ^{232}Th , respectively. These isotopes decay in the detector volume and make background events. Progenies of radons can attach to the detector and radiation from them could also be background events. Details on the radon emanation will be discussed in section 6.5.

Several groups developed low background MPGDs through material screenings because this can be a persistent background source once the detector with radioactive contamination is installed in TPC. A low background MicroMegas was developed for TREX-DM[41], dark matter search experiment with a gaseous detector. A low background Microbulk MicroMegas was also developed for CAST[42]. A low alpha-ray emission μ -PIC has been developed for NEWAGE[43]. Details on material screening for NEWAGE experiment is described in section 4 and 5.1. In this thesis, a development of a low background μ -PIC, LBG μ -PIC, and expected improvement of NEWAGE sensitivity with the LBG μ -PIC will be described and discussed.

4 Low radioactivity measurement

Detectors for low radioactivity measurements, HPGe detectors, surface alpha-ray counters and radon detectors, are reviewed in this chapter. These methods were used for the material screening and radon emanation measurement for the LBG μ -PIC development discussed in Chapter 6.

4.1 Motivation of low radioactivity measurement

Expected count rates from physics targets, or the signals, are low in rare event search experiments, *e.g.* dark matter searches, neutrinoless double beta decay searches etc. From this point of view, it is required to maintain low background condition of the detector over a long period. Backgrounds mainly originate from radioactive isotopes contaminated in the detector material, materials in the laboratory environment, and the surrounding rocks. Isotopes with long half-lives, ^{238}U and ^{232}Th and their progenies (U/th-chains, Figure 9.1), ^{40}K , and ^{60}Co are well-known background sources. To achieve a low background condition, materials with extremely low radioactivities should be selected as the detector components. HPGe detectors, surface alpha-ray counters and radon detectors are often used for the material screening. These detectors and material screening method for the LBG μ -PIC development is reviewed in the following sections.

4.2 HPGe detector

High Purity Germanium (HPGe) detector is a semiconductor detector used to measure gamma-rays with high energy resolutions $O(1\text{ keV})$. Because of its high energy resolution, HPGe detectors are used for a precise measurement of U/Th-chain contaminations in samples by detecting gamma-ray emissions. An example of energy spectrum with a HPGe detector is shown in Figure 4.1.

The HPGe detectors we used in this study were at the Kamioka Observatory in Kamioka Mine under Mt. Ikenoyama, at 2700 m water equivalent underground. These detectors were manufactured by CANBERRA. In this study, both p-type and n-type HPGe detectors were used. Sample volume of the HPGe detector were cylindrical and their diameter and height were roughly 15 cm and 17 cm. The sample volume was surrounded by 17.5 cm thickness of lead and 5 cm thickness of copper to shield gamma-rays and beta-rays from outside. To suppress the backgrounds from radon, the sample area was continuously flushed with radon free air, which has less than a few tens of mBq/m³ radon. The detector head was cooled by liquid nitrogen (LN₂) to reduce the thermal noise.

Sample measurement

The following preparation was made for the sample measurement of the μ -PIC components with the HPGe detector. The sample, for example sheet-like one, was cut into $5 \times 5\text{ cm}^2$ square size of pieces to fit in the sample volume. These pieces were stacked and packed in an EVOH (ethylene-vinylalcohol copolymer) bag and the inside of the bag was purged with pure air to reduce the residual radon gas. EVOH is a high barrier plastic material to protect the samples from the radioactive radon isotopes in the room air. The sample

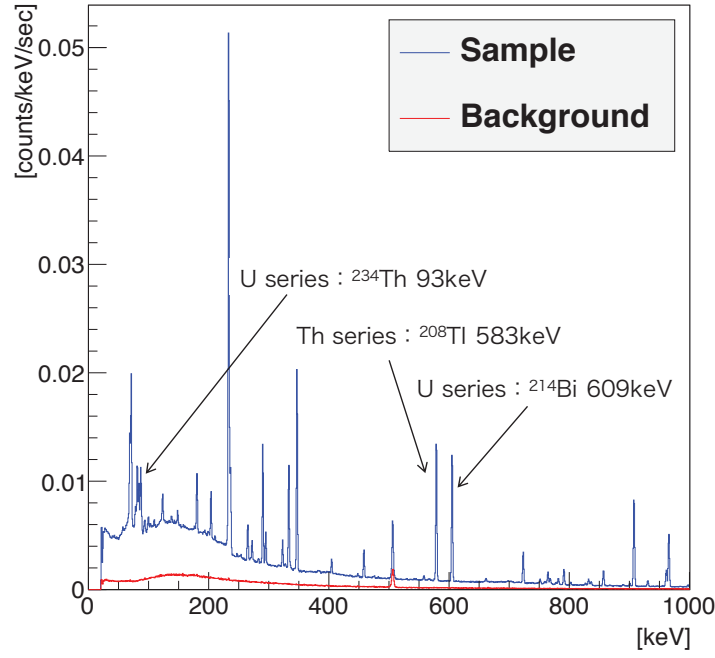


Figure 4.1: An example of measured energy spectrum of a sample (old μ -PIC core material ([44])). The energy peaks are of the gamma-rays from U/Th-chains in the sample.

was then placed in the sample volume and the gamma-rays from the radio-impurities in the sample were measured.

One of the measured energy spectra of an old μ -PIC core with the HPGe detector is shown in Figure 4.1. The blue line shows an energy spectrum of gamma-rays from the sample and the red one shows a background energy spectrum. In this histogram, we can see some peaks in the sample spectrum corresponding to gamma-ray peaks from U/Th-chain contaminations in the sample. We can obtain the amount of radioactive impurities in the sample from the count rates and detection efficiencies of the gamma-rays at the peak energies and branching ratio of the gamma-rays. Uranium chain is often treated as three parts; upper, middle, and lower streams. The upper stream is the series of decay chain from ^{238}U to ^{234}U . The middle one is the series of decay chain from ^{230}U to ^{214}Po or ^{210}Tl . Because ^{226}Ra and ^{210}Pb have relatively longer half-lives than the isotopes of their upper or lower streams nuclides, radioactive equilibriums can be broken at ^{226}Ra and ^{210}Pb . Therefore, both radioactivities in the uranium upper and middle streams need to be measured separately to check the radioactive equilibrium. For the analysis of U/Th-chains impurities, the 93 keV line from the ^{234}Th decay in uranium upper stream, the 609 keV line from the ^{214}Bi for uranium middle stream and the 583 keV line from ^{208}Tl for thorium chain were used.

Table 4.1 summarizes the energies and branching ratios of these isotopes. To analyze U/Th-chain impurities, we subtract background spectrum from the sample measurement and use this net spectrum for analysis. Peaks in the net spectrum were fitted with Gaussian distributions and we can obtain a count rate S [count/sec] from obtained parameters.

A radioactivity of R_i corresponding to the rate S can be calculated as follows,

$$R_i = \frac{S}{B_i \times \epsilon_i}, \quad (35)$$

where B_i is the branching ratio of the gamma-ray emission and ϵ_i is the gamma-ray detection efficiency of the HPGe detector. The detection efficiency was calculated with a Monte Carlo simulation using Geant4, a simulation toolkit for radioactivity and its reaction with material. Material components and shape of each sample were implemented in the simulation geometry and physics interactions between detector material and radiation were simulated and tracked using Geant4. We commonly showed the results as the

Series	Isotopes	gamma-ray energy [keV]	B_i [%]
^{238}U upper stream	^{234}Th	93	5.4
^{238}U middle stream	^{214}Bi	609	46.1
^{232}Th	^{208}Tl	583	84.5

Table 4.1: Energies and branching ratios of the isotopes used for the determination of radioactive of impurities.

contaminations equivalent to ^{238}U or ^{232}Th assuming the radioactive equilibrium. In this condition, U/Th chain contamination content X can be obtained as follows,

$$X = \frac{1}{M_s} \frac{A}{N_A} N_0 \quad (36)$$

$$N_0 = \frac{R}{\lambda} \quad (37)$$

$$\lambda = \frac{\ln 2}{T_{1/2}}, \quad (38)$$

where M_s is the mass of the sample, A is the atomic number of the isotope, N_A is Avogadro's number, N_0 is the number of the atoms, R is the radioactivity, λ is the decay constant of the isotope and $T_{1/2}$ is the half-life of ^{238}U or ^{232}Th .

4.3 Surface alpha-ray counter

Surface alpha-rays are the alpha-ray backgrounds from the detector material facing the gas detection volume. In particular, ^{210}Pb and ^{210}Po in the uranium chain are of the great importance. Ultra-Lo 1800 (XIA Inc.)[\[45\]](#)[\[46\]](#)[\[47\]](#)[\[48\]](#) is an alpha-ray counter used for measurements of alpha-ray emission rates from the surface. Ultra-Lo 1800 is an ion chamber which can measure the induced charge from ions and electrons created by an alpha-ray. The detection area is a circle with a diameter of 30 cm and events from outside this area will be rejected by a surrounding veto counter. The achievable background rate of the Ultra-Lo 1800 is about $10^{-5} \alpha/\text{cm}^2/\text{hr}$. The Ultra-Lo 1800 used in this study was located at the Kamioka Observatory in Kamioka Mine, where cosmogenic backgrounds was negligible.

The main component of the surface alpha-ray is 5.3 MeV alpha-rays from ^{210}Po decay. The main origins of this surface alpha-ray is uranium progenies embedded on the material

surface by ^{222}Rn decays. The component of the energy range between $2.5 < E < 4.8$ MeV is categorized as “bulk” alpha-rays and the energy range between $4.8 < E < 5.8$ MeV is categorized as surface alpha-rays. Alpha-rays from inner volume of the material deposit more energies in the material than those from the surface of the material. Using this feature, whether radioactive contamination is on surface or inside of material can be determined by measured alpha-ray energy spectrum. We used the low background technology established by XMASS group to measure surface alpha-ray with Ultra-Lo 1800[49].

Sample measurement procedure

The candidate materials is packed in an EVOH bag with pure air in order to protect the surface from contamination and radon progeny implantations prior to the measurement. The sample was then transported to Kamioka Observatory. The sample was taken out of the bag and placed on the Ultra-Lo sample holder. The detector was purged with argon gas for 90 minutes to lower the humidity and flush out the radon contamination. To avoid the effect of humidity and radon background and unstable of gas humidity, the first-day data was excluded from the analysis.

4.4 Radon detector

Radioactive noble gas radon (^{222}Rn and ^{220}Rn) are well-known serious background sources for many rare event search experiments. Radon concentration in air, water and noble gases are measured with radon detectors. Radon detectors with electrostatic collection method are widely used (e.g. in Super-Kamiokande[50]). Radon emanation rate, the emission rate of radon into gas from the materials, should be reduced for low background experiments and it is important to measure the rate. The detection principle of the electrostatic method and radon emanation rate in this work is described in the following subsections.

4.4.1 Radon measurement

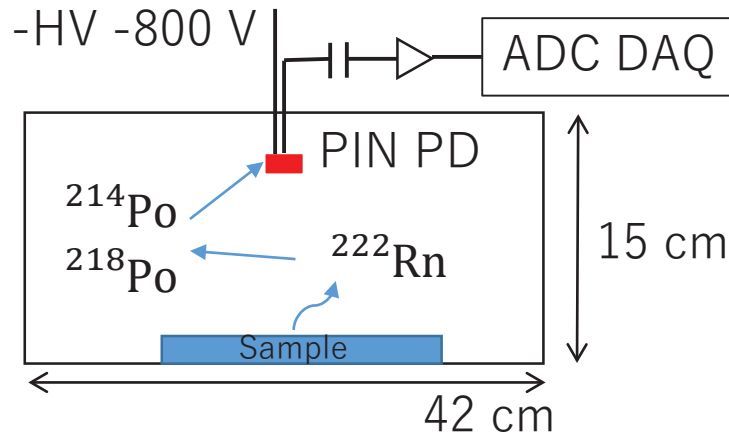


Figure 4.2: Radon detector schematic diagram. Red square is the PIN Photo diode, and blue one is the sample.

The principle of the radon concentration measurement with a radon detector is as follows. Isotopes of polonium, ^{218}Po and ^{214}Po , are in the uranium chain and have approximately 90 % chance to be positively-charged when they are produced. In the electrostatic collection method, a PIN Photo Diode (PIN: p-i-n junction, intrinsic silicon is introduced between p and n layer. Hereafter, PIN-PD) in the detector is biased at a negative high voltage and the detector vessel is grounded. These positive polonium ions are collected by the electric field and attach to the PIN-PD (red box in Figure 4.2). Alpha-rays from the decay of these polonium isotopes will be detected with the PIN-PD. Schematic diagram of these processes are shown in Figure 4.2. Since a radioactive equilibrium will be established between ^{214}Po and ^{222}Rn because of their half-lives, the count rate of ^{214}Po decay correspond to the ^{222}Rn concentration. Calibration Factor is a conversion factor from the count rate of ^{214}Po into the ^{222}Rn concentration, which is described in section 4.4.3 later. From the count rate of the decay of polonium ion at PIN-PD and the Calibration Factor, we can obtain the radon concentration in the gas. An example of alpha-rays spectra from radon progenies is shown in Figure 4.4. The count rate within the “signal region” is used for the ^{214}Po count rate.

The polonium ions, $^{218}\text{Po}^+$ and $^{214}\text{Po}^+$, can be neutralized in a gas and its probability strongly depends on the humidity in the gas. Since the detection efficiency of polonium ions is dropped when the humidity is high, it is important to check the humidity in the gas and keep the humidity low to maintain the detection efficiency. For the radon measurement, the count rate for ^{214}Po , not ^{218}Po , is generally used. There are several reasons for this. First, alpha-ray energy emitted from ^{218}Po (6.003 MeV) is very close to that from ^{212}Bi (6.051 MeV, isotope in the thorium chain) and these energy values are possibly indistinguishable with the PIN-PD energy resolution. Second, as can be seen from the decay chain of uranium9.1, count rate of alpha-ray from ^{214}Po is the sum of collected ions in the form of $^{218}\text{Po}^+$ and $^{214}\text{Po}^+$. So the detection efficiency of ^{214}Po is generally higher than that of ^{218}Po . Finally, $^{218}\text{Po}^+$ can be neutralized in the vessel but when ^{214}Po is produced it has another chance to be positive ion and can be collected to PIN-PD by the electric field. These are the reasons that the alpha-rays count rate of ^{214}Po is higher than that of ^{218}Po , as will be shown in Figure 4.4.

The radon emanation rate for a material is the rate that the produced radon can escape from the material. A radioactivity of ^{222}Rn in a detector will be the same as a radon emanation rate from ^{226}Ra in a sample because that half-life of ^{226}Rn (1.6×10^3 years) is much longer than that of ^{222}Rn (3.82 days) and a radioactive equilibrium will be established between them in the vessel in few weeks. Therefore we can obtain a radon emanation rate from ^{226}Ra in the detector using ^{222}Rn concentration in the detector.

4.4.2 Detector setup

A radon detector was newly developed at Kobe University for the radon emanation measurement in this study. The schematic drawings and the photograph of the detector are shown in Figures 4.2 and 4.3, respectively. The detector has a sample volume of $42 \times 42 \times 15 \text{ cm}^3$ (27 L), which is large enough to measure the μ -PICs with a size of $41 \times 41 \text{ cm}^2$, including the relay board. The vessel is made of SUS304 and its inner surface was electropolished. A windowless PIN-PD, Hamamatsu S3590-09, was used and located 5 cm below the top of the vessel. No window type PIN-PD was selected to measure the alpha-ray energy precisely without any energy loss at the window.

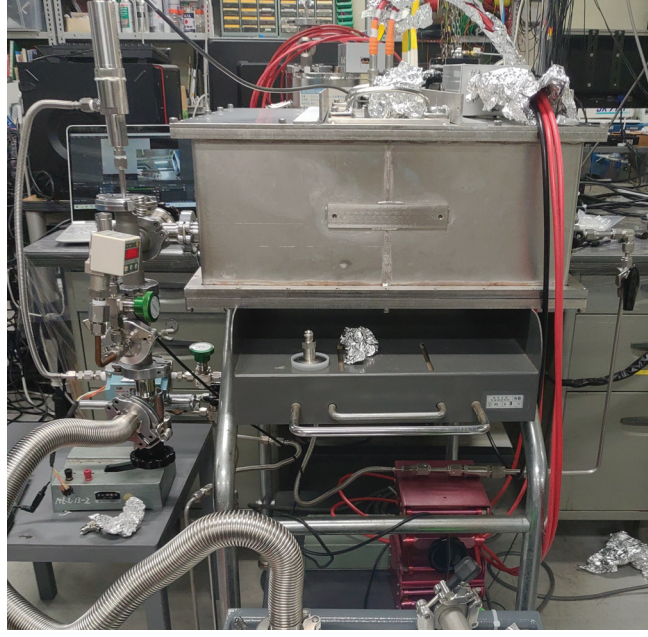


Figure 4.3: Radon detector setup at Kobe University.

Charges from the PIN-PD was read by a charge-sensitive amplifier, CS-515 (CLEAR-PULSE CO., LTD.), then amplified and shaped with $2 \times$ LF356 op-amps (Texas Instruments Inc.). The output signal of the amplifier was digitized and recorded with an waveform digitizer ADALM2000 (Analog Devices Inc., 2ch 12 bit ADC digitizer, ± 2.5 V input range) and a multi-channel-analyzer, MCA8000D (Amptek Inc., Multi Channel Analyzer), was used in the in radon source calibration. ADALM2000 was connected to a Raspberry Pi 4B, one of the single board computers with Raspberry Pi OS (Linux based OS). The MCA8000D was read with a Windows PC and only the pulse height from the waveforms was recorded. Detail of the detector calibration is described in Section 4.4.3.

The procedure of the radon emanation measurement is as follows. Wipe the inside of the radon detector carefully and set a sample material in the detector. Evacuate the vessel with a turbomolecular pump down to 1 Pa and fill with pure air. Set the pressure inside the detector to 800 Torr, 5% higher than the atmospheric. The pressure of the whole system was monitored with a pressure gauge (GC-61, Nagano). The bias high voltage was supplied and DAQ was started to count ^{214}Po decays. Instruments used for this radon detector were summarized in Table 4.2.

After the radon emanation measurement, usually for a few weeks, the count rate histogram over the measurement duration was fitted with a function,

$$C = A \times (1 - 2^{-x/T}) \quad (39)$$

where C is the count rate of detected events, A is a constant rate when radioactive equilibrium is established. x is the elapsed time in days since the detector was filled with pure air. $T = 3.82$ is the half-life of ^{222}Rn in days. The radon emanation rate from the sample material can be calculated with a calibration factor and the decay rate of ^{214}Po , as described in the previous subsection.

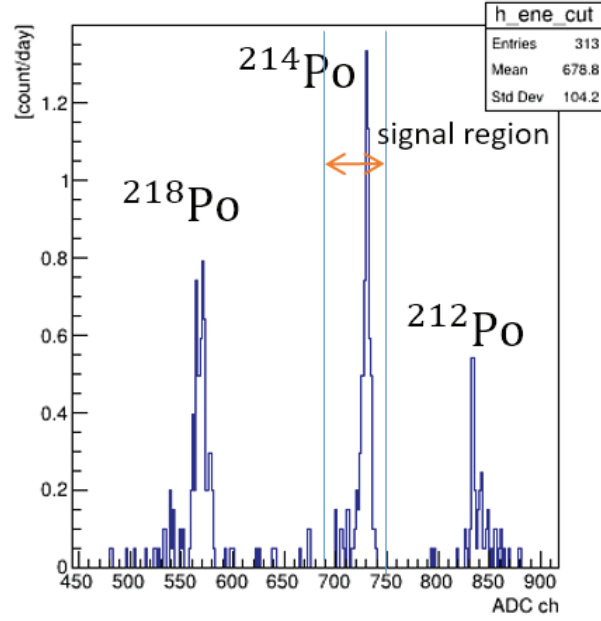


Figure 4.4: Alpha-ray energy spectrum of radon progeny decays obtained with the radon detector for a sample measurement. ADC value region between 690 and 750 events were counted as ^{214}Po signal in this measurement.

4.4.3 Detector calibration

The detector was calibrated for its detection efficiency of polonium ions. The result of the calibration is expressed in terms of “Calibration Factor” (CF), which converts from the count rate of ^{214}Po ([count/day]) to the radon concentration ([mBq/m³]). Its humidity dependence for a given gas is important to measure. A setup diagram for the calibration is shown in Figure 4.5. A radon source of ^{226}Ra (PYLON RNC) with a known activity (78.3 Bq) was set in the loop and used as the radon source. The absolute humidity in the gas was monitored with a dew point meter, DMT152 (Vaisala Inc.). The absolute humidity was controlled by changing the flow rate through MS4A type molecular sieve (Molecular Sieve Tube in the Figure 4.5). The MS4A type molecular sieve does not absorb radon atoms because its pore size is smaller than radon atoms but catch water molecules because its pore size is larger than water molecules. No relation between flow rate through the molecular sieve and the ^{214}Po count rate was observed.

CF is obtained from the following equations.

$$\text{Calibration Factor}(CF) = \frac{^{214}\text{Po count rate}[\text{count/day}]}{^{222}\text{Rn concentration}[\text{mBq/m}^3]} \quad (40)$$

$$= \frac{^{214}\text{Po count rate}[\text{count/day}]}{^{226}\text{Ra source radioactivity}[\text{mBq}]/(\text{Volume}[\text{m}^3])} \quad (41)$$

The method to obtain this Calibration Factor in the following manner. Wipe the inside of the radon detector carefully in the same way as sample measurement, and set up the calibration system as shown in Figure 4.5. A ^{226}Ra source (PYLON RNC) can be used only under atmospheric pressure. Except the ^{226}Ra source, set the all valves and the bypass line open and evacuate the whole calibration system with a turbomolecular

pump down to 1 Pa and fill with pure air (G1 grade). The pressure inside the detector was set to 800 Torr, 5% higher than the atmospheric. The pressure of the whole system was monitored with a pressure gauge (GC-61, Nagano). Start the circulation pump with flow rate at 500 mL to circulate the gas in the system. The dew point, flow rate and gas pressure were monitored by slow monitor system on Raspberry Pi with ADS1115 ADC system and these values were recorded in a database for check and visualization. The bias high voltage was supplied and DAQ was started to count ^{214}Po decays. Open the valves of ^{226}Ra source and start the circulation pump to pass the gas through circulation line. ^{222}Rn from the ^{226}Ra source will be circulated in the line. About a week later, a radioactive equilibrium is reached in the calibration system and ^{222}Rn radioactivity in the calibration system is equal to a radioactivity of ^{226}Ra source specification. From this radon radioactivity and the detector volume, the radon concentration can be obtained. With the ^{214}Po count rate, calibration factor CF can be obtained from Eq.(41)

Absolute humidity can be controlled by changing the flow rate through the molecular sieve tube when the valves of molecular sieve tube are opened. The absolute humidity dependence on the calibration factor can be obtained by changing the absolute humidity like this way.

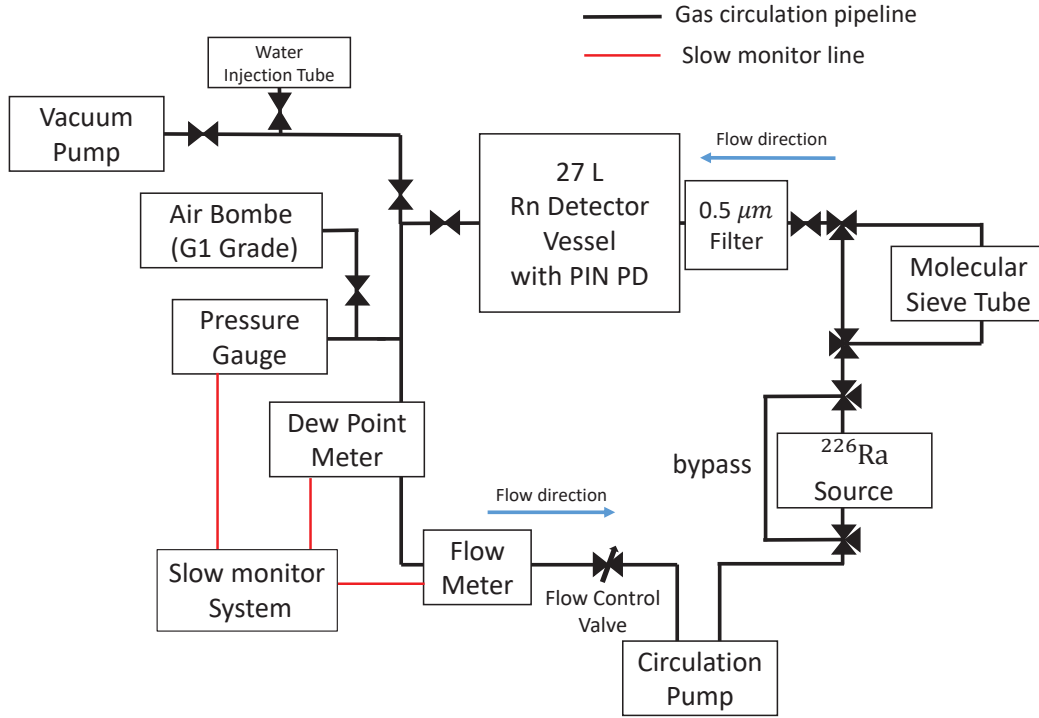


Figure 4.5: A gas circulation diagram of the calibration system.

Results of the calibration is shown in Figure 4.8. Systematic error of this calibration is summarized in Table 4.3. From this calibration result, calibration factor at some values of absolute humidity was obtained but no significant absolute humidity dependence was observed in this calibration procedure. The reason is thought to be that the distance between the PIN-PD and polonium ions (maximum: to the vessel bottom) was too short to neutralize the ions in the gas.

In radon emanation measurement of samples, discussed in later section, this calibration factor without any dependence of absolute humidity was used for the count rate

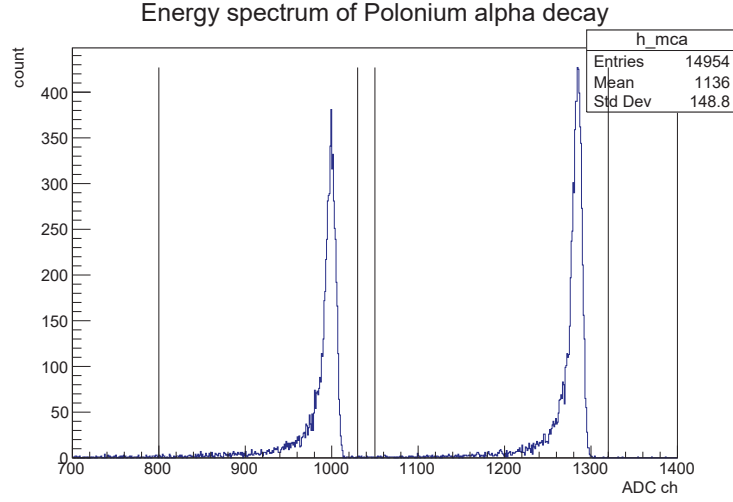


Figure 4.6: Energy spectrum obtained with the calibration. Events with ADC channel between 800 and 1030 were taken as ^{218}Po alpha-rays and those with ADC channel between 1050 and 1320 were taken as ^{214}Po alpha-rays. This ^{214}Po count rate was used for the radon detector calibration.

Instruments (name in Fig.4.5)	Manufacturer	Type
Pressure Gauge	Nagano	GC61
Dew point meter	Vaisala	DMT152
Flow meter	azbil	CMS9500BSRN200000
Circulation Pump	Enomoto	MX-808ST-S
PIN Photo diode	Hamamatsu	S3590-9

Table 4.2: Summary of instruments for radon calibration and measurement

Table 4.3: Systematic error components of Calibration Factor

Component	Error
The radioactivity of the Radon source error[51]	$\pm 5\%$
Dew point meter error	$\pm 2\%$
Volume error of total system	$\pm 2\%$
Total	$\pm 6\%$

comparison.

Ideal calibration factor and measured calibration factor

From the calibration source radio activity, the vessel volume and Eq.(41), an ideal calibration factor (CF_{ideal}) of the radon detector can be obtained as Eq.(43).

$$CF_{\text{ideal}} = \frac{50\% \times 90\% \times 78.3\text{Bq} \times (24 \times 60 \times 60)}{(78.3 \times 10^3\text{Bq})/(27.3/1000[\text{m}^3])} \quad (42)$$

$$\simeq 1.1[(\text{count}/\text{day})/(\text{mBq}/\text{m}^3)] \quad (43)$$

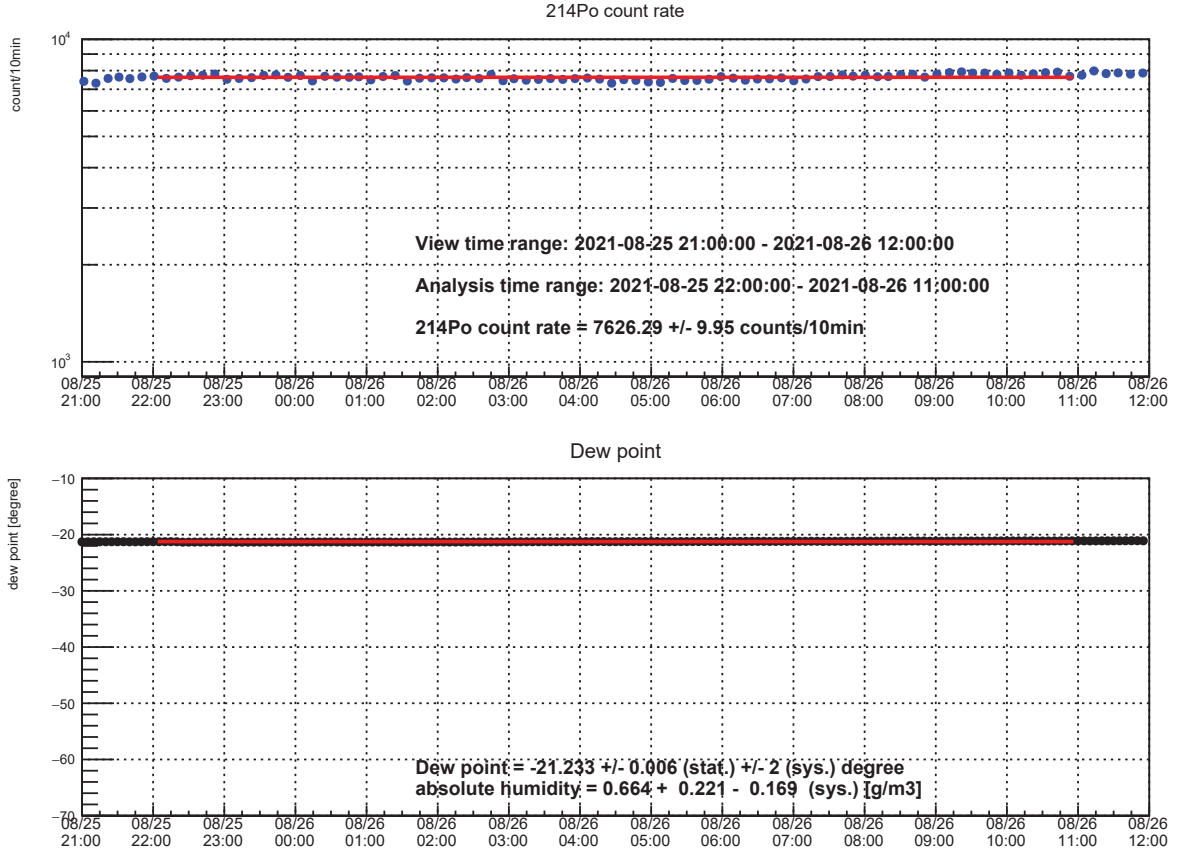


Figure 4.7: Calibration data example of the absolute humidity dependence. In this time range, count rate and dew point were stable. The count rate of ^{214}Po and dew point data plot were fitted with constant values and used for the calibration.

The value of CF_{ideal} is 1.1 by assuming that 90 % of ^{218}Po will be positive and the probability of alpha-ray detection on PIN PD is 50 %. The difference between CF (~ 0.4) and CF_{ideal} (~ 1.1) could come from the PD position in the detector, non-optimal electric field formation and the possibility of alpha-ray partial energy deposit on depletion layer of PIN PD.

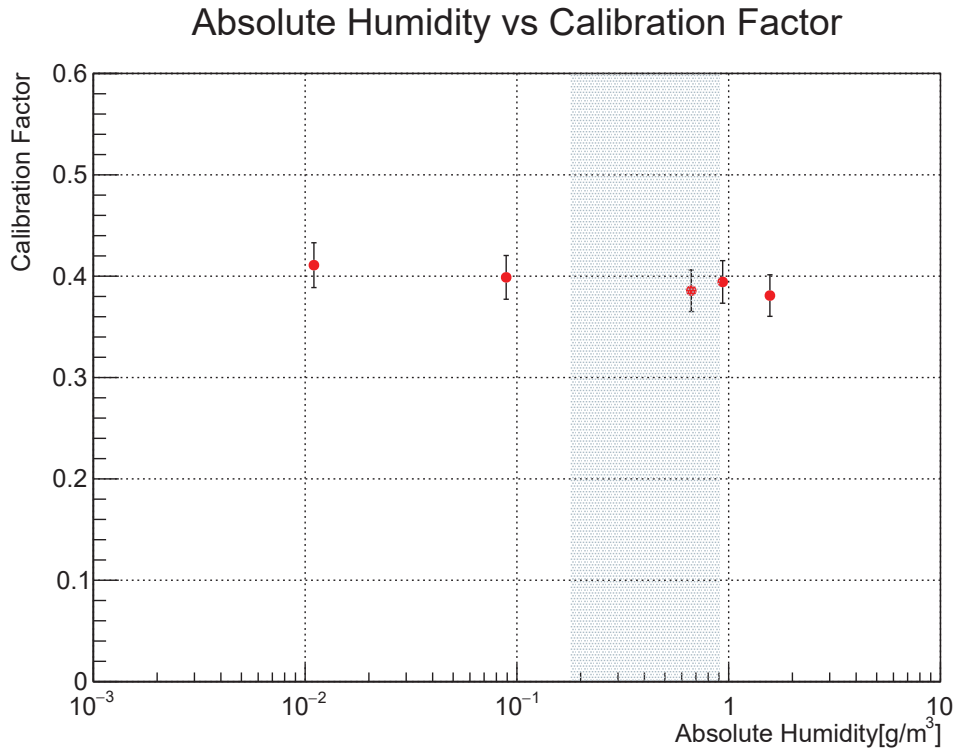


Figure 4.8: Calibration factor measurement results of the radon detector. Obtained CF values $[(\text{count}/\text{day})/(\text{mBq}/\text{m}^3)]$ are shown as a function of the absolute humidity $[\text{g}/\text{m}^3]$. The error bar contains both statics and systematic errors (Table 4.3). The shadow region is the absolute humidity region where the radon emanation from samples were performed.

5 Review of NEWAGE

NEWAGE, one of the directional dark matter search experiments with a gaseous detector, is reviewed in this section. In the first half of this chapter (section 5.1) the basic specification of NEWAGE is given, and in the second half of this chapter (section 5.2) the backgrounds of NEWAGE are reviewed.

5.1 Detector

NEWAGE (NEw general WIMP search with an Advanced Gaseous tracker Experiment) is a directional dark matter search experiment using a three-dimensional gaseous TPC, with a two-dimensional imaging device, μ -PIC, as an MPGD readout. Details on MPGD and TPC is reviewed in Chapter 3. This experiment has been running in the Kamioka Observatory at the Institute for Cosmic Ray Research of the University of Tokyo since 2007 (Figure 5.1).

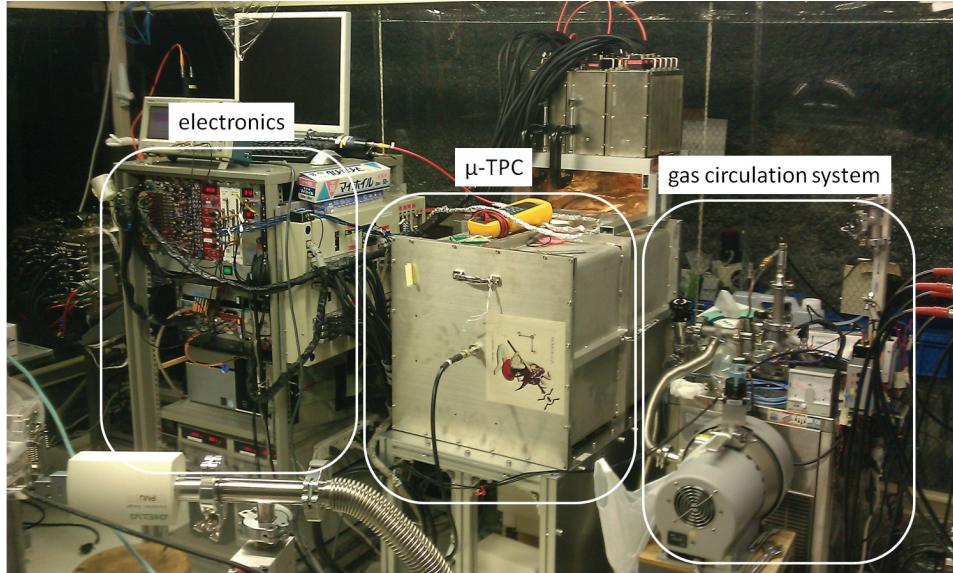


Figure 5.1: Photograph of the NEWAGE system in Kamioka Observatory. Image Source: Taken from K.Nakamura Doctor Thesis[52]

5.1.1 Setup

The current detector of NEWAGE is called NEWAGE-0.3b'' detector. NEWAGE-0.3b'' has a μ -TPC with a drift length of 41 cm, using a GEM (Gas Electron Multiplier) as the pre-amplifier and a μ -PIC with a detection area $30.72 \times 30.72 \text{ cm}^2$ as a two-dimensional imaging readout (Figure 5.3 and Figure 5.2). The μ -PIC was fabricated using printed circuit board technology. This detector collects charge by the strip readout of $400 \mu\text{m}$ spacing made from 768 channels of anodes and cathodes, respectively. The Gas Electron Multiplier (GEM) is used as a pre-amplifier of gaseous detector. This is because the μ -PIC is prone to discharge when trying to obtain high gas gain in low pressure gas, and the μ -PIC can become unstable due to the discharge. This TPC field cage was made of PEEK (polyether ether ketone) and copper wires, in 1 cm intervals, to form a uniform

electric field. PEEK is used in the detector because it is known for a low-outgassing and low radioactive contamination. The schematic diagram of μ -TPC is shown in Fig.5.3.

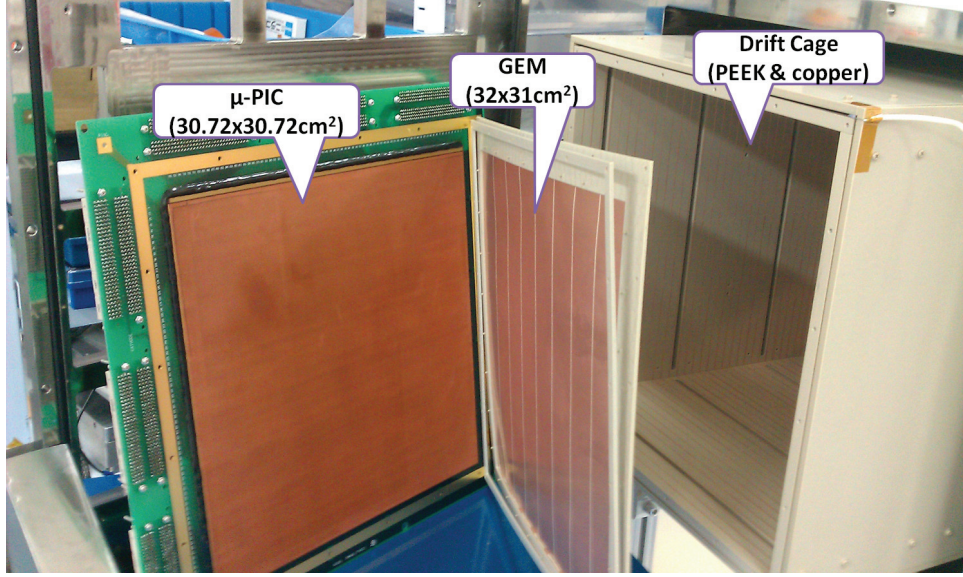


Figure 5.2: Photograph of the inside of NEWAGE TPC. Drift cage, μ -PIC and GEM are shown. Image Source: Taken from K.Nakamura Doctor Thesis[52]

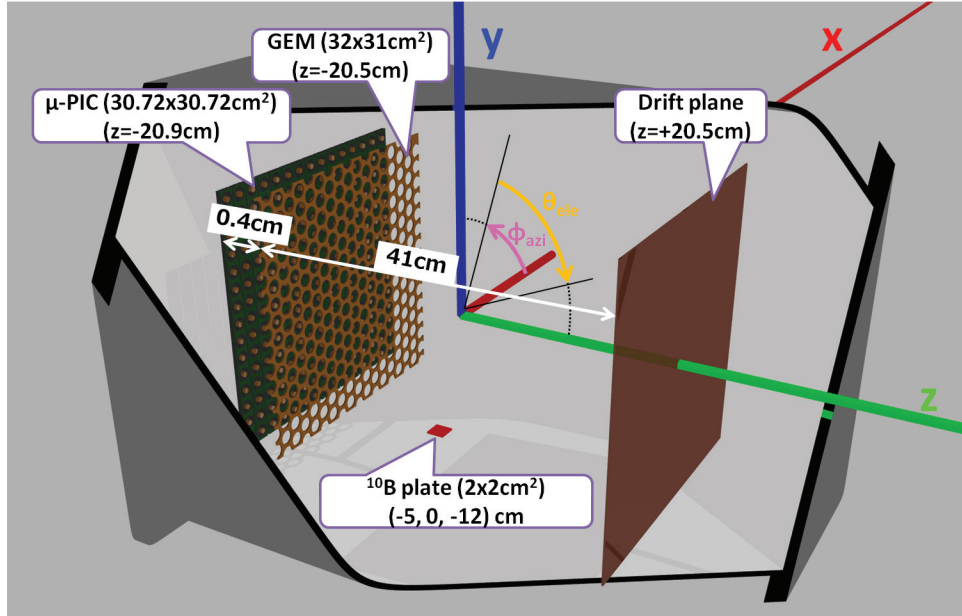


Figure 5.3: Schematic diagram of the NEWAGE TPC. Detector components and XYZ coordinates are shown. ^{10}B plate is used for the energy calibration. Image Source: Taken from K.Nakamura Doctor Thesis[52]

CF_4 76 Torr ($= 0.1$ atm) is used as a detector medium gas for dark matter searches in NEWAGE([53], [54], [32]). The parameter of CF_4 gas, which is used in NEWAGE now, is shown in Table.5.1. The reason for using CF_4 is that the fluorine nuclei in CF_4

molecule can have a large cross section of SD interaction with the dark matter candidate, WIMP. Another reason is that the electron diffusion in the CF_4 gas is smaller than that in other gases (Figure 5.4) and thus position resolution is better. Electron diffusion and drift velocity in CF_4 gas at 76 Torr simulated with MAGBOLTZ[55] are shown in Figure 5.4 and Figure 5.5, respectively.

Density	3.76 g/L (288 K, 1 atm)
Melting / Boiling point	89.55 K / 143.35 K
W-value	34 eV

Table 5.1: Properties of CF_4 (carbon tetrafluoride) gas used in the NEWAGE TPC.

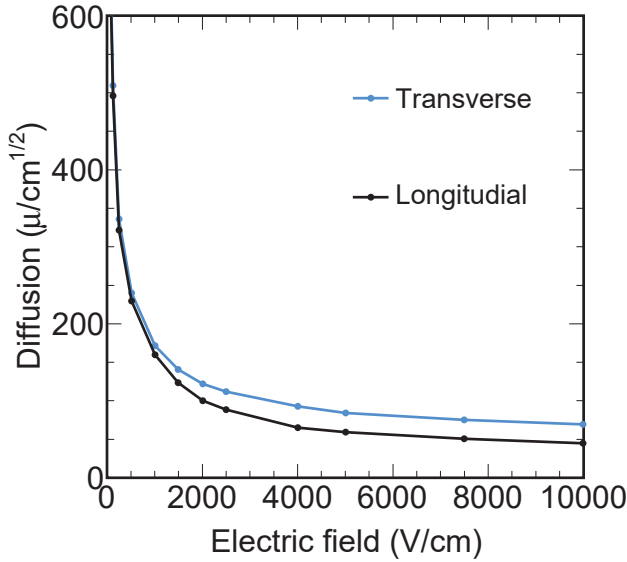


Figure 5.4: Simulated electron diffusion in CF_4 gas as a function of electric field by MAGBOLTZ[55]. Plot Source: Taken from T.Ikeda[56]

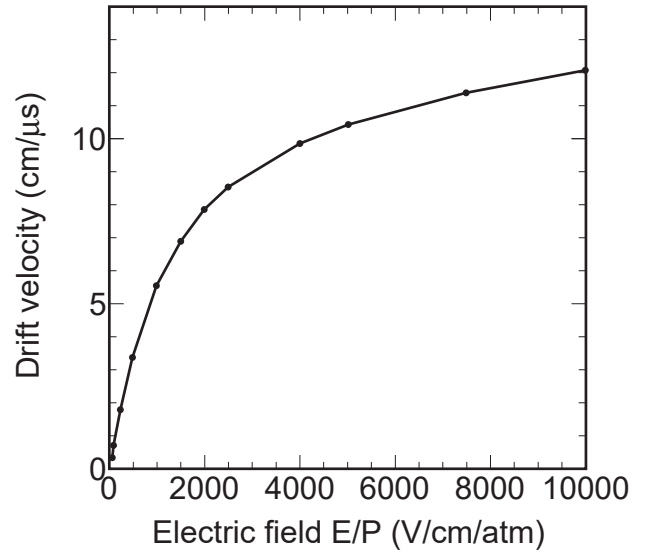


Figure 5.5: Simulated electron drift velocity in CF_4 gas as a function of electric field by MAGBOLTZ[55]. Plot Source: Taken from T.Ikeda[56]

To achieve a long operation of dark matter search experiment with a gaseous TPC, it is required to keep the gas purity because it affects the detector performance, such as gas gain and drift velocity of an electron. In addition to this, in the terms of backgrounds in the TPC, it is also required to reduce radon concentration in the TPC for the long operation at low level, which is important for the dark matter search experiment. In general, the most of detector components, such as metal, plastic, resin and glass-fiber, contain radioactive isotopes ^{238}U and ^{232}Th . ^{222}Rn and ^{220}Rn can emanate continuously from these materials into the TPC. These radon isotopes and their progenies can decay in the detector volume and emit alpha-rays, gamma-rays and beta-rays. They could be serious backgrounds for the dark matter search. The effect of these radon backgrounds will be discussed in section 5.2.2. Cooled charcoal is used as the filtration material to keep

the gas purity and reduce radon concentration in NEWAGE-0.3b” TPC (Figure 5.6). The amount of the cooled charcoal is 100 g (TSURUMICOAL 2GS) and this charcoal is cooled to 230 Kelvin by a refrigerator. The flow rate of this circulation system is set to about 500 mL/min.

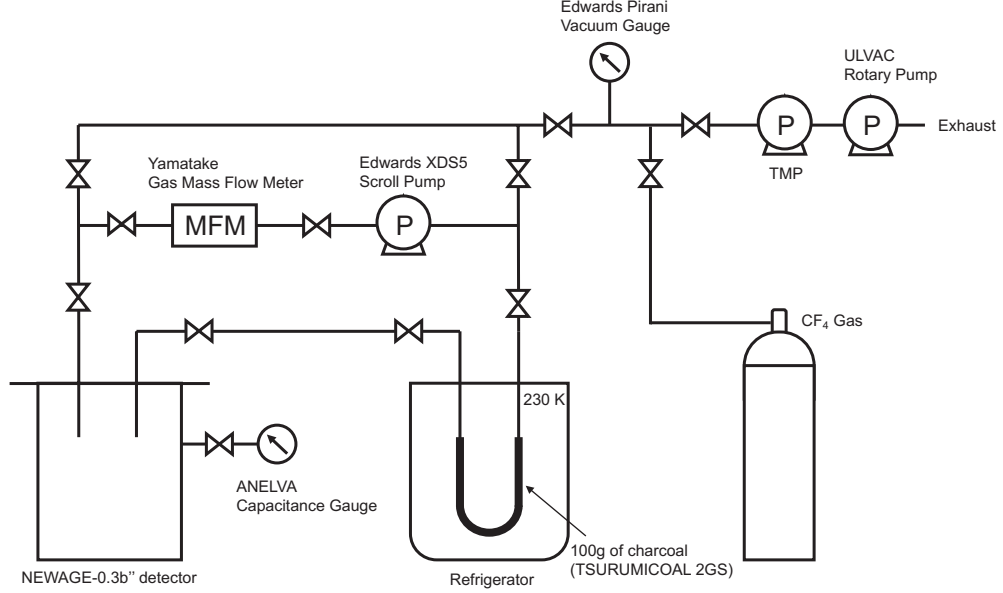


Figure 5.6: Schematic diagram of the gas circulation system of NEWAGE-0.3b”. Figure Source: Taken from T.Ikeda Doctor Thesis[56]

The number of radon atoms N_N in the TPC without a circulating filtration system can be written as follows:

$$N_{Rn} = \frac{R_0}{\lambda_{Rn}} (1 - e^{-\lambda_{Rn}t}), \quad (44)$$

where R_0 is a generation rate of radon and λ_{Rn} is the time constant of the radon, $\ln 2/T_{Rn}$. This equation is valid for both ^{222}Rn and ^{220}Rn and T_{Rn} is the half-life time of radon, 3.82 days and 55.6 seconds for ^{222}Rn and ^{220}Rn , respectively. From their half-lives and Eq.(44), how long it takes to reach radioactive equilibrium can be estimated, as follows. Because the half-life of ^{222}Rn is 3.82 days, the number of ^{222}Rn atoms will gradually increase and reach radioactive equilibrium in a week. On the other hand, the half-life of ^{220}Rn is only 55.6 seconds, so the number of ^{220}Rn atoms rapidly reaches radioactive equilibrium within several minutes.

When a radon circulating filtration system is installed in the detector system and radon atoms can be trapped with a filtration, the number of radon atoms in the TPC can be written as follows.

$$N_{Rn} = \frac{R_0}{\lambda_{Rn} + FP/V} (1 - e^{-(\lambda_{Rn} + FP/V)t}), \quad (45)$$

where F is the flow rate of the circulation system, V is the volume of the TPC and P is the radon absorption probability by the filtration, for example cooled charcoal. Due to its long half life, ^{222}Rn can be reduced effectively with that circulating filtration system, about one order of magnitude[52]. However, due to the limitation of the circulation rate with the circulation pump, it takes much longer time than the ^{220}Rn half-life to circulate gas through whole gas system and it is difficult to remove ^{220}Rn before its decay because of its short half-life. This difficulty in removing ^{220}Rn is applied to NEWAGE-0.3b” because of its system volume and circulation rate, as described previously.

In the view of the difficulty in removal of ^{220}Rn , it is important to select detector materials with lower ^{220}Rn emanation rate and develop a micro patterned gaseous detector using lower background materials. The detail of radon emanation backgrounds will be reviewed in section 5.2 later.

5.1.2 Data acquisition system

Figure 5.7 is a conceptual diagram of the data acquisition system (DAQ) of the NEWAGE. Signals from the μ -PIC anodes and cathodes strips, 768×2 channels, are amplified, shaped and digitized by the ASD (Amplifier-Shaper-Discriminator, ASD Chip: SONY CXA3653Q). The signal output from this ASD is then sent to an FPGA-based coordinate position encoder, and finally sent to a VME memory board, from which data acquisition PC collects data. The waveforms collected at the cathodes of the μ -PIC is summed for 64 channels and the waveform is recorded by a 100 MHz sampling Flash ADC (FADC). The rise time of the signal at the anode and cathode of the μ -PIC and the time during when the signal is over the threshold (Time-Over-Threshold: ToT) are calculated. The rise time and TOT are sent to the VME memory board and collected by the PC.

5.1.3 Low alpha μ -PIC (LA μ -PIC)

In the previous results ([53] and [54]), “standard μ -PIC” was used as a readout detector for the dark matter searches. Surface material of this μ -PIC contained a glass cloth which is contaminated with radioactive isotopes, such as uranium and thorium chains (see Figure 9.1). These radioactive contamination caused surface alpha-ray backgrounds and limited the dark matter search sensitivity of NEWAGE. A low alpha (emitting) μ -PIC (LA μ -PIC), which used a low alpha-ray emitting material on the surface of μ -PIC, was developed and manufactured[43] to improve the sensitivity. A directional sensitivity to WIMP of the NEWAGE was improved by factor 15 (in Fig.5.8, [32]) from the old result using the standard μ -PIC [53]. However, to explore “DAMA region” in which DAMA claimed discovery of dark matter, further more improvement in sensitivity of the NEWAGE is required. The sensitivity of the NEWAGE was known to be limited also by the background events from ambient gamma-ray, ambient neutrons and radons. Detail on these background will be reviewed and discussed in the next section.

5.2 Backgrounds sources of NEWAGE

Backgrounds events of NEWAGE can be divided into two types, external backgrounds and internal backgrounds, in the view of their origin. The external backgrounds are the

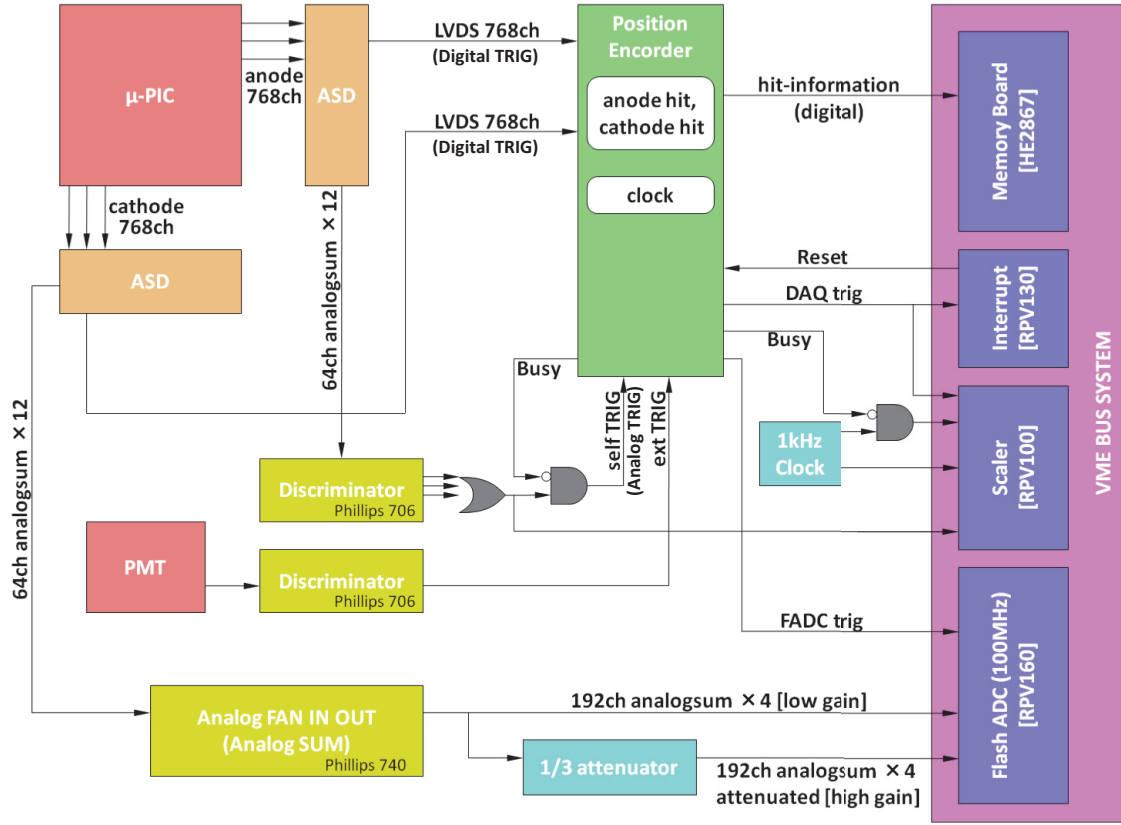


Figure 5.7: Schematic diagram of data Acquisition (DAQ) System of NEWAGE-0.3b".
Figure Source: Taken from K.Nakamura[52]

backgrounds from outside of detector: for example, ambient neutrons, ambient gamma-rays and cosmic muons. The internal backgrounds are the backgrounds originated from detector inside, such as radons and alpha-rays, from the detector materials. From previous science runs and background study[32][56], main components of the external backgrounds were ambient gamma-rays and ambient neutrons and main components of the internal backgrounds were radon backgrounds (Table.5.4). In this case “radon backgrounds” are ^{220}Rn and ^{222}Rn decay events, alpha-rays are emitted from the radon decays.

For rare event search experiments, such as dark matter search and neutrinoless double beta decay search experiments, the search sensitivities are often limited by the backgrounds and attempts have been made to reduce these backgrounds.

5.2.1 External backgrounds

Remaining external background of NEWAGE is reviewed in this subsection.

Ambient gamma-ray

Ambient gamma-ray is one of the external backgrounds, which mainly comes from the decay of natural isotopes such as ^{40}K , and uranium/thorium-chain progeny isotopes in the cavern rocks (the nucleus which emit gamma-ray and its gamma-ray energy are shown

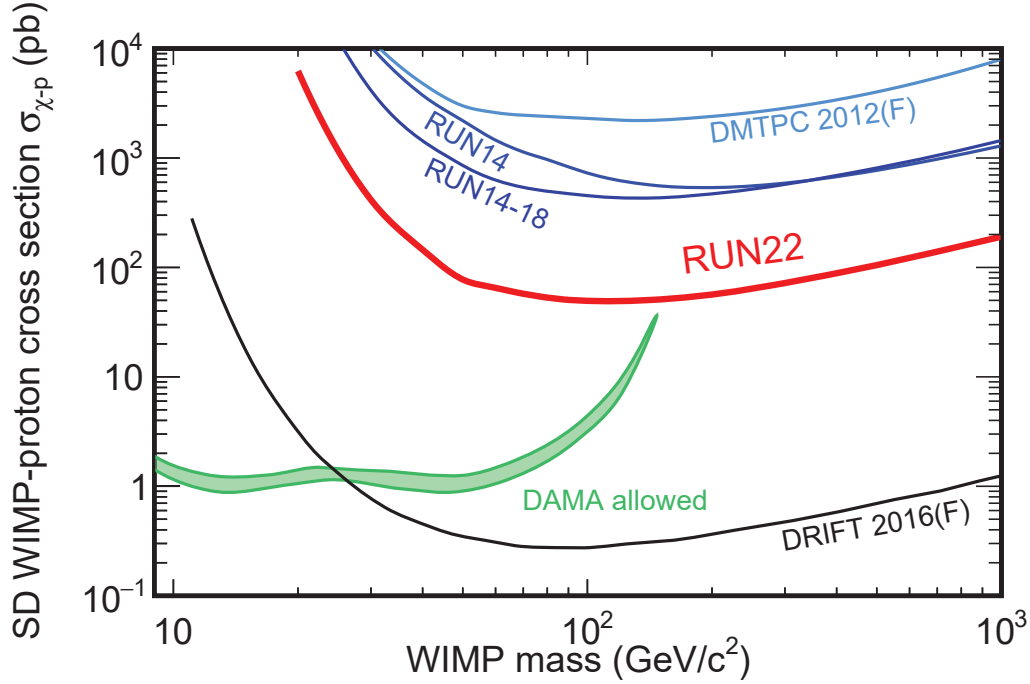


Figure 5.8: Upper limit on the SD WIMP-proton cross section (90% C.L.) as a function of WIMP mass [32]. In RUN22 result (red line), limits to WIMP was improved by a factor 15 from RUN14-18 (blue line) result.

in Figure 9.1). In Laboratory B at Kamioka Observatory, where NEWAGE detector is located, ambient gamma-ray flux was measured with a $5 \times 5 \times 1 \text{ cm}^3$ CsI(Tl) scintillator and unfolded in 2008[57]. The ambient gamma-ray spectrum is shown in Figure 5.9. Expected energy rate of the ambient gamma-ray in NEWAGE TPC was simulated. The estimated ambient gamma-ray energy spectrum is shown in Figure 5.10[56] and the expected event rate in the energy range of 50-60 keV was 1.4×10^{-1} [counts/keV/kg/days].

Ambient neutron

Ambient neutron is one of the external backgrounds, mainly from (α, n) reactions which is triggered by the alpha-ray from uranium and thorium chain, spontaneous fission of ^{238}U and cosmic ray spallation in the cavern rock. Ambient neutron flux in Kamioka Laboratory was estimated with a ^3He detector [58] and is shown in Figure 5.11. The expected event rate of ambient neutron in the NEWAGE TPC in the energy range of 50-60 keV was $(3.1 \pm 0.8) \times 10^{-2}$ [counts/keV/kg/days].

5.2.2 Internal backgrounds

By developing a LA μ -PIC, alpha-ray background from the surface of the detector was successfully reduced by about a factor 50 and then radon background became one of the significant remaining background in the NEWAGE TPC.

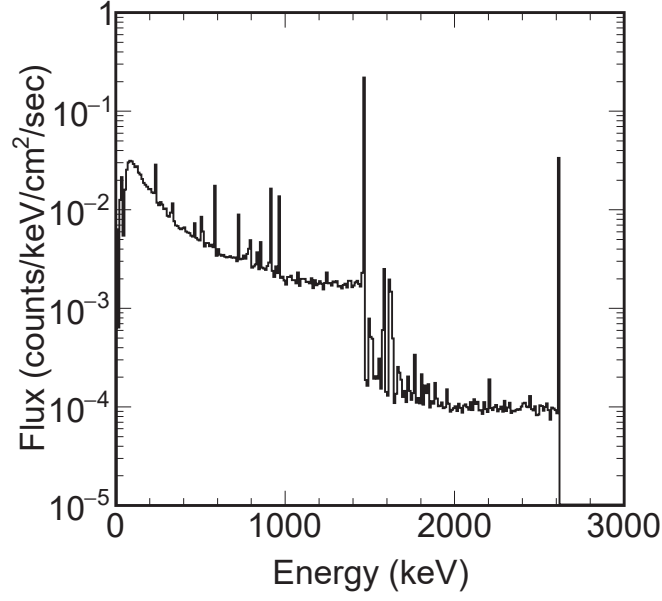


Figure 5.9: Ambient gamma-ray flux in Laboratory B at Kamioka Observatory estimated with CsI(Tl) scintillator measurement [56][57]. This gamma-ray flux comes from the decay of ^{40}K , uranium and thorium chain.

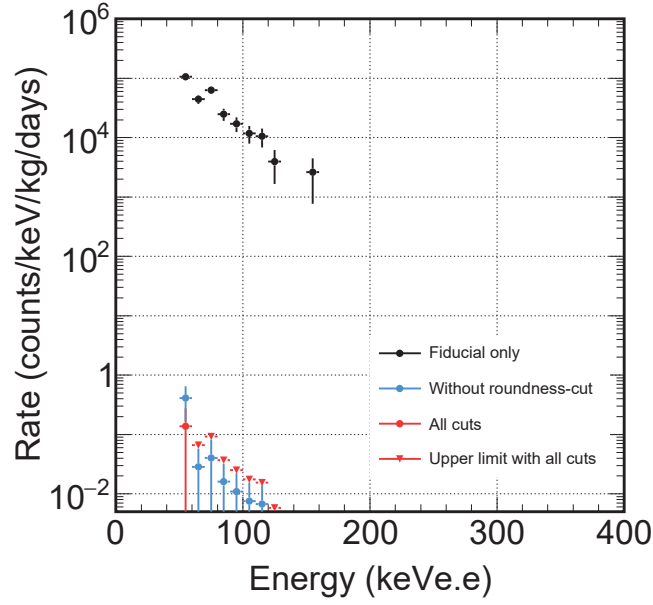


Figure 5.10: Estimated ambient gamma-ray event rate in the NEWAGE TPC from simulation.

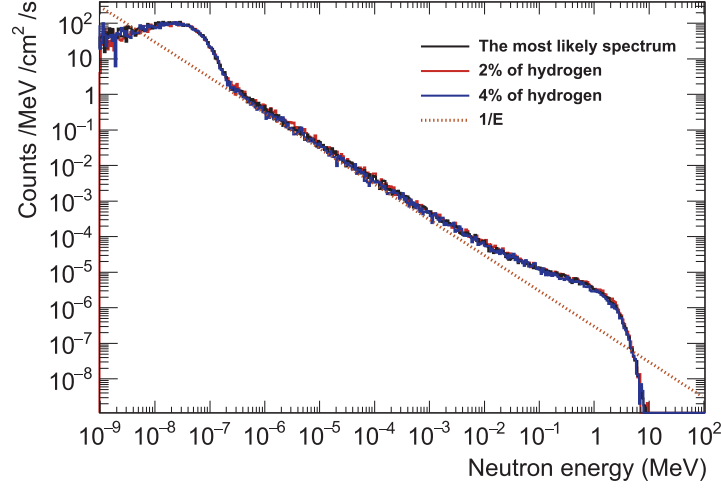


Figure 5.11: Estimated ambient neutron flux in Laboratory B at Kamioka Observatory from ^3He detector measurement[58].

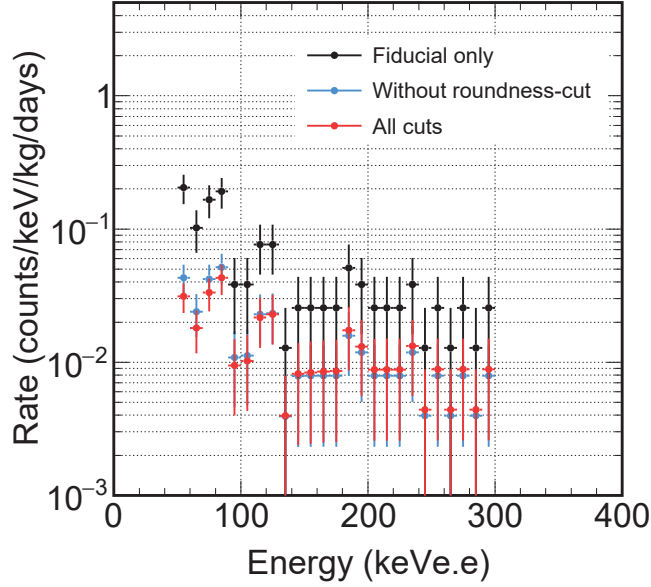


Figure 5.12: Estimated ambient neutron event rate in the NEWAGE TPC[56] from simulation.

Surface alpha-ray emission

Alpha-ray emission rate from the surface of the $\text{LA}\mu\text{-PIC}$ was measured by the Ultra-Lo counter (as described in Chapter 4) to estimate the surface alpha-ray background. The measured alpha-ray emission rate of the $\text{LA}\mu\text{-PIC}$ surface was $(2.1 \pm 0.5) \times 10^{-4}$ alpha/cm²/hr. Expected background spectrum by the surface alpha-rays is shown in Figure 5.13. A large part of raw events of alpha-ray could be removed by energy-length cut (from black dot to

blue dot). With roundness cut, which is the parameter indicating the size of the electron diffusion, events which are close to the detector are rejected because of small electron diffusion (from blue dot to red triangle, red triangle shows the upper limit of expected rate).

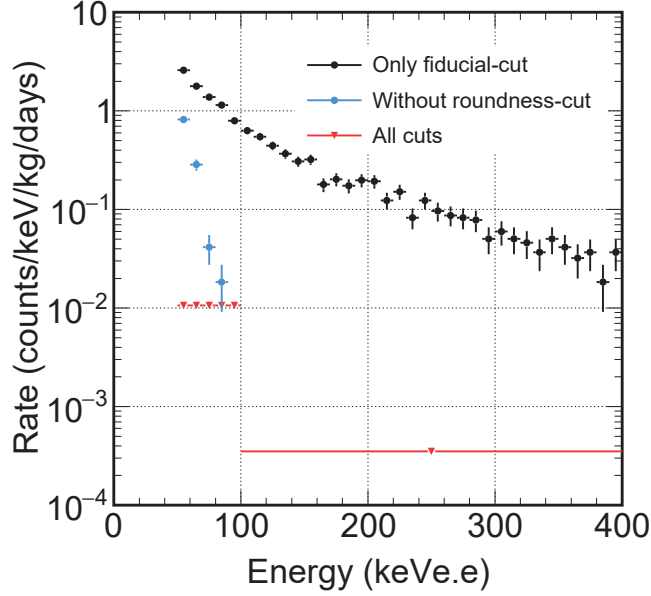


Figure 5.13: Estimated alpha-ray event rate from the LA μ -PIC surface. Black dot is the result of only fiducial-cut. The blue dot is the spectrum without roundness-cut. The red triangle is upper limit of expected rate.

Bulk and surface alpha-rays were evaluated separately, as described in Chapter 4. The bulk alpha come from radioactive contamination near the surface in the material and surface alpha comes from surface of materials, literally. Bulk alpha can be reduced by material screenings and replacement of materials. For surface alpha, if materials are in the atmosphere which contains radon gas, the surface of the material could be embed by radon progenies and this embed radon progenies could be surface alpha-ray source. This radon embedding process can be suppressed to some extent by storing the materials and the detector in a radon free atmosphere.

Table 5.2: Ultra-Lo surface alpha-ray measurement result of LA μ PIC and candidate component of material. In this table, the unit of alpha emission is [$\alpha/\text{cm}^2/\text{hr}$].

Sample	$2.5 < E < 4.8 \text{ MeV}$	$4.8 < E < 5.8 \text{ MeV}$
LA μ -PIC	$(9.38 \pm 2.97) \times 10^{-5}$	$(2.35 \pm 0.48) \times 10^{-4}$
Copper sheet(12 μm)	$(1.94 \pm 0.46) \times 10^{-4}$	$(1.14 \pm 0.36) \times 10^{-4}$
Quartz + Resin	$(3.82 \pm 0.46) \times 10^{-4}$	$(2.29 \pm 0.36) \times 10^{-4}$

Alpha-ray from radon decay

Radioactive noble gas ^{222}Rn and ^{220}Rn are the progeny of uranium and thorium chain, respectively (Figure 9.1). These radon isotopes decay and emit alpha-ray. In a gaseous TPC, e.g. the NEWAGE detector, electron recoil events from beta-ray and gamma-ray backgrounds can be distinguished from nuclear recoil events using energy deposit over length (dE/dx) because the electron recoil events deposit small dE/dx but the nuclear recoil events deposit large dE/dx in the gas medium. Alpha-ray from radon decay deposits a large energy of about 6 MeV in a gas TPC and these events have a long track. These events can be distinguished from low energy nuclear recoil events with short track in the gas TPC. But if the alpha-ray deposits a large energy in the detector materials and deposit only small energy in the gas TPC, it is difficult to distinguish such alpha-ray events from nuclear recoil events and these alpha-ray events can be severe background source for a dark matter search. In our previous studies, the fraction of events from these radon isotopes was determined from simulation and measured spectrum (Figure 5.14). From these fit result and simulation, background rate from radon isotopes ^{222}Rn and ^{220}Rn , Figure 5.15 and Figure 5.16 respectively, also were estimated. The radon concentration in the NEWAGE TPC was also estimated to be ^{222}Rn and ^{220}Rn were $(5.3 \pm 2.1) \times 10^{-1} \text{ mBq/m}^2$ and $5.7 \pm 0.3 \text{ mBq/m}^3$, respectively. These radon concentration result indicated the existence of radon emanation sources in the NEWAGE TPC. Detector components were screened with HPGe detector and surface alpha-ray counter measurement were performed to identify the radon sources.

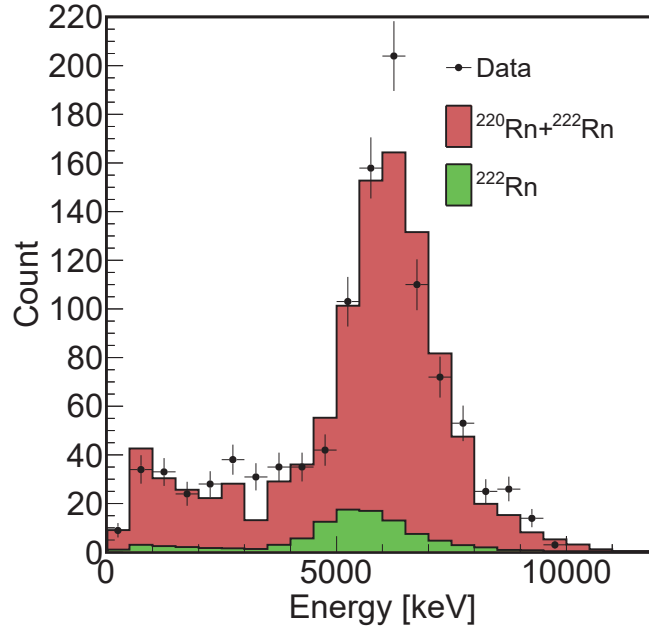


Figure 5.14: Estimated and observed spectrum from radon decay alpha-rays[56]. The black points are measured data. The green histogram shows simulated alpha-ray events from ^{222}Rn decay and the red one shows alpha-ray events from ^{222}Rn and ^{220}Rn decays.

Materials of detector components were screened with the HPGe measurement for

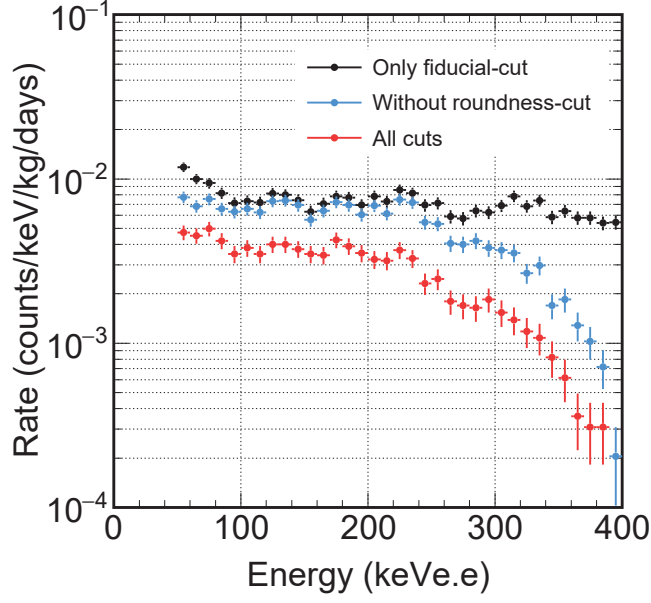


Figure 5.15: Estimated alpha-ray event rate from ^{222}Rn (radon-222) decay[56].

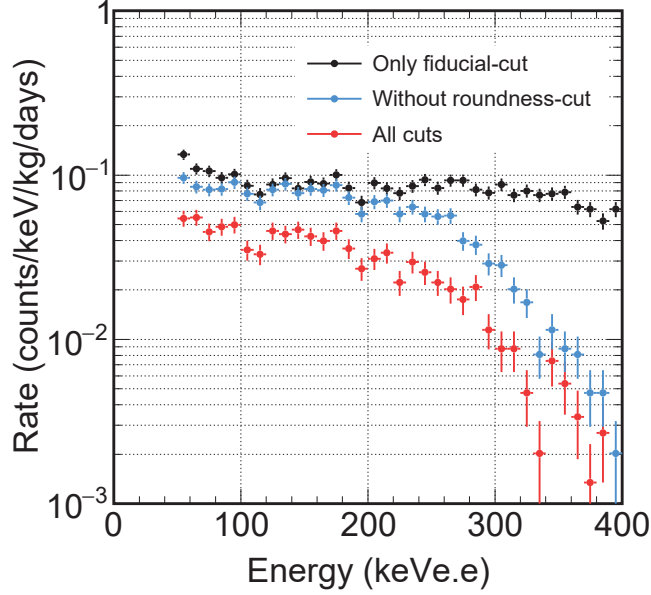


Figure 5.16: Estimated alpha-ray event rate from ^{220}Rn (radon-220) decay[56].

checking of radon emanation. This result is shown in Table.5.3. From this measurement result, LA μ -PIC core material and solder resist which was used on the surface were identified as the candidate sources of radon emanation. Even though the surface material of μ -PIC was replaced with a low background material to reduce surface alpha-ray emis-

sion in LA μ -PIC development, the materials used in LA μ -PIC were still the candidate of radon emanation source due to U/Th-chain contamination in materials.

From this measurement result, development of new detector LBG μ -PIC was started to reduce the amount of U/Th chain contamination in the detector materials to avoid radon emanation and to suppress backgrounds. Details on this development will be described in section.6.

Table 5.3: Radio purity sample screening results of the LA μ -PIC and the old μ -PIC with the HPGe detector. The unit of results is all [ppm](ppm: 10^{-6} g/g) (The results of (a) and (b) are taken from [44])

ID	Sample	^{238}U upper stream	^{238}U middle stream	^{232}Th
(a)	PI(w/GC) 800 μm	$(7.6 \pm 0.1) \times 10^{-1}$	$(7.8 \pm 0.1) \times 10^{-1}$	3.42 ± 0.03
(b)	PI(wo/GC) 5 μm + epoxy 75 μm (LA μ -PIC surface)	$<2.98 \times 10^{-3}$	$<2.86 \times 10^{-2}$	$<6.77 \times 10^{-3}$
(d)	Solder resist	$(3.9 \pm 0.1) \times 10^{-1}$	$<2.3 \times 10^{-3}$	$(4.2 \pm 0.1) \times 10^{-2}$

5.2.3 Backgrounds summary

Expected backgrounds are shown in Table.5.4 as a background summary from estimated remaining backgrounds in the NEWAGE. From this background estimation, the largest components of the backgrounds is ambient gamma-ray, one of the external backgrounds.

Source	w/ roundness
Ambient gamma-rays	1.5 ± 1.5
Ambient neutrons	$(3.5 \pm 0.9) \times 10^{-1}$
^{222}Rn	$(5.3 \pm 2.2) \times 10^{-2}$
^{220}Rn	$(6.1 \pm 0.7) \times 10^{-1}$
LAuPIC surface	$<1.2 \times 10^{-1}$
Total	2.5 ± 1.5
Measurement	2.0 ± 1.4

Table 5.4: Estimated number of backgrounds in 50-60 keV energy bin[32].

These external background can be reduced with some shields. From the point of background reduction with shields, water or copper or lead shield would be effective. In the previous study[56], the backgrounds were found to be reduced by more than one order of magnitude easily. If the ambient gamma-ray background is reduced by more than one order of magnitude, the most serious background source will be the radons. If we assume that the radon backgrounds ^{222}Rn and ^{220}Rn are reduced by over one-order in addition, the total background rate will be reduced by over one-order and the sensitivity to dark matter can be improved.

6 Development of Low-background μ -PIC

Studies reviewed in the previous chapter concluded that the main internal background source is radon gas emanating from the detector material. Development of a LBG μ -PIC, low background μ -PIC, was started to reduce these radon backgrounds. Development of a LBG μ -PIC and its performance evaluations are described in this chapter.

Requirements on the performance for the LBG μ -PIC for the dark matter search are set as follows. With this detector performance, it is required that over 90 % of 50 keV nuclear recoil events should be multiplied by gas gain of more than 1000 with the LBG μ -PIC. This is equivalent to the performance of the LA μ -PIC for detecting nuclear recoils. The LA μ -PIC showed a gas gain of more than 1000 gas gain with argon-ethane (9:1) at 760 Torr[43] and this is equivalent to detecting a nuclear recoil of 50 keV energy in 76 Torr CF₄ gas.

6.1 Material screening and results

There are two ways to reduce the radon backgrounds: using a dedicated filter and replacing the detector materials with lower radioactive contamination. NEWAGE implemented cooled activated carbon in the gas circulation system as the former (see Chapter 5.1 and Ref. [52] for more details). A low background molecular sieve is being developed as an improvement of this radon filtration[59]. Current filtering system with cooled activated carbon is capable of reducing ²²²Rn taking account of the half-life (3.82 days) of ²²²Rn and the circulation rate (125 L chamber volume and 0.5 L/min circulation rate). ²²²Rn radon events rate was found to be reduced by one order of magnitude with the cooled activated carbon in our previous study[52]. In contrast to ²²²Rn, ²²⁰Rn has a half-life of only 55.6 seconds, so it is very difficult to remove ²²⁰Rn radon from the gas with the filtering system before it decays in the detector. The latter approach, a replacement of the material used in the detector with low radon emanation materials, is required to reduce ²²⁰Rn background. In particular, making the readout device (μ -PIC) with low background materials is a very important development item to reduce ²²⁰Rn background. The core material used in the LA μ -PIC had a certain amount of U/Th chain contaminations and they would be radon sources as we discussed in Chapter 5. The material screening method was described in Chapter 4. We decided to develop a new μ -PIC, called “Low-background μ -PIC” (hereafter LBG μ -PIC) to reduce the radon background.

Screening results

Several material samples were screened as the candidates of the LBG μ -PIC material. These materials, such as detector core material candidates, surface copper and solder resist were screened with the HPGe detector for the U/Th contamination and the surface alpha-ray counter, Ultra-Lo, for the surface alpha contamination. As described in the Chapter 4. Obtained results are the following. A polyimide plate with a thickness of 800 μ m is used as a base, “core”, material in a standard μ -PIC (used as a detector in [53]) and a LA μ -PIC(Low- α μ -PIC)[43]. The core polyimide is reinforced with glass cloth (PI(w/GC)). As we saw in Chapter 4, this material, especially the glass cloth part, contains a large amount of radioactive impurities ((a) in Table 6.1) and this could be the radon emanation source. Synthetic quartz sheet is generally known to be low radioactive

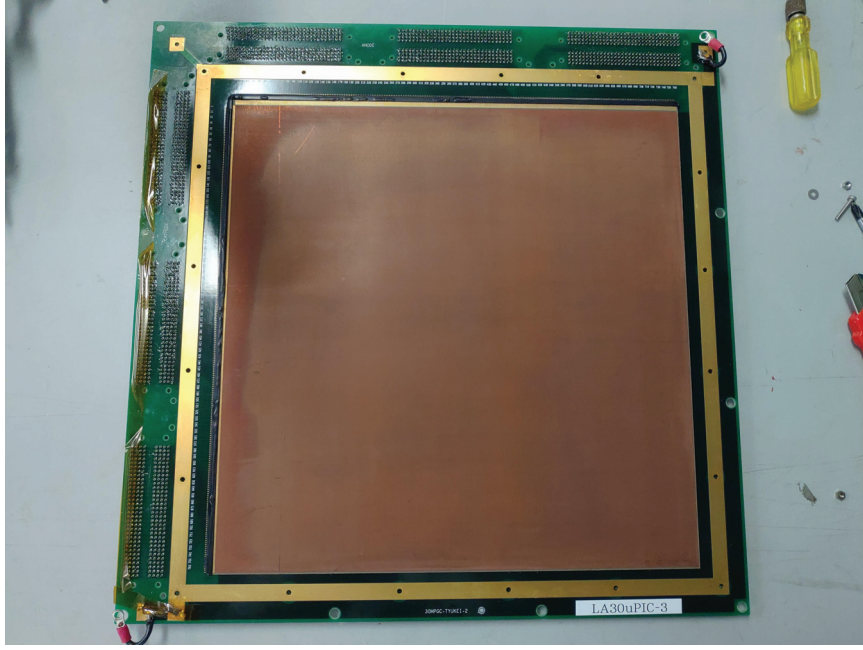


Figure 6.1: Photograph of the LA μ -PIC (Name: LA30uPIC-3). This is the same type of the LA μ -PIC as the one currently in use in Laboratory B at Kamioka Observatory. The green part of the surface is the PCB region, which was coated with solder resist for insulation.

and can be a replacement for the glass cloth. We found two candidates of resin reinforced with synthetic quartz. The difference was the glass transition temperature at which the material undergoes a glass transition, or softened. Results are shown as (b) and (c) in Table 6.1. Item (b) showed a better result in terms of the radioactivity, while it turned out that its glass transition temperature, T_g , may not high enough to withstand the manufacture process, e.g. thermal pressing process. To be on the safe side, it is decided to use (c) as the core material of the LBG μ -PIC. It should be noted that even (c) is much less ($< 1/100$) contaminated compared to (a) and satisfies our requirement.

Surface alpha-rays of the candidate materials were measured with the Ultra-Lo and the result is shown in Table 6.2. The alpha emission rate of the High T_g synthetic quartz sheet with resin was found to be on similar level to that of the copper sheet.

6.2 Manufacturing of LBG μ -PIC

6.2.1 Control of radon progeny embedding

In general, room air contains radon from the soil and walls in the building with an average radon concentration of 10 to 100 Bq/m³. Half-lives of ²¹⁰Pb and ²¹⁰Po, progenies of ²²²Rn in the uranium chain, are 22.2 years and 138.4 days, respectively. If these isotopes with long-lives are produced as decay products of the radons on the surface of the detector, they can be alpha-ray emission sources for a long time [60]. To avoid this, the materials used for manufacturing of LBG μ -PIC was stored in an EVOH bag with radon free air (G1 Grade pure air) as the same way as material screening, described in Chapter 4. This procedure was applied to almost all materials used for the LBG μ -PIC.

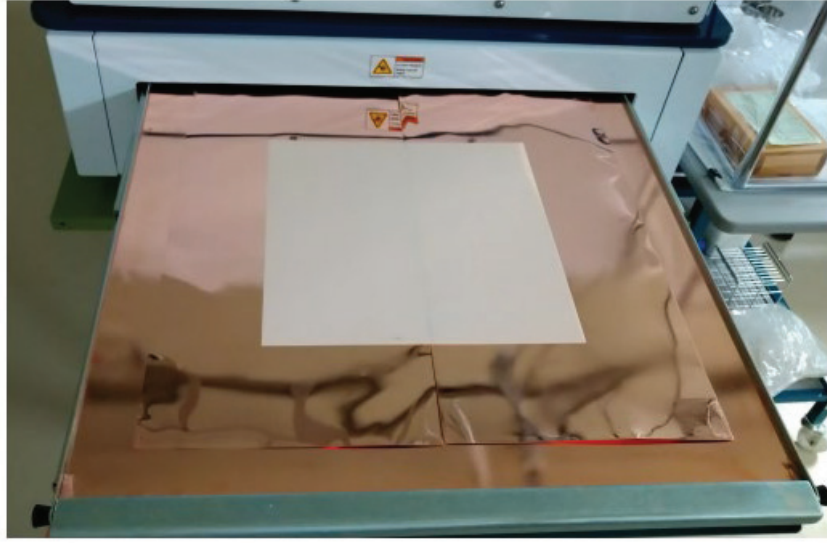


Figure 6.2: Synthetic quartz with resin materials for the LBG μ -PIC core. This photograph was taken before the surface alpha-ray measurement with the Ultra-Lo and the white sample is seen on the sample holder made of copper.

Table 6.1: Radio-purity screening results with a HPGe detector. 90%upper limits are shown for the results of (b) and and that of ^{238}U middle stream of (d) whereas 1σ errors are shown for other results. The unit of results is all ppm (ppm: 10^{-6} g/g).

ID	Sample	^{238}U upper stream	^{238}U middle stream	^{232}Th
(a)	PI(w/GC) 800 μm (LA μ -PIC core)	$(7.6 \pm 0.1) \times 10^{-1}$	$(7.8 \pm 0.1) \times 10^{-1}$	3.42 ± 0.03
(b)	Quartz+Resin (Low T_g) (Shinetsu Chem. Ltd.)	$< 2.4 \times 10^{-3}$	$< 1.3 \times 10^{-3}$	$< 3.7 \times 10^{-3}$
(c)	Quartz+Resin (High T_g) (Shinetsu Chem. Ltd.) (LBG μ -PIC core)	$(5.6 \pm 5.2) \times 10^{-3}$	$(5.1 \pm 1.0) \times 10^{-3}$	$(1.2 \pm 0.4) \times 10^{-2}$
(d)	Solder resist	$< 2.3 \times 10^{-3}$	$(3.9 \pm 0.1) \times 10^{-1}$	$(4.2 \pm 0.1) \times 10^{-2}$

Table 6.2: Surface alpha-ray measurement results with the Ultra-Lo. The unit of alpha-ray emission rate is $[\alpha/\text{cm}^2/\text{hr}]$.

Sample	$2.5 < E < 4.8 \text{ MeV}$	$4.8 < E < 5.8 \text{ MeV}$	Total
Copper Sheet (anode and cathode)	$(1.94 \pm 0.46) \times 10^{-4}$	$(1.14 \pm 0.36) \times 10^{-4}$	$(3.08 \pm 0.58) \times 10^{-2}$
Quartz+Resin (Low T_g) (Shinetsu Chem. Ltd.)	$(1.02 \pm 0.27) \times 10^{-4}$	$(1.25 \pm 0.30) \times 10^{-4}$	$(3.64 \pm 0.51) \times 10^{-4}$
Quartz+Resin (High T_g) (Shinetsu Chem. Ltd.)	$(3.82 \pm 0.46) \times 10^{-4}$	$(2.29 \pm 0.36) \times 10^{-4}$	$(6.11 \pm 0.58) \times 10^{-4}$

6.2.2 Structural changes from LA μ -PIC

In the development of the LBG μ -PIC, not only the materials used for the detector but also the structure of the detector were changed as shown in Figure 6.3. Solder resist was used as insulation material on a large area of the PCB surface in the relay board of the LA μ -PIC (green part of Figure 6.3a). The LA μ -PIC consists of a PCB relay board (green part of Figure 6.3a) and the detector (Yellow part of Figure 6.3a). These two components were combined with epoxy glue physically and wire-bonded electrically. They may be contaminated by radioactivity during the assembly process. The LBG μ -PIC was redesigned so that the relay board and the detector part were made in one piece. This change eliminated the assembly process and the risk of contamination decreased. (Figure 6.3b). The area of solder resist was limited to the vicinities of the connectors. This change reduced the area of the solder resist to 1/15. The area of this solder resist

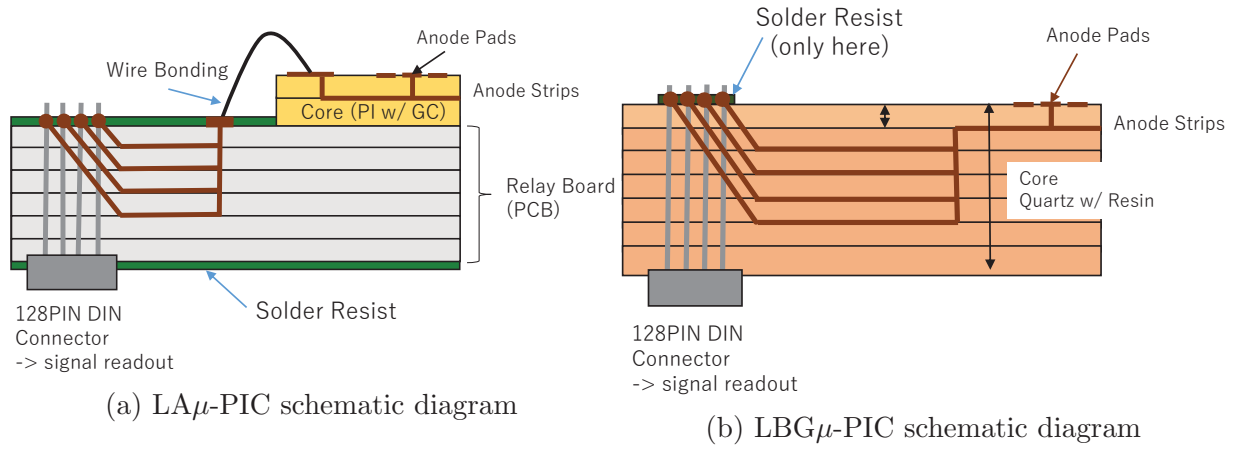


Figure 6.3: Schematic side-views of LA μ PIC and LBG μ PIC. The brown lines in the detector core is the signal wires and connected to anode strips and cathode strips (not shown in this diagrams). Green parts in the LA μ -PIC and LBG μ -PIC are solder resist parts.

and usage of welder should completely be removed in future. This is a remaining task for the next versions.

This LBG μ -PIC (Figure 6.4) was manufactured by DNP (Dai Nippon Printing Co., Ltd.) as well as LA μ -PIC was. In contrast to the LA μ -PIC, the area of solder resist, the green surface in Figure 6.4, was reduced and the resin area is visible.

6.3 Detector performance measurement

The performance of LBG μ -PIC as a gaseous detector was precisely evaluated. Prior to that, a visual inspection with human eyes and electric short-circuit between anodes and cathodes were checked by applying voltage to anodes. These inspections showed no major defect.

6.3.1 Setup for gain measurement

The detector performances, gas gain and gain uniformity, were investigated. The detector performance of the LBG μ -PIC was measured with a test chamber setup. The schematic

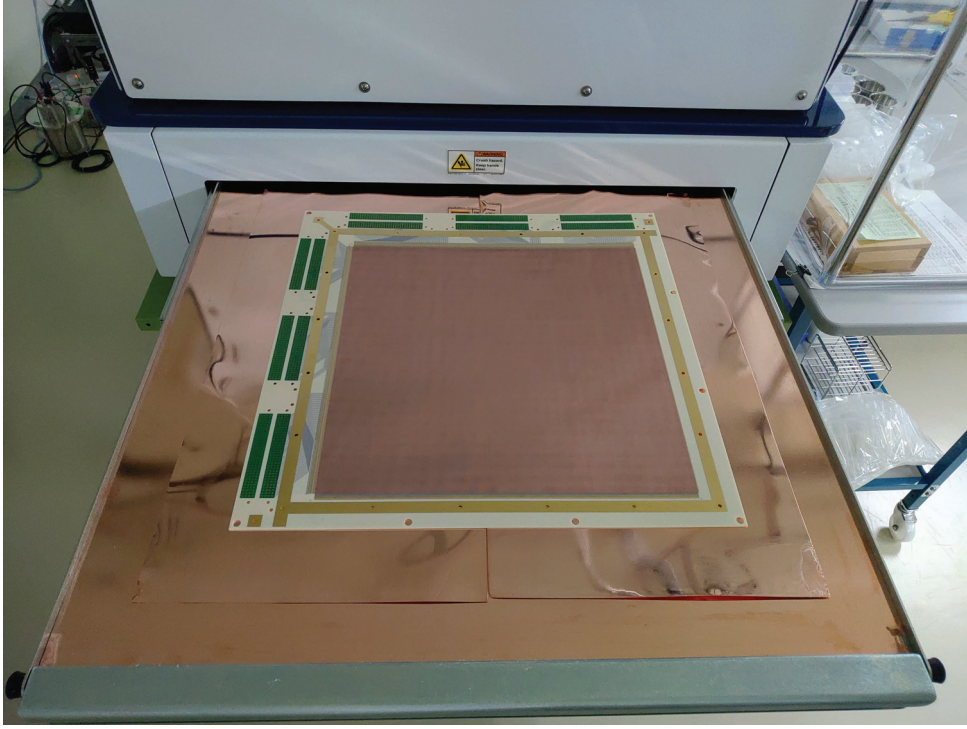


Figure 6.4: Photograph of the developed LBG μ -PIC.

drawings and parameters of the performance test are shown in Figure 6.5 and Table 6.3, respectively. For this measurement, pre-mixed Ar + C₂H₆ 9:1 (1 atm) gas was used. The test chamber (Figure 6.6) had $6 \times 6 + 1 = 37$ holes on its top plate. The detector was irradiated with characteristic 5.9 keV X-rays from ⁵⁵Fe through the Kapton windows of 125 μ m thickness at these holes. Drift plane was made of stainless mesh and drift length was 0.9 cm.

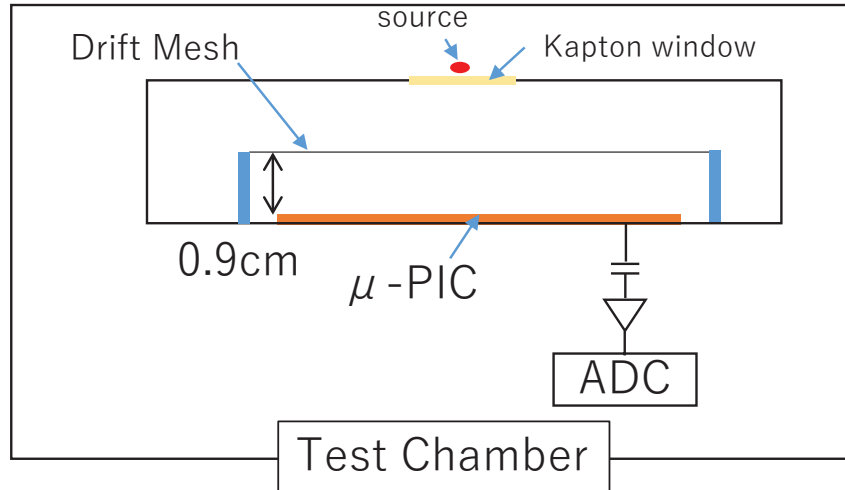


Figure 6.5: The measurement setup of the test chamber. The Kapton window hole in this diagram corresponds to the one of holes in Figure 6.6

The anode and cathode strips of the LBG μ -PIC were connected to ‘CR board’ which

has both capacitor and resistor to read signal with AC coupling from anode and cathode strips. Six strips were connected on the CR board and readout with an Amplifier input. This amplifier had a pre-amplifier CR-110 (Cremat Inc.) and a shaper (CR-RC Gaussian shaping circuit, two LF356). Output of the shaper was connected to a waveform digitizer ADALM2000 (12 bit ADC, ± 2.5 V input range) and the waveforms were recorded.

Measurement method

When $\text{Ar} + \text{C}_2\text{H}_6$ gas is irradiated with 5.9 keV X-rays, electron-ion pairs will be created by ionization of gas molecules. The gas gain is defined as follows,

$$G_{\text{gas}} = \frac{W_{\text{Ar}} \times Q}{5.9 \text{ keV} \times q_e} \quad (46)$$

$$Q = (C_{\text{ADC}} + B)/A, \quad (47)$$

where G_{gas} is the gas gain and W_{Ar} is the W-value of argon (see section 3), C_{ADC} is the recorded charge in ADC value and q_e is the elementary charge. The values of A and B are the calibration factor of the amplifier known by injecting test pulses. From calibration, the measured A and B values are 2.27 and 31.0, respectively.

Table 6.3: Setup of the LBG μ -PIC test measurement.

Gas	Ar + C ₂ H ₆ (9:1) 1 atm
Drift electric field	0.55 kV/cm
Anode voltage	+520 V
Calibration source	⁵⁵ Fe (5.9 keV X-ray)

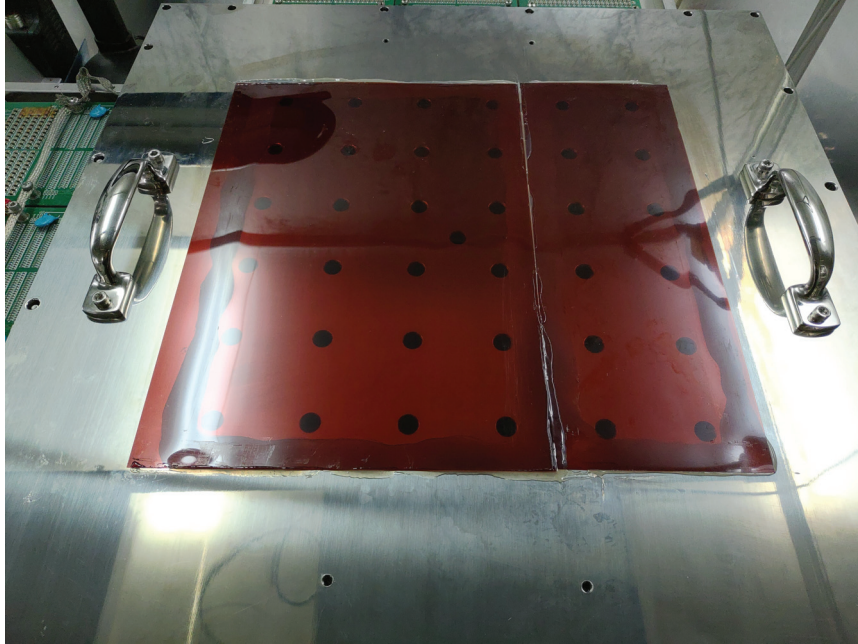


Figure 6.6: Photograph of the test chamber. 36+1 holes are made on the top of vessels. The detector was irradiated with 5.9 keV X-rays for the gain measurement.

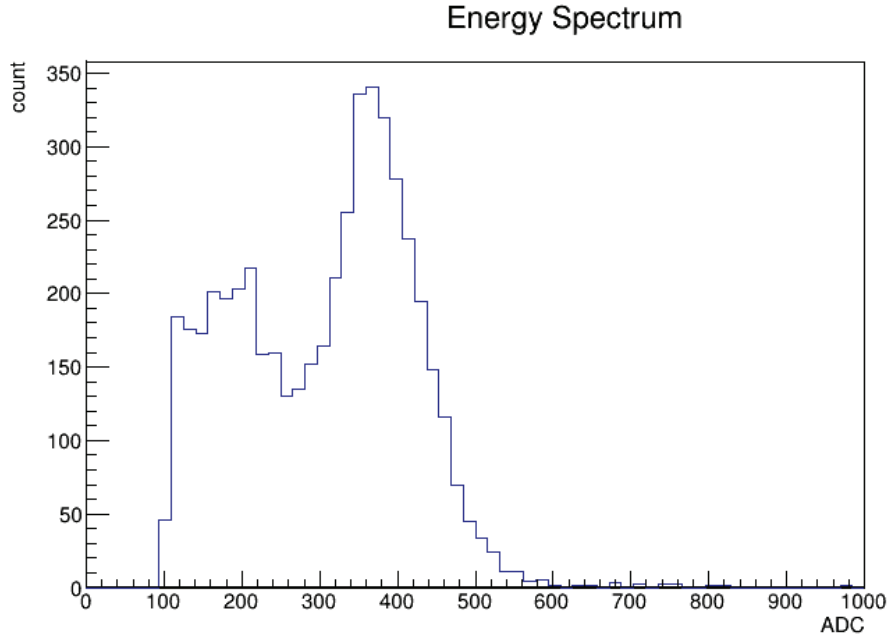


Figure 6.7: Example of a calibration spectrum with an ^{55}Fe source. The peak around 380 ADC channel corresponds to the ^{55}Fe 5.9 keV main peak.

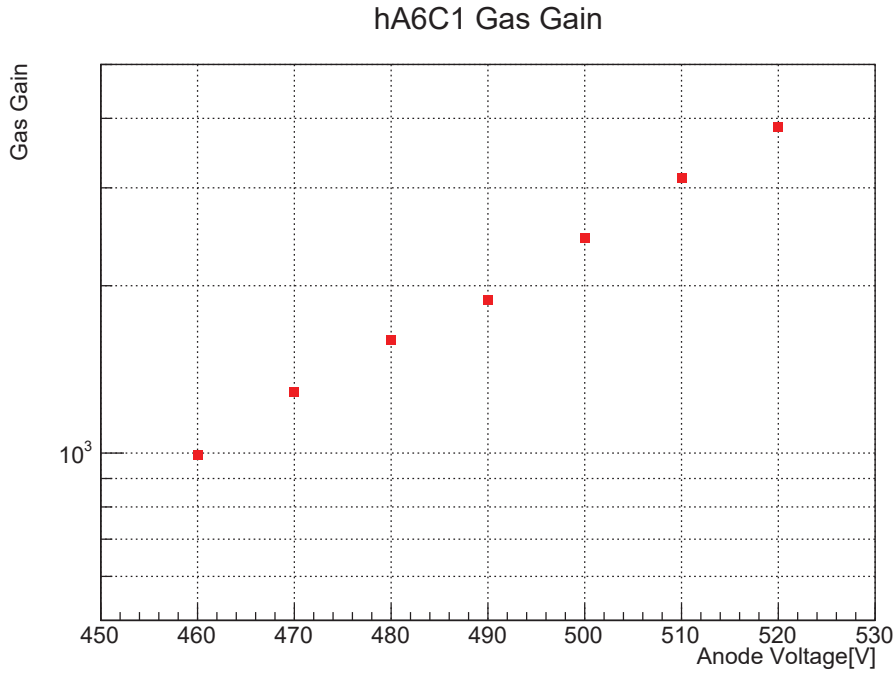


Figure 6.8: Gain curve of the LBG μ -PIC. The anode voltage was scanned from 460 to 520 V . Discharges occurred above 530 V, which limited the measurement.

6.3.2 Measurement result and gain uniformity

The gas gain uniformity and other properties as a gaseous detector were investigated. Gas gains were measured at 36 sampling points right above the holes to sample gain. The

central hole was named hCC and used as a for gain reference position to correct any time variation of the gain.

Figure 6.7 shows an energy spectrum of ^{55}Fe 5.9 keV X-ray obtained with the setup configuration in Table 6.3. The charge of this spectrum was obtained by Gaussian fitting and the gas gain was obtained from Eq. (46). The gas gain dependence of the anode voltage, or a gain curve, was measured by changing the anode voltage. A gain curve is shown in Figure 6.8. From this gain curve, it was confirmed that this LBG μ -PIC detector works properly as a gas detector. Gas gains at 36 sampling points were measured. Figure 6.9 shows the gas gain position dependence of the LBG μ -PIC. The whole area scan result for 36 points is shown in the left figure, while a result on a detailed scan for a limited area is seen in the right figure. From relative gas gain map (Figure 6.9) and the gain curve (Figure 6.8) at one sampling point which is correspondndig to a relative gain of 1.29 in Figure 6.9, the expected mean gas gain at anode voltage of 510 V was 2100.

Anode voltage was set at 520 V. The gas gains were normalized with the mean value 4700. A gain non-uniformity was seen in both left and right figures of Figure 6.9. Detailed dependence investigation shown in the right figure revealed gain position dependencies even in a small area. For example, although the position (a) and (b) in right figure are less than 10 mm apart, their gas gain difference was more than double. Relative gas gain distribution of 36 position results is shown in Figure 6.10. The standard deviation of this LBG μ -PIC gas gain result is 30% ($=\sigma_{LBG30cm}$). Same parameter of LA μ -PIC was 16 ± 3 % ($=\sigma_{LA30cm}$), for reference [43]).

As a result of this investigation, the followings were found.

- A gas gain non-uniformity was seen, as shown in Figure 6.9. The position dependence had a small-scale ($< 10\text{mm}$) structure.
- The mean gas gain 2100 at anode voltage of 510 V was achieved.
- The gas gain is larger than 1000 at all the sampled positions, which satisfies the requirement for the gas gain.

6.3.3 LBG μ -PIC structure

The electrodes were investigated with an optical microscope in order to investigate the reason of the gain non-uniformity. A Keyence VHX-2000[61] system at Kobe University was used for this investigation. Figure 6.11 and Figure 6.12 are photographs taken with the microscope. Figure 6.11 is a detailed view of a low gain position and Figure 6.12 is a detailed view of a high gain position. They are indicated as (a) and (b) in Figure 6.9 (a) and (b). In Figure 6.11, almost all anodes look small and narrow at the top area, in contrast to the anodes in Figure 6.12. More close-up photos and cross section profiles of Figure 6.11 and 6.12 are Figure 6.13 and Figure 6.14, respectively. The cross section profile was also taken with the microscope. From these cross section profile, an anode of high gain position was found to have been well formed and the surface of the anode was formed to the same height as that of cathode (Figure 6.13). However for the low gain position, the anode was not formed well and was found to be buried in the resin (Figure 6.14).

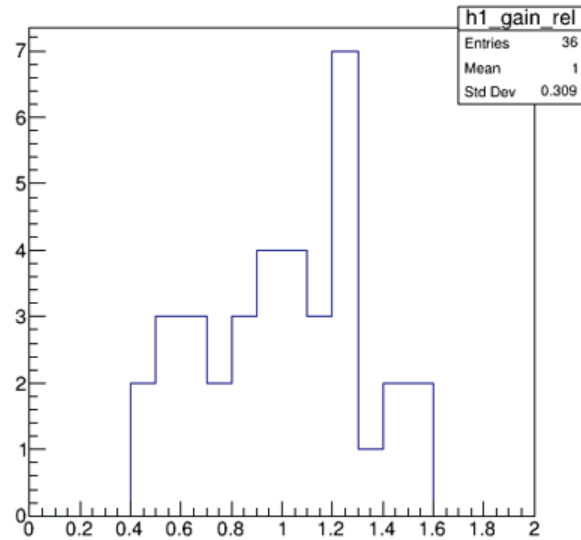
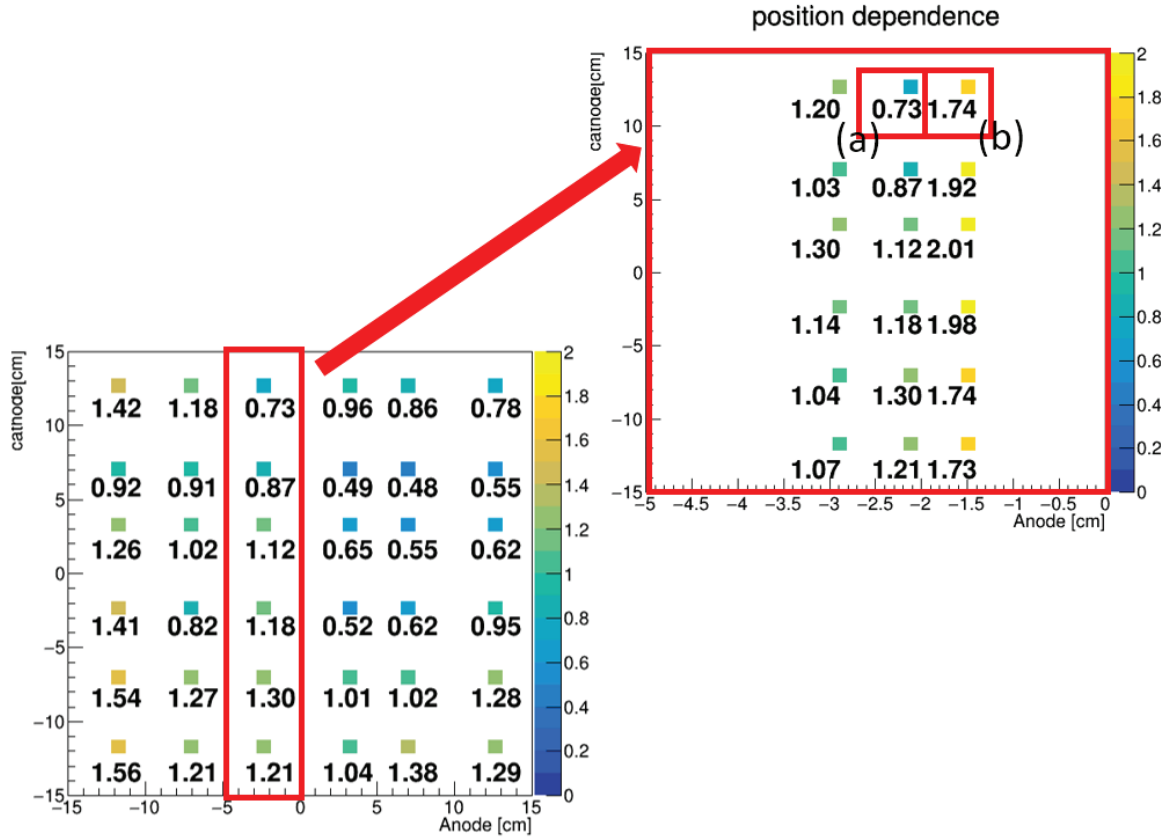


Figure 6.10: Distribution of relative gas gains of the LBG μ -PIC.

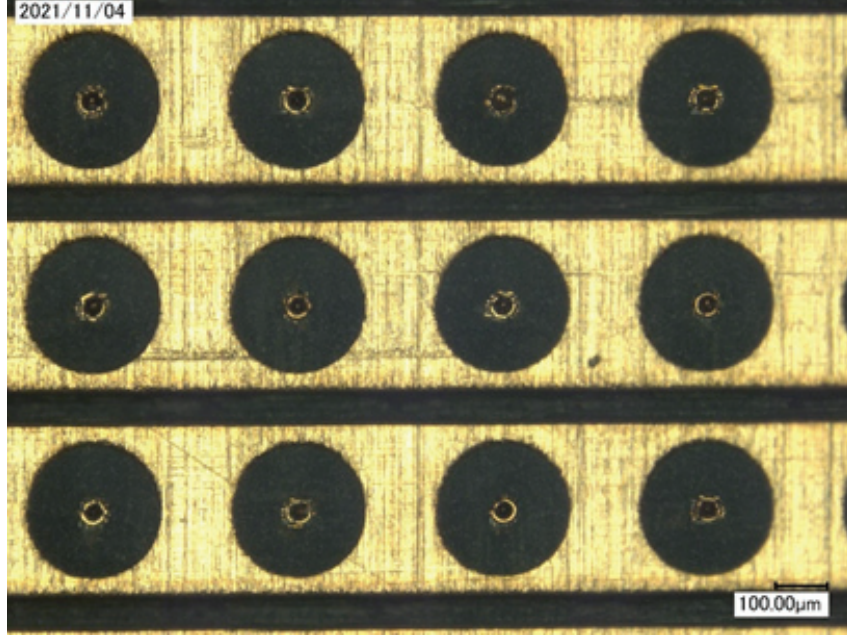


Figure 6.11: A detailed view of the electrodes in the low-gain area indicated as (a) in Figure 6.9.

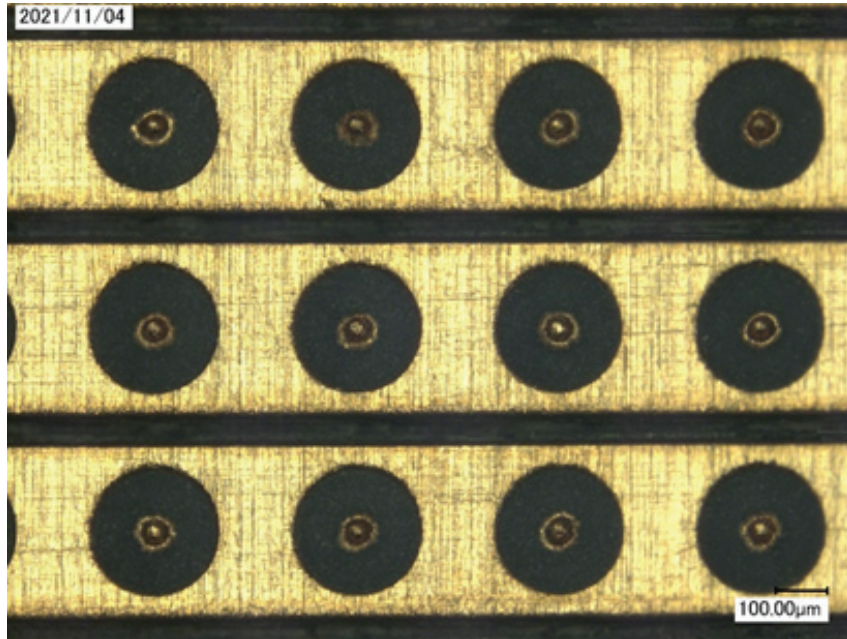


Figure 6.12: A detailed view of the electrodes in the high-gain area indicated as (b) in Figure 6.9.

6.3.4 Gas gain and detector structure

In a previous research on the μ -PIC [62], the gas gain was found to strongly depend on the anode height from measurement and simulation study. When anode height was very low, electrons are not collected to the anode properly but end up on the area between anode and cathode in the simulation study. In this LBG μ -PIC case, if some part of anodes are

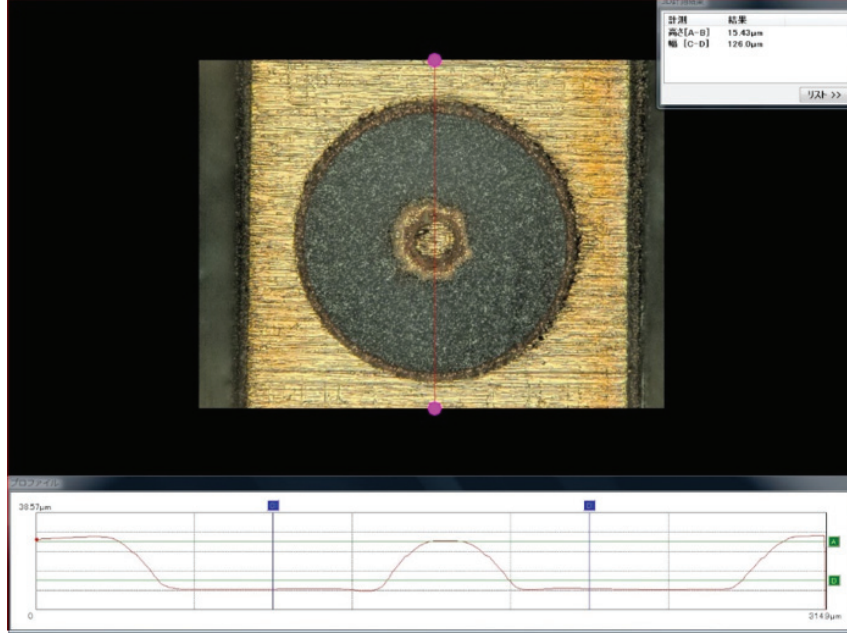


Figure 6.13: Microscope view of an anode electrode in the high-gain area of the LBG μ -PIC(top) and its cross section profile (bottom).

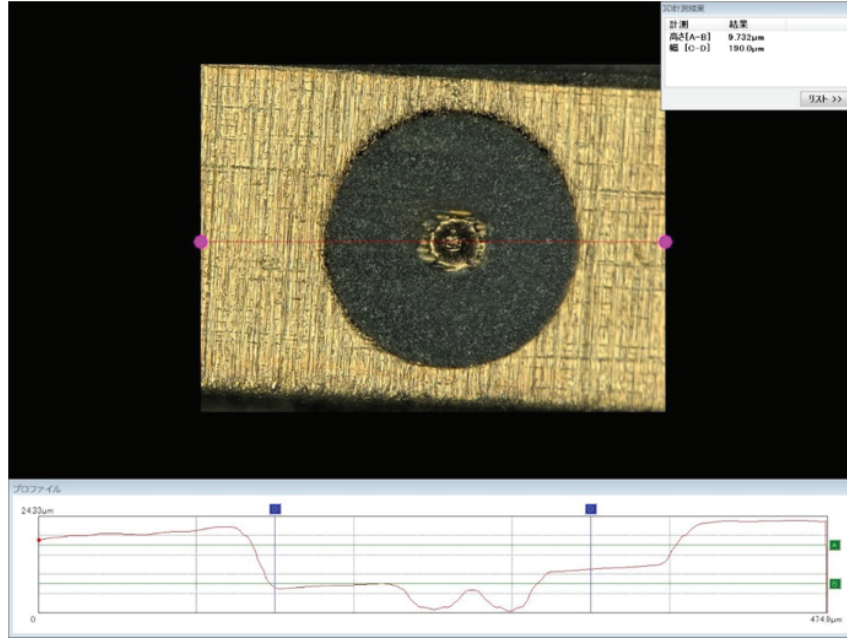


Figure 6.14: Microscope view of an anode electrode in the low-gain area of the LBG μ -PIC(top) and its cross section profile (bottom).

not well formed and their height is very low, gas gain of the these anode location could be low.

We confirmed this dependence by an updated simulation. The setup of the simulation was as follows. For the geometry and the electric field calculation, gmsh[63] and Elmer[64] were used. Garfield++[65] was used for the gas gain simulation. The gas and pressure were same as the ones for the measurement. The geometry and electric field were imported

from the elmer calculation results. To simulate the anode height dependence of the gas gain, the anode height were scanned in the simulation. The simulation result is shown in Figure 6.16.

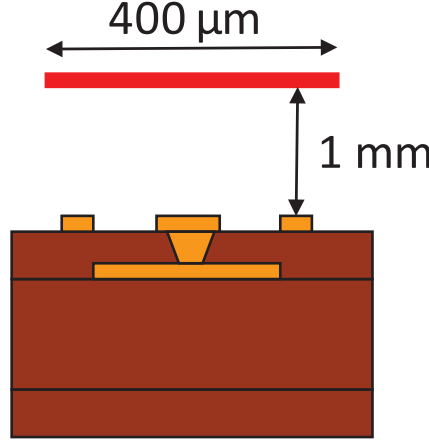


Figure 6.15: Start position of electrons in Garfield++ simulation (start position is marked as a red line in this Figure). This figure is taken from [44]

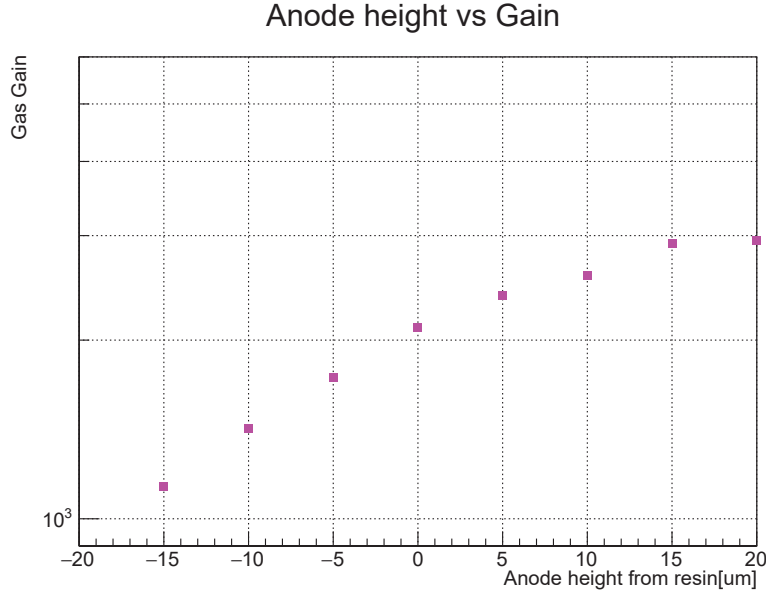


Figure 6.16: Garfield++ simulation results for the gain dependence on the anode height.

In Figure 6.16, anode height from resin = 15 μm is the design value of the LBG μ -PIC. Gas gain drops and halves at anode height at about -5 to -10 μm . This anode height dependence of the gas gain could contribute the gas gain non-uniformity result of the LBG μ -PIC, at least partially. The possible reasons of this gas gain drop at very low anode height is as follows. It is possible that when the distance between cathode top and anode top is longer than the normal μ -PIC distance, the effective electric field is weaker and the gas gain drops. It is also possible that because some part of electric flux from the

cathode go through the resin part of μ -PIC, the collected electrons by electric field will end up on the resin and these electrons do not contribute to the gas gain.

One hypothesis of the reason why the anodes were low is that the anode electrodes were over-etched because of the fluctuation of the copper layer. Etching process to anode and cathode might have “washed out” the anodes. Investigating of the cause of this was the remaining task for the future improvement of the next low background detector.

6.4 Surface alpha-ray emission measurement

We measured surface alpha-ray emission rate of LBG μ -PIC with Ultra-Lo. This result and the results of materials are compared in this subsection. Material for the LBG μ -PIC, copper sheet and quartz with resin results, are shown in Table 6.4. From the area ratio of these materials used on the top of the detector, the weighted rates were calculated (listed as “Weighted” in the table). The material-level alpha-ray emission rate was found to be consistent with the one of the final product (LBG μ -PIC) within the error. This result confirmed that there was no contamination of surface alpha-ray during the detector production process; materials were handled appropriately as described in Section 6.2.1.

Sample	$2.5 < E < 4.8 \text{ MeV}$	$4.8 < E < 5.8 \text{ MeV}$	Total
Copper sheet(12 μm)	$(1.94 \pm 0.46) \times 10^{-4}$	$(1.14 \pm 0.36) \times 10^{-4}$	$(3.08 \pm 0.58) \times 10^{-4}$
Quartz + Resin	$(3.82 \pm 0.46) \times 10^{-4}$	$(2.29 \pm 0.36) \times 10^{-4}$	$(6.11 \pm 0.58) \times 10^{-4}$
Weighted	$(2.75 \pm 0.65) \times 10^{-4}$	$(1.63 \pm 0.51) \times 10^{-4}$	$(4.38 \pm 0.82) \times 10^{-4}$
LBG μ -PIC	$(2.50 \pm 0.41) \times 10^{-4}$	$(2.12 \pm 0.28) \times 10^{-4}$	$(4.62 \pm 0.41) \times 10^{-4}$

Table 6.4: Ultra-Lo surface alpha-ray measurement results of the manufactured LBG μ -PIC and its component of materials. In this table, the unit of the alpha emission is $\alpha/\text{cm}^2/\text{hr}$. “Weighted” means the expected alpha emission rate from LBG μ PIC calculated by taking into account the area ratio of copper sheet and quartz with resin.

6.5 Radon emanation measurement

Radon emanation of the LBG μ -PIC was measured with the radon detector described in Section 4. ^{222}Rn was measured in this measurement. The circulation system was not used for this measurement to avoid the effect of the background in the circulation systems.

The results of the radon emanation measurement, ^{214}Po decay count rate, are shown in Figure 6.17 and Figure 6.18 for the LBG μ -PIC and LA μ -PIC measurements, respectively. The background data was also taken without any sample and the result is shown in Figure 6.5. Results of these measurements are summarized in Table 6.5.

In the same way as described in Chapter 4, measured time evolution of the count rate of ^{214}Po was fitted with a function $A \times (1 - 2^{-x/T})$, excluding the data of first day. Parameter A was treated as the count rate of ^{214}Po , at a radioactive equilibrium. (x : elapsed time from the air was filled. T : half-life of ^{222}Rn)

In Table.6.5, the raw count rates of ^{214}Po and calculated radon emanation rates for three measurements are summarized. A significant radon emanation reduction from the LA μ -PIC was observed. The radon emanation rate of the LBG μ -PIC and the BG were consistent to each other within statistical error. The absolute humidity in the vessel

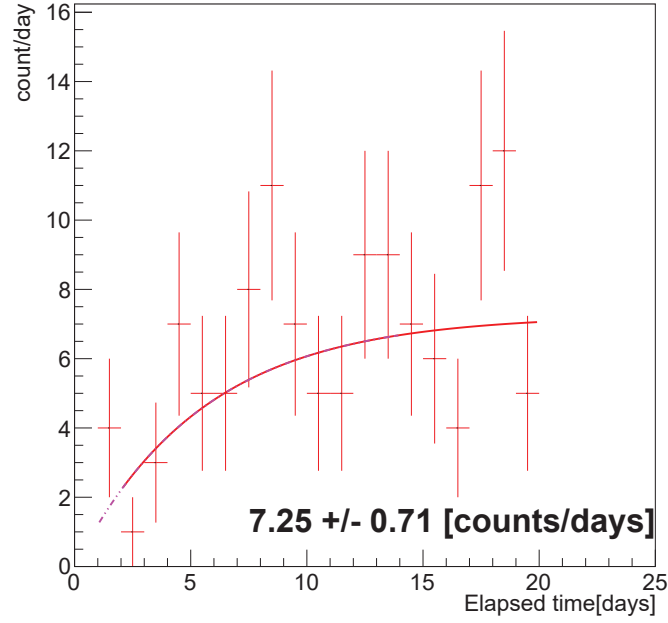


Figure 6.17: ^{214}Po count rate as a function of the elapsed date for the LBG μ -PIC.

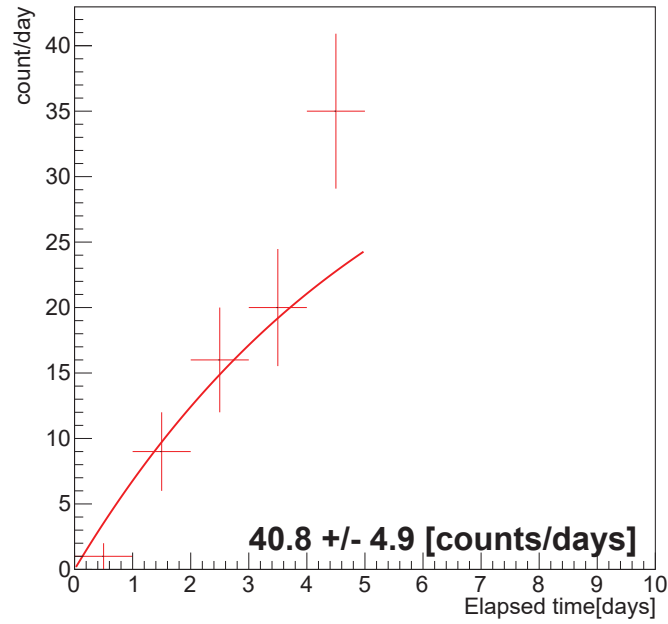


Figure 6.18: ^{214}Po count rate as a function of the elapsed date for the LA μ -PIC.

during these measurements was in the range of shadow in Figure 4.7. In this range, no significant absolute humidity dependence of the calibration factor was expected so the ^{214}Po count rates can be used for the rate comparison between sample measurements.

Table 6.6 shows the radon emanation results after the BG subtraction. LA μ -PIC - BG

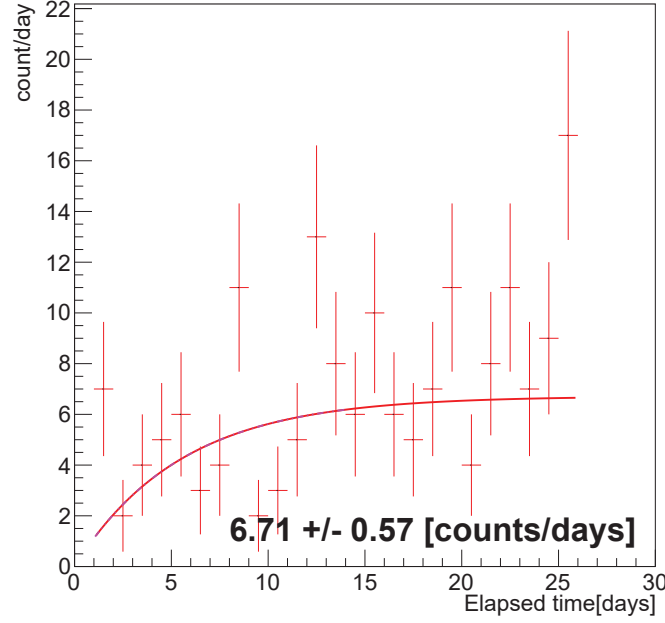


Figure 6.19: ^{214}Po count rate as a function of the elapsed date for the BG.

Table 6.5: Radon emanation measurement results

Sample	Duration[days]	^{214}Po rate [count/day]	[mBq/m ³]
LBG μ -PIC	20.0	7.25 ± 0.71	18.1 ± 2.9
LA μ -PIC	5.0	40.8 ± 4.9	102.0 ± 18.3
BG	26.0	6.71 ± 0.57	16.9 ± 2.4

Table 6.6: Radon emanation measurement results after the background subtraction.

Sample	^{214}Po rate [count/day]	[mBq/m ³]	[mBq/ μ -PIC]
LA μ -PIC – BG	34.1 ± 4.9	85.2 ± 17.4	2.3 ± 0.5
LBG μ -PIC – BG	0.5 ± 0.9 <2.3 (90 % C.L.)	1.3 ± 2.3	0.04 ± 0.06 <0.17 (90 % C.L.)

is the rate of LA μ -PIC minus BG and LBG μ -PIC – BG is the rate of LB μ -PIC minus BG. The radon emanation rate of the LA μ -PIC, currently used in NEWAGE, was obtained for the first time. The radon emanation rate from the LA μ -PIC was 2.3 ± 0.5 [mBq/ μ -PIC]. While that for the LBG μ -PIC was 0.04 ± 0.06 [mBq/ μ -PIC], which corresponds to upper limit of this rate is 0.17 [mBq/ μ -PIC]. The reduction ratio of radon emanation could be estimated using only ^{214}Po rate from this result and other parameters, such as volume and Calibration Factor, were not used.

An upper limit of 2.3 [count/day] was set to the LBG μ -PIC (BG subtracted) rate from this measurement. As a ratio of radon emanation reduction, mean values of LA μ -PIC and LBG μ -PIC after subtracting the background were used and the reduction rate was calculated to be $34.1/2.3 = 14.8$. From this, it was confirmed that radon emanation form

the μ -PIC was reduced by more than one order of magnitude from the LA μ -PIC to the LBG μ -PIC by changing the materials. This result was consistent with that the reduction ratio of U/Th chain contaminations in the detector material was less than one hundredth, discussed in Section 5.2. The confirmed reduction rate of radon emanation was one tenth because the sensitivity of this radon detector was limited due to the radon detector's background level, about 20 [mBq/m³].

Feasibility of ^{220}Rn measurement

As discussed in the previous section, ^{222}Rn emanation was reduced by the replacement of the detector material. However, the measurement confirmed the reduction of only ^{222}Rn and not ^{220}Rn . In section 5.2, ^{220}Rn was counted as the serious background source of NEWAGE. This is because ^{222}Rn could be removed by cooled charcoal but ^{220}Rn was difficult to remove due to its short half-life.

The detection efficiencies of ^{222}Rn and ^{220}Rn as a function of pressure were reported in a previous study[66] and the research shows that ^{220}Rn detection efficiency is the maximum at about 20 mbar (1 atm = 1013.25 mbar), very lower pressure than atmospheric pressure, with their radon detector setup. This is because that the velocity of ions at low pressure is faster than that at atmospheric pressure, and it is needed to collect $^{216}\text{Po}^+$, which is ^{220}Rn 's progeny and has only 145 ms half-life, before it decays. In addition to this, due to the short of half-life of ^{220}Rn gas should not be circulated in the gas system. It is also preferable that the distance between the PIN-PD and the sample is close and they are in the same vessel to collect $^{216}\text{Po}^+$ rapidly. From these reasons, a radon detector with low pressure will be required to measure ^{220}Rn concentration and emanation in a gas with our detector.

The ^{220}Rn emanation rate will be estimated in Section 7.2.1 using the HPGe results and ^{222}Rn emanation result.

6.6 Summary

A micro pattern gaseous detector "LBG μ -PIC" was developed as a low background detector for a dark matter search experiment, NEWAGE. The gas gain measurement showed a gas gain non-uniformity which was two times larger than that of LA μ -PIC. This non-uniformity was observed even in very small area of 1 cm. From observations with microscope and simulation study, this gain non-uniformity could be attributed to the anode formation failure and this should be fixed at the next production of the low background detector. A new radon detector was developed and the method to measure radon emanation from $40 \times 40 \text{ cm}^2$ size sample and established. Low background materials, which contain very small amount of radioactive contamination, were selected as the component materials for the LBG μ -PIC. Thanks to that, the radon emanation of LBG μ -PIC was more than one order of magnitude lower than that of the LA μ -PIC.

7 Discussion

An expected sensitivity of NEWAGE with the LBG μ -PIC developed in this study is discussed in this chapter.

7.1 Gain uniformity

LBG μ -PIC achieved a mean gas gain of 2100 with a position dependence of 30 % of σ/E at 510 V as reviewed in Section 6.3. With this detector performance, over 90 % of 50 keV nuclear recoil events can be multiplied by gas gain of more than 1000 with the LBG μ -PIC. The LBG μ -PIC satisfies the requirements for the dark matter search which was defined in Section 6 in the terms of detecting nuclear recoil events. A relative gas gain map of LBG μ -PIC was measured as shown in Figure 6.9 in chapter 6. By using this gas gain map, gas gain position dependence of the LBG μ -PIC can be corrected and this enables the detector to measure the recoil energy more precisely and energy resolution will be improved.

7.2 Background reduction and sensitivity

A WIMP sensitivity improvement will be discussed based on the reduction ratio of the backgrounds of LBG μ -PIC.

7.2.1 Radon emanation reduction

As described in Chapter 5, the main background sources of the NEWAGE are the ambient gamma-rays, ambient neutrons, ^{222}Rn and ^{220}Rn . The count rate of ambient gamma-rays and ambient neutrons as external backgrounds between 50-60 keV are estimated to be 1.5 ± 1.5 and $(3.5 \pm 0.9) \times 10^{-1}$ [count/keV/kg], respectively[56]. As internal backgrounds, the count rate of ^{222}Rn and ^{220}Rn as internal backgrounds between 50-60 keV are estimated to be $(5.3 \pm 2.2) \times 10^{-2}$ and $(6.1 \pm 0.7) \times 10^{-1}$, respectively. ^{220}Rn and ^{222}Rn backgrounds are thought to be fatal because they are emanated from the material in the detector semi-permanently. The radioactive contaminations of newly developed LBG μ -PIC was investigated. The amount of ^{222}Rn emanation from LBG μ -PIC was found to be reduced to one-fifteenth of the amount of that from LA μ -PIC. Although the reduction ration of ^{220}Rn was not directly confined in the radon emanation measurement due to ^{220}Rn 's short half-life time, as discussed in Section 6.5, it can be estimated from the HPGe results and the reduction ratio of ^{222}Rn emanation radon. To estimate the ^{220}Rn emanation rate, an effective emanation depth D_e is introduced. This is a parameter based on a simple model: here we assume that radons can emanate from the depth less than D_e before they decay. An effective emanation area S_e is also introduced. The amounts of uranium and thorium chain contaminations in a unit volume are defined as C_U and C_{Th} , respectively. Because ^{220}Rn has shorter half-life (55.6 seconds) than ^{222}Rn (3.82 days) does, D_e of ^{220}Rn ($= D_{e,Th}$) will be much less than that of ^{222}Rn ($= D_{e,U}$). This model leads to effective volumes $S_e D_{e,Th}$ and $S_e D_{e,U}$, from which ^{220}Rn and ^{222}Rn can emanate, respectively. Therefore the estimated radioactivity in the area can be expressed as $S_e D_{e,Th} C_{Th}$ and $S_e D_{e,U} C_U$. The estimated radon emanation rate per area per depth calculated from the amount of uranium and thorium chain contaminations (in Table 5.3 and Table 6.1) is

shown in Table 7.1. In Table 7.2, the area of the each material part and the estimated emanation rate per μm of radons are summarized. Using this table and the effective depth of radon emanation, radon emanation rates can be estimated.

Material	Density[g/cm ³]	C_U [mBq/cm ² / μm]	C_{Th} [mBq/cm ² / μm]
LA μ -PIC core	1.86	1.80×10^{-6}	2.59×10^{-6}
LBG μ -PIC core	1.60	1.11×10^{-8}	7.80×10^{-9}
Solder resist	1.09	5.28×10^{-7}	1.86×10^{-8}

Table 7.1: Radon emanation rates per area[cm²] and depth[μm], C_U and C_{Th} for ^{222}Rn and ^{220}Rn , respectively.

μ -PIC type	Part	S_e [cm ²]	$S_e C_U$ (^{222}Rn) [mBq/ μm]	$S_e C_{Th}$ (^{220}Rn) [mBq/ μm]
LA	Solder resist	2300	1.21	0.04
LA	Core	450	0.81	1.16
LA	Total	-	2.02	1.20
LBG	Solder resist	153	0.08	0.003
LBG	Core	2147	0.024	0.017
LBG	Total	-	0.104	0.020

Table 7.2: Effective surface areas of μ -PIC's part S_e and estimated radon emanation $S_e C_U$ and $S_e C_{Th}$ for ^{222}Rn and ^{220}Rn , respectively.

In Chapter 6, the upper limit of 15 mBq was set on the ^{222}Rn emanation rate of the LBG μ -PIC. An independent estimation from the HPGe measurement provides the radon emanation rate per depth is $S_e C_U = 0.104$ [mBq/ μm]. These two parameters give an effective depth of ^{222}Rn emanation from LBG μ -PIC as $D_{e,U} = 0.15$ [mBq] / 0.104 [mBq/ μm] = 1.5 [μm].

Because the half-life of ^{222}Rn (3.82 days) is much longer than that of ^{220}Rn (55.6 seconds), ^{222}Rn has the larger chance of emanating into gas from the material than that of ^{220}Rn . Therefore it is natural to assume $D_{e,U} \gg D_{e,Th}$. Then the effective depth $D_{e,U}$ is used for ^{220}Rn emanation depth, $D_{e,Th}$, as a very conservative assumption. We then obtain that an upper limit of ^{220}Rn radioactivity from the LBG μ -PIC is $1.5 \mu\text{m} \times 0.020$ [mBq/ μm] = 0.03 [mBq].

With the volume of NEWAGE's TPC, 0.123 m^3 , the estimated ^{220}Rn concentration in NEWAGE TPC can be calculated to be 0.24 [mBq/m³]. From Chapter 5 ([56]), ^{220}Rn concentration was estimated to be 5.7 ± 0.3 [mBq/m³]. Comparing these results, ^{220}Rn reduction ratio from LA μ -PIC to LBG μ -PIC can be estimated to be more than a factor of 20. From this result and the ^{222}Rn concentration measurements result shown in Chapter 6, NEWAGE background rate of ^{222}Rn and ^{220}Rn will be reduced by factor 15 and 20, respectively.

7.2.2 Background reduction

Before LBG μ -PIC was developed, even if the outer shield was placed on the NEWAGE detector to reduce ambient gamma and ambient neutron, ^{220}Rn was still remaining as

the main component of the backgrounds and the sensitivity cannot be improved. Radon emanation background is expected to be reduced with the LBG μ -PIC, as discussed in previous section. The main background of NEWAGE is also ambient gamma-ray, but radon background of NEWAGE can be reduced by using LBG μ -PIC so the reduction of ambient gamma-ray background is directly leading to improve the sensitivity of NEWAGE. From previous background study with simulation[56], with water and lead shield both ambient gamma-rays and ambient neutrons backgrounds are expected to be reduced by more than factor 10 (Section 5.2.1). From Chapter 6, the reduction ratio of ^{222}Rn was estimated to be factor 15 with the radon detector and from previous subsection the reduction ratio of ^{220}Rn was estimated to be more than factor 20, with installing LBG μ -PIC in the detector.

7.2.3 Sensitivity estimation

Having all the measurement and assumptions as discussed above, an overall background rate estimated with the background reduction by this study is shown in Table 7.3 together with the previous one (RUN 22) as the reference. We assumed a reduction of factor 10 for the ambient gamma-rays and neutrons. The background rate will be reduced to less than 1/10 that of RUN22 and a corresponding expected sensitivity of the NEWAGE is shown in Figure 7.1. A improvement of more than factor 10 from RUN22 is expected.

Source	RUN 22	w/ LBG μ -PIC
Ambient gamma-rays	1.5 ± 1.5	$(1.5 \pm 1.5) \times 10^{-1}$
Ambient neutrons	$(3.5 \pm 0.9) \times 10^{-1}$	$(3.5 \pm 0.9) \times 10^{-2}$
^{222}Rn	$(5.3 \pm 2.2) \times 10^{-2}$	$(3.5 \pm 1.5) \times 10^{-3}$
^{220}Rn	$(6.1 \pm 0.7) \times 10^{-1}$	$(3.1 \pm 0.4) \times 10^{-2}$
μ -PIC surface	$< 1.2 \times 10^{-1}$	$< 1.2 \times 10^{-1}$
Total	2.5 ± 1.5	$(2.2 \pm 1.5) \times 10^{-1}$

Table 7.3: Estimated number of backgrounds summary in 50-60 keV (RUN22[32]), and expected background with LBG μ -PIC and shieldings (w/ LBG μ -PIC).

As shown in Table 7.3, with LBG μ -PIC and the outer shieldings the background rate in 50-60 keV can be reduced by over one-tenth. The expected sensitivity to WIMP of NEWAGE from this backgrounds reduction is shown in Figure 7.1, assuming an exposure of 11 kg-days, ten times of the one at RUN22 (107.6 days, 1.12 kg-days).

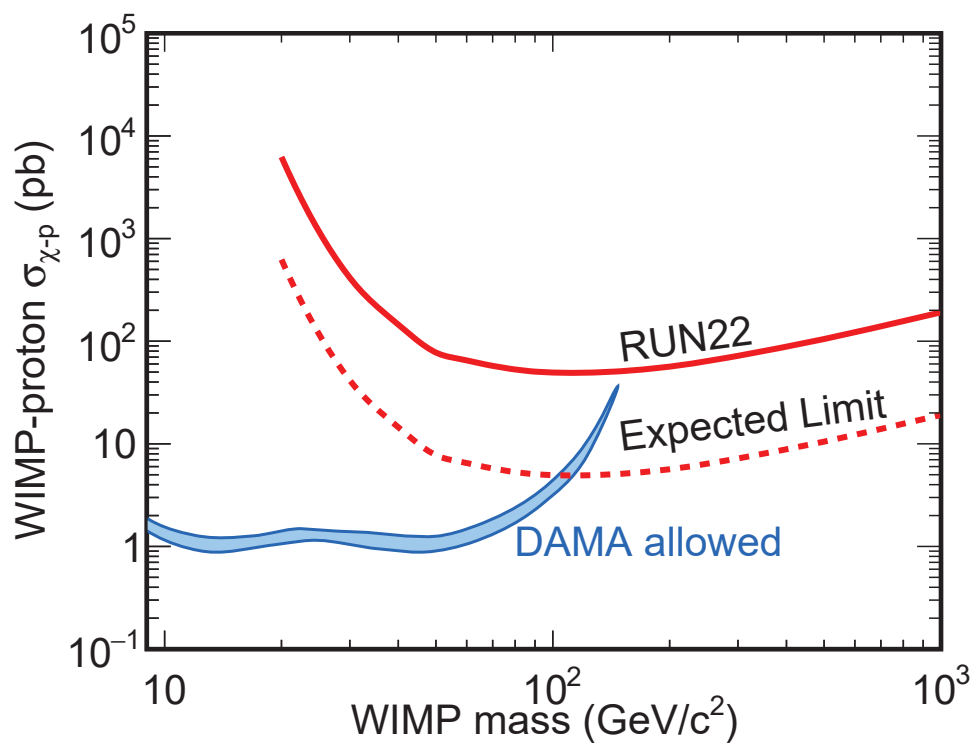


Figure 7.1: Upper limits (90% C.L.) on the SD WIMP-proton cross-section as a function of the WIMP mass. Expected sensitivity from the background using the LBG μ -PIC and external shield with an 11 kg $\cdot$ days exposure is shown as red dotted line.

8 Conclusions

NEWAGE is a directional sensitive dark matter search experiment with a μ -TPC using a μ -PIC as a readout device. Radon backgrounds from the decay of U/Th chain contaminations in materials used in the μ -PIC were found to be backgrounds that limited the sensitivity to the dark matter of NEWAGE. We developed a low background μ -PIC, LBG μ -PIC, which used materials with less radioactive contaminations than the previous one, LA μ -PIC. LBG μ -PIC with a detector size of $30 \times 30 \text{ cm}^2$ was produced in this development. Materials used in the LBG μ -PIC were screened with the HPGe detector and the surface alpha-ray counter in advance. The performance of the LBG μ -PIC as an MPGD was measured. The LBG μ -PIC showed the gas gain of 2100 at 760 Torr argon-ethane (9:1) mixture with an anode voltage of 510 V. This gas gain was sufficient for detecting nuclear recoil events at the dark matter search experiment. A radon detector was newly developed to measure emanation rate of the isotope of radon, ^{222}Rn , from the μ -PICs. The ^{222}Rn emanation rate from the LA μ -PIC was measured for the first time. The emanation rate from the LBG μ -PIC was found to be less than 1/15 of that from the LA μ -PIC. ^{220}Rn emanation rate from the LBG μ -PIC was estimated to be 1/20 of the rate of the LA μ -PIC using the reduction ratio of the ^{222}Rn emanation and the amount of radioactive contaminations in the detector materials. The total backgrounds rate in the detector's energy region of 50-60 keV was estimated to be less than 1/10 of the rate of the previous run. An expected dark matter search sensitivity of the NEWAGE was improved by about 10 times compared to the previous run by assuming the reduced background rate and 11 kg·days exposure.

9 Appendix

9.1 Uranium / Thorium decay chain

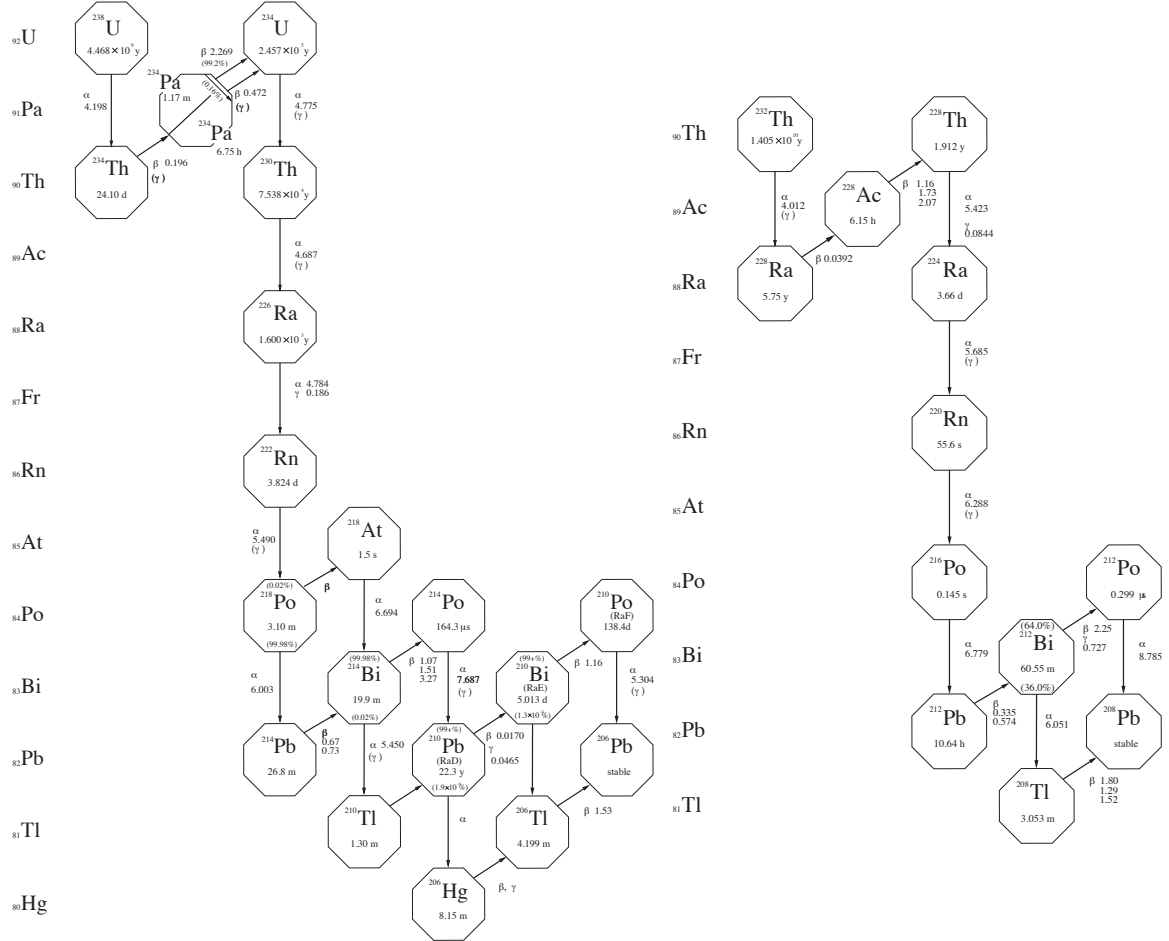


Figure 9.1: Decay diagram of uranium and thorium chains[67].

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