Performance of the drift chamber beta-ray momentum analyzer for double beta decay experiments

N. Ishihara\textsuperscript{1,2,*}, T. Ohama\textsuperscript{1}, Y. Yamada\textsuperscript{1}, Y. Kato\textsuperscript{1,3}, T. Inagaki\textsuperscript{1}, G. Iwai\textsuperscript{1}, H. Iwase\textsuperscript{1}, M. Kawai\textsuperscript{1}, Y. Kondou\textsuperscript{1}, Y. Makida\textsuperscript{1}, K. Takahashi\textsuperscript{1}, N. Ujiie\textsuperscript{1}, K. Tanaka\textsuperscript{3}, M. Tonooka\textsuperscript{3}, R. Hamatsu\textsuperscript{4}, T. Ishikawa\textsuperscript{4,10}, H. Igarashi\textsuperscript{4,11}, T. Ito\textsuperscript{4}, M. Kakizaki\textsuperscript{4,12}, H. Kakuno\textsuperscript{4}, S. Kitamura\textsuperscript{4}, T. Sumiyoshi\textsuperscript{4}, T. Yoshioka\textsuperscript{4}, T. Ishizuka\textsuperscript{6}, N. Tamura\textsuperscript{6}, Y. Sakamoto\textsuperscript{7}, Y. Nagasaka\textsuperscript{8}, and R. Ito\textsuperscript{9}

\textsuperscript{1}High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801, Japan
\textsuperscript{2}The Graduate University for Advanced Studies, Hayama, Kanagawa 240-0193, Japan
\textsuperscript{3}SCTEC, 1-4-31 Yaba, Gyoda-cho, Saitama 361-0051, Japan
\textsuperscript{4}Tokyo Metropolitan University, Hachioji, Tokyo 192-0398, Japan
\textsuperscript{5}Fukuoka Institute of Technology, 3-30-1 Washirohigashi, Higashi-ku, Fukuoka 811-0295, Japan
\textsuperscript{6}Niigata University, 8050 Ikarashi 2-no-cho, Niitsu-ku, Niigata 950-2181, Japan
\textsuperscript{7}Tohoku Gakuin University, 2-1-1 Tenjinzawa, Izumi-ku, Sendai, Miyagi 981-3193, Japan
\textsuperscript{8}Hiroshima Institute of Technology, 2-1-1 Miyake, Saeki-ku, Hiroshima 731-5193, Japan
\textsuperscript{9}Smart Education, Ltd., 2-4-2 Nishigotanda, Shinagawa-ku, Tokyo 141-0031, Japan
\textsuperscript{10}Present address: Japan Atomic Energy Agency, Oarai, Chiba, 305-0804, Japan
\textsuperscript{11}Present address: REPLIC, 2-28-4 Nishi-ku, Tokyo 170-0004, Japan
\textsuperscript{12}Present address: Fukushima Prefecture, 2-16 Sugita, Suwa, Nagano 395-3193, Japan

\textsuperscript{*}E-mail: nobuhiro.ishihara@kek.jp

Received March 15, 2017; Revised May 11, 2017; Accepted May 29, 2017; Published July 29, 2017

One of the most important problems in neutrino physics is whether neutrinos are Majorana particles or Dirac ones. If a neutrino has a Majorana nature, neutrinoless double beta decay (0νββ) certainly takes place. On the other hand, there is a theory in which neutrinoless quadruple beta decay (0ν4β) is possible, allowing for lepton number violation by four units, even if a neutrino has a Dirac nature. Since the half-lives of both 0ν2β and 0ν4β are theoretically expected to be very long, detectors have to have an excellent capability to eliminate backgrounds. We have been developing a series of electron momentum analyzers called the drift chamber beta-ray analyzer (DCBA) at KEK for double beta decay experiments. DCBA consists of drift chambers detecting charged particle tracks, and a superconducting solenoid serving a uniform magnetic field. Since the momentum acceptance is in the region of 0.5–3.5 MeV/c, it is easy to eliminate background particles like alpha particles, protons, and muons, which have much higher momenta because of their large masses. The particle identification property and the 3D position determination capability are powerful tools to search for 0ν2β and 0ν4β events. In this article, we describe the performance of DCBA as well as the details of the detector construction processes.

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1. Introduction

It has been confirmed by neutrino oscillation experiments that neutrinos have mass [1–4]. However, neutrino oscillations take place whether neutrinos are Majorana particles or Dirac ones. If the Majorana nature of neutrinos exists, the seesaw mechanism will be supported, which would naturally explain why the known neutrinos are so light [5,6]. Also, so-called leptogenesis, in which the
extremely heavy right-handed neutrino in the seesaw mechanism plays important roles, becomes a possible scenario in the early universe [7]. The experiment of neutrinoless double beta decay (0ν2β) is realistically the only way to confirm the Majorana nature, and in addition its half-life measurement can determine the absolute mass scale of the neutrino with the help of the nuclear matrix element calculation [8,9]. However, the 0ν2β event has not yet been confirmed.

On the other hand, even if neutrinos are Dirac particles, it has been pointed out by J. Heeck and W. Rodejohann that neutrinoless quadruple beta decay (0ν4β) is possible by constructing a simple model that allows for lepton number violation by four units [10]. The half-life of 0ν4β is theoretically estimated as longer than that of 0ν2β.

A lot of experiments searching for 0ν2β and/or 0ν4β are in progress and scheduled all over the world, as presented at the Neutrino 2016 conference [11].

In order to study 0ν2β and 0ν4β against many backgrounds, a detector has to have excellent capabilities for (i) energy resolution at the Q-value, (ii) elimination of backgrounds, and (iii) accommodation of a sufficient decay source amount.

We have been developing a series of momentum analyzers called the drift chamber beta-ray analyzer (DCBA) at KEK for realizing these capabilities [12–16]. DCBA can selectively obtain the momentum of each electron in a limited region by measuring the radius and the pitch angle of a helical track in a uniform magnetic field. In order to show the performance of DCBA, this article presents the design philosophy, characteristics of drift chambers, and a superconducting solenoid magnet, together with some experiences of data analyses for the half-life measurement of two-neutrino double beta decay (2ν2β) from 100Mo. Several discussions will be also presented about background events and a future project called the magnetic tracking detector (MTD), searching for 0ν2β and 0ν4β.

2. Design philosophy of DCBA

There are two types of detector for double beta decay experiments that have been carried out and will be proposed in the future [11]. One is called the calorimetry type, in which the detector and the source material are unified. This type measures the sum kinetic energy of two beta-rays. The following are examples of this type: Ge detectors for 76Ge (GERDA and MAJORANA), Te ones for 130Te (CUORE and SNO+), Xe ones for 136Xe (EXO, KamLAND-Zen, and NEXT), and scintillators/semiconductors containing source materials such as 48Ca (CANDLES) and 114Cd (COBRA).

The other is called the tracking type, where thin plates of source material are interleaved in tracking detectors. This type can measure the kinetic energy of each beta-ray and the angle between two beta-rays. It is possible to use any source material, if its thin plate is available. Only NEMO3/SuperNEMO and DCBA/MTD are of this type. The former obtain beta-ray energy using scintillation calorimeters and the latter do so by measuring its momentum.

As is well known, the sum energy spectrum of two beta-rays shows a broad bump in the case of conventional double beta decay accompanied by two antielectron neutrinos (2ν2β). In contrast, in the case of 0ν2β, the sum energy spectrum shows a spike at the Q-value. Since the theoretically expected half-life of 0ν2β is as long as 10^{25–26} y, in comparison with the half-lives of 2ν2βs, which are measured as 10^{18–20} y depending on decay nuclei, 2ν2β events near the Q-value become backgrounds in searching for 0ν2β events. Therefore the energy resolution around the Q-value is very important to find the spike.

Another method to distinguish 0ν2β events from 2ν2β ones is to measure the energy spectrum of a single beta-ray. According to Ref. [8], in the case of 2ν2β, the single beta energy spectrum shows a bump with a peak in a lower energy region than Q/2. In the case of 0ν2β, the spectrum...
shows a bump with a peak at $Q/2$ or two bumps with symmetric peak positions, depending on the production mechanisms, namely neutrino mass term dominance or right-handed current term dominance. In other words, while the single beta energy spectrum of $2\nu 2\beta$ shows an asymmetric bump, that of $0\nu 2\beta$ shows a symmetric bump. As for the production mechanism, it will be solved only by information on the angle between the two beta-rays emitted. In any case mentioned above, the transition of $0^+ \rightarrow 0^+$ is considered.

Since DCBA is able to obtain information on each beta-ray, it can measure both the single beta energy spectrum and the sum energy spectrum of two beta-rays. A kinetic energy $T$ of a single beta-ray is easily calculated from the momentum $p$ measured by DCBA as

$$T = (p^2 + m_e^2)^{1/2} - m_e,$$

where $m_e$ is the electron mass. In addition, DCBA can measure the angle between two beta-rays from their track information.

### 2.1. Nuclear decay source and backgrounds

Serious backgrounds come from natural radioactive decays of isotopes, what we call thorium and uranium decay chains. Since kinetic energies of decay products remarkably decrease beyond 3.0 MeV, $^{100}$Mo and $^{150}$Nd are adopted as decay sources, the $Q$-values of which are 3.03 MeV and 3.37 MeV, respectively. Also, the theory predicting $0\nu 4\beta$ has pointed out that $^{150}$Nd is the most favorable decay source, because the $Q$-value of the transition from $^{150}$Nd to $^{150}$Gd is the largest at 2.08 MeV [10].

Natural abundance is also an important factor to be considered. It is 9.6% for $^{100}$Mo and 5.6% for $^{150}$Nd. Though $^{48}$Ca has the highest $Q$-value of 4.27 MeV, it is out of consideration here because of its very low natural abundance of 0.19%.

Since DCBA is designed to be able to measure the momentum in the region of 0.5–3.5 MeV/c, which corresponds to a kinetic energy region of 0.2–3.0 MeV, heavy ionizing particles like muons, protons, and alpha particles are automatically eliminated because of their large momenta. Therefore, cosmic rays escaping through from veto counters are easily rejected in scanning processes.

One serious background from the decay source may be from $^{214}$Bi, the $Q$-value of which is 3.3 MeV, close to the values of $^{100}$Mo and $^{150}$Nd. Just after its single beta decay, the daughter nucleus $^{214}$Po occasionally produces an internal conversion electron of 1.32 MeV. If the electron emitted from $^{214}$Bi beta decay has an energy of around 1.8 MeV, the sum energy of the two electrons becomes close to the $Q$-value of $^{100}$Mo. However, we can eliminate the backgrounds by using the single electron energy spectrum, which will have a spike at 1.32 MeV from internal conversion electrons.

Usually the daughter nucleus $^{214}$Po emits gamma-rays instead of the internal conversion electron. When a gamma-ray causes Compton scattering in the decay source, a recoil electron sometimes comes out from the source. If the interaction points of the beta decay from $^{214}$Bi and the Compton scattering are close to each other, the event looks like a double beta decay. The $^{214}$Po decays to $^{210}$Pb by emitting an alpha-ray with a half-life of 164 $\mu$s. DCBA can detect the alpha-ray by a double buffer system installed in the data acquisition system [17], as mentioned later. Two techniques of catching an internal conversion electron and a delayed alpha emission are powerful tools to eliminate backgrounds caused by $^{214}$Bi, which we call BiPo events.

Another tough background may be from $^{208}$Tl, with a $Q$-value of 4.99 MeV. A beta decay of $^{208}$Tl into $^{208}$Pb is followed by many modes emitting gamma-rays that cause Compton scatterings. The event composed of a beta-ray from $^{208}$Tl and a recoil electron by the Compton scattering is similar to
a double beta decay event. Double Compton scattering in the decay source should also be seriously considered, because the $Q$-value of $^{208}$Pb is as high as 3.71 MeV.

The position measurement capability of DCBA is the only way to distinguish a double beta decay event from those backgrounds. DCBA can determine the original point of a track on the decay source plate. If two tracks start at the same original point, which we call the vertex point, the event is considered as a double beta decay. If the two start points are different, the event is classified as a combination of a beta-ray from $^{208}$Tl and an electron from Compton scattering or as double Compton scattering. Therefore the position resolution on the source plate is very important.

After Compton scattering, Möller scattering sometimes takes place in the source plate. This event is very difficult to distinguish from a double beta decay event by position measurement, even with excellent accuracy. However, since two electrons scattered and recoiled from Möller scattering generally have small energies, the background events may not have a serious effect on the $0\nu2\beta$ experiments, in particular in the case of the $^{150}$Nd source plate.

2.2. Tracking detector

DCBA has tracking detectors similar to jet-type drift chambers, one example of which has been used as the vertex detector [18] in the VENUS experiment at TRISTAN in KEK. This type of drift chamber has multiparticle detection capability in the wide sensitive region with the usage of a flash analog-to-digital converter (FADC). Wire numbers required in the chamber are much smaller than those of conventional drift chambers. This is favorable from the viewpoint of reducing materials in the tracking space region.

One difference between the DCBA chamber and a conventional jet chamber is that the electron drift region between the anode and cathode wire planes is covered by source plates and isolated from the next chamber. Therefore, the so-called left–right ambiguity, which complicates the track pattern, does not take place.

The relation between the momentum of the beta-ray and the radius of the helical track in a uniform magnetic field is expressed as

$$p \cos \lambda = 0.3rB,$$

where $p$ is the momentum in MeV/c, $\lambda$ the pitch angle of the helical track, $r$ the track radius in cm, and $B$ the magnetic flux density in kG.

In order to get an accurate track radius, multiple scatterings between a beta-ray and the chamber gas should be suppressed to be as small as possible. The chamber gas should also be nonflammable because double beta decay experiments are executed in underground rooms. This is why He gas mixed with a small amount of CO$_2$ is selected as the chamber gas, where CO$_2$ is a quench gas.

2.3. Solenoid magnet

In DCBA, a beta-ray suffers multiple scatterings from gas molecules, and its long trajectory is much deformed. This is the main reason for deterioration of the energy resolution. Thus a smaller curvature is desired to reduce the effect of multiple scattering. Equation 2 shows that a larger $B$ can reduce $r$ under the same $p$.

In the previous test facility, DCBA-T2, the magnetic flux density was limited to 0.8 kG maximum in a cylindrical volume of 0.5 m diameter and 1.0 m length, because the electric power supply was not available to operate the conventional copper conductor solenoid beyond 0.8 kG.
Fig. 1. A picture of DCBA-T2.5. The signal cables mentioned in Sect. 3.3 come out through the holes of the SCSM endplate to the FADC crate controller.

In order to search for $0\nu\beta\beta$ and investigate the effective neutrino mass $<m_{\beta\beta}>$ down to 30–50 meV, we need an energy resolution better than 5.0% (FWHM) at the $Q$-value. According to simulation studies using Geant4, the magnetic flux density in DCBA-T3, which is the next step in the DCBA series, is required to be around 2.4 kG to realize an energy resolution of about 4% (FWHM), as discussed later.

From the viewpoint of energy saving, a superconducting solenoid magnet (SCSM) is the most suitable device to produce the required flux density uniformly in a large volume and thus DCBA-T3 SCSM has been constructed and operated to measure its magnetic field [19]. Since the operation of the SCSM is much easier than that of the conventional magnet used in DCBA-T2 and the drift chambers of DCBA-T3 are now under construction, the present experiment has been executed with a combination of DCBA-T2 drift chamber and DCBA-T3 SCSM. Therefore we call the present facility DCBA-T2.5, which was operated at 0.8 kG for three years and at 0.6 kG for two years intermittently, as described in Sect. 6. A picture of DCBA-T2.5 is shown in Fig. 1.

3. Details of detector components

3.1. Drift chamber and source plate

Figure 2 shows the endplates supporting the wires of a pair of drift chambers. The right-handed coordinate system is also depicted in the figure, where the $X$ and $Z$ axes are horizontal and $Y$ is vertical. The $Z$ axis is also defined as a magnetic field direction. One can see the wire configurations of the drift chambers from the pattern of the endplate drawings.

A decay source plate is installed in the central part between the two left and right drift chambers. The plate is composed of two sheets of 50 μm thick molybdenum (Mo), which are laid out and interleaved between two aluminum window frames, 1 mm thick each, as shown in Fig. 3. In the figure, the size of one window is 130 mm and 280 mm in the $Y$ and $Z$ directions, respectively.
Fig. 2. Drawings of chamber endplates showing wire configurations. The front view endplate (a) shows the anode and cathode wire patterns and the upside view (b) the pickup wire pattern.

Natural Mo contains 9.6% $^{100}$Mo; accordingly, the amount of the double beta decay source is 0.03 mol.

A drift chamber has five kinds of wires, the anode, pickup, cathode, field-shaping, and guard wires, respectively. The specifications of these wires are described in Table 1. The anode wire plane, where 40 wires are strung with 6 mm pitch in the $Z$ direction, is located at 4 mm distance from the Mo sheet. The pickup wire plane, composed of 40 wires with 6 mm pitch, is located at 6 mm distance from the Mo sheet. The pickup wires are strung in the $Y$-direction, crossing the anode wires with a 2 mm gap. The cathode wire plane, composed of 40 wires with 6 mm pitch, is located 96 mm away...
Table 1. Specifications of wires used in the drift chamber.

| Wire name       | Number of wires | Material            | Diameter | Tension | Potential |
|-----------------|-----------------|---------------------|----------|---------|-----------|
| Anode           | 40              | Gold-plated tungsten| 20 μm    | 35 g    | 1500 V    |
| Cathode         | 40              | Gold-plated aluminum| 80 μm    | 90 g    | −1800 V   |
| Pickup          | 40              | Gold-plated aluminum| 80 μm    | 90 g    | −420 V    |
| Field-shaping   | 40              | Gold-plated aluminum| 80 μm    |         |           |
| Guard           | 2               | Copper beryllium (CuBe)| 140 μm  | 200 g   | −2000 V   |

from the Mo sheet; therefore, the tracking region is 92 mm between the cathode and the anode wire planes. The cathode wires are strung in the Z-direction, parallel with the anode wires.

Since the drift chambers were assembled with too many parts to keep gastight, a gas container was constructed to keep the chamber gas pure enough to guarantee a long path length for drift electrons. After the installation of drift chambers into the gas container, the container was installed into SCSM.

3.2. Signal detection

A drift chamber of DCBA-T2 has 40 cells, each of which is 92 mm in the X-direction, 6 mm in the Y-direction, and 240 mm in the Z-direction. Every cell has an anode wire strung in the Z-direction at one end of the X-direction and a cathode wire also strung in the Z-direction at the other end of that. When a charged particle traverses the cell, ionizations occur in the chamber gas along the particle trajectories. Electrons and ions produced by the ionization drift toward the anode and cathode wires, respectively.

When the drifting electrons come to near the anode wire, they are quickly accelerated by the high electric field gradient around the wire, and produce a primary ionization avalanche. The avalanche electrons are instantaneously absorbed into the anode wire; on the other hand, the ions go out from the anode wire toward negative potential electrodes, namely, several pickup wires and the cathode wire; also, some of the ions move to the Mo sheet of the ground potential.

While an anode signal is induced by ions leaving the anode wire, a pickup signal is induced by those coming to the pickup; thus the signal polarities of the anode and the pickup are negative and positive, respectively. Since ions move along lines of electric force, all ions leaving the anode wire go out not only to pickup wires but also to the cathode wire in the cell and to the Mo sheet. Therefore, the intensity of the anode signal is stronger than that of the pickup signal.

3.3. Signal readout electronics

The preamplifier cards are essentially the same type used in the VENUS vertex detector at TRISTAN [18], except for the cards for the pickup signals. All of the signals in the VENUS vertex detector are negative pulses, but the pickup signals in DCBA-T2 are positive ones, as described in Sect. 3.2. Therefore the input parts of the pickup cards have been remodeled.

Since a preamp card has 8 channels, 20 cards have been used to cover 160 channels in total; namely, 5 cards × 2 for the anode signals, and another 5 cards × 2 for the pickup signals from both drift chambers. The total power consumption of the preamp cards is about 27 W. In order to keep the chamber temperature constant, those cards have been mounted on the outsides of the endplates of the gas container, 10 cards for anode signals are on one side and another 10 cards for pickup signals are on the other side.
Signal cables of 3 m length have been connected from the signal ports mounted on the endplates of the gas container to the FADCs, which are mounted on a crate controller. Details of the FADC are presented elsewhere [17]. One crate controller accommodating 10 FADCs for anode signals is located at the outside of SCSM, as shown in Fig. 1, where one can see 10 signal cables coming from the inside of SCSM to the FADC crate. The other FADC crate for pickup signals is located on the opposite side of SCSM.

3.4. Trigger system

Block diagrams of the event trigger system are shown in Fig. 4. Each FADC board has a so-called programmable logic device (PLD), programmed to produce a trigger pulse when at least 3 out of 8 channels accept signals during a 5 μs period. The trigger outputs from the 10 FADCs are called AL0 to AL4 for the left drift chamber, and AR0 to AR4 for the right one. Since only anode signals are used for the event trigger, the readout system for pickup signals does not appear in Fig. 4.

As described later in Sect. 4, many cosmic rays come into each drift chamber, producing many trigger pulses. However, those cosmic-ray backgrounds have been able to be reduced by the coincidence trigger system between the left and right chambers. Two beta-rays from a double beta decay have a higher emission probability in a back-to-back direction, as the angular correlation $A$ of double beta decay events is given as

$$ A = 1 - \beta_1 \beta_2 \cos \theta, $$

where $\beta_1 = p_1/E_1$ and $\beta_2 = p_2/E_2$, and $\theta$ is the angle between two beta-rays.

An event trigger pulse is produced as follows. As mentioned previously, the left and right chambers have anode readout lines called AL0–4 and AR0–4, respectively. When one pulse from the ALs overlaps with another pulse from the ARs during a 5 μs period, the so-called coincidence circuit
Fig. 5. Time chart of data-taking for two consecutive events with the double buffer function.

shown as AND1 in Fig. 4 produces two pulses. One pulse is the trigger pulse for a regular back-to-back track event. The trigger pulse is delayed for 25 $\mu$s by gate generator 1 (G.G. 1) to stop writing all memories mounted on 20 FADC boards.

The other pulse from the AND1 is for taking data of a BiPo event, described previously. The pulse from a back-to-back event by the beta decay from $^{214}$Bi to $^{214}$Po is held for 800 $\mu$s by G.G. 2. The alpha particle, which is emitted from $^{214}$Po with a delaying time of about 160 $\mu$s, is caught in either the left or right drift chamber. The 800 $\mu$s held pulse and the delayed one are used to make another trigger pulse for the BiPo event by going through the AND2 circuit. The trigger pulse is also delayed for 25 $\mu$s by G.G. 1 to become the stop signal.

However, a muon crossing the source plate also often satisfies the back-to-back condition. In order to reject such events, a veto-counter system composed of a plastic scintillator array is prepared, being shown as USC0 to USC3 above the magnet yoke and DSC0 to DSC3 under the yoke. The veto pulse width of 100 $\mu$s at G.G. 3 is to cover the time region of 20 $\mu$s for drift electrons in the chamber.

3.5. Data acquisition

All data in the FADC memories are sent to a central processing unit (CPU) and stored in the main memory, as shown in the time chart depicted in Fig. 5. Every FADC memory has a capacity of 40 $\mu$s time length. The maximum drift time of an electron is about 20 $\mu$s in the tracking region between an anode wire and a cathode one. When a trigger pulse is made by a track going through near the anode wire plane, other tracks near the cathode wire plane are certainly recorded. This is because the trigger pulse is delayed by 25 $\mu$s in G.G. 1 to become a stop pulse, as shown in Fig. 4; 25 $\mu$s delayed time covers the drift time of about 20 $\mu$s for a track near the cathode wire plane. In the case that the event is triggered by a track near the cathode wire plane, the memory time of 40 $\mu$s makes it possible to record tracks near the anode wire plane.

In the time chart, a pulse from the CPU starts writing data from chamber signals in the memory-A of every FADC channel. When a trigger signal comes from the trigger logic, a stop pulse is produced with a 25 $\mu$s time delay in order to stop writing data in the memory-A. At the same time, a start pulse is automatically produced and starts writing data in the memory-B of every FADC channel, and also the event flag-A becomes ON in the CPU. While the flag-A is ON, all data in the memory-A of the FADCs are read out. If the next trigger signal does not come in the reading-out duration of all the memory-As, the flag-A becomes OFF just after the reading of the data is completely finished, and
then the memory-A starts writing after a clear pulse. The dead time is 0.22 s, which is defined as the
time between stop and start for writing in the memory-A, including data transfer.

When the next signal comes during the memory-A readout, the signal is written in the memory-B,
which already starts writing data, and the pulse delayed by 25 $\mu$s stops writing in the memory-B.
This is the case in the BiPo event as mentioned in Sects. 2.1 and 3.4.

If the readout of memory-A is not yet finished, the readout of memory-B waits until the it is. When
the readout of memory-B starts, the memory-A is in an idle state. After all the memory-Bs are read
out, a clear pulse from the CPU resets all states; namely, memories-A and B become ready to write,
and flags-A and B become non-active states. Just after all states are reset, the CPU produces a start
pulse again to start writing the memory-A, as in the initial state.

4. Operation
DCBA-T2.5 is operated on the Fuji experimental floor in KEK to measure the half-life of $2\nu2\beta$ from
$^{100}\text{Mo}$. Though the experimental floor is about 16 m below ground level, there is nothing to shield
against cosmic rays in the large space volume, except for thin slate ceilings 4 m above ground level.
Usually, these kinds of experiments are executed in underground areas with 1 km or more depth of
water equivalence to avoid the background effects of cosmic rays. As described later in Sect. 6, we
need to continue the DCBA operation on the Fuji experimental floor in order to pursue R&D for the
future project in parallel.

Since only a 5 cm thick iron plate of the magnet yoke works as a shield against cosmic rays, the
two drift chambers have suffered many backgrounds from cosmic rays. As mentioned in Sect. 3.4,
the trigger logic has been assembled by taking the coincidence of the left and right chamber signals,
and, in addition, plastic anticounters have been installed above and under the magnet yoke as a veto;
the trigger rate has thus finally become about 0.1 Hz.

The chamber gas is supplied from a gas cylinder, in which 90% He and 10% CO$_2$ are premixed
at about 18 MPa maximum pressure, and its flow rate is kept to about 100 cc/min by regulating
the pressure difference between the cylinder output and the chamber. The flow rate is monitored at
both sides of the chamber inlet and outlet. The chamber pressure is kept around 1015 hPa, being
monitored within $\pm$1 hPa accuracy by a hydro-pressure gauge, which simply consists of a water
U-tube. Since the pressure gauge is also able to control the chamber pressure up to 30 hPa, there has
been no trouble in cases of low atmospheric pressure. The status of the data-taking can be monitored
from anywhere in the world on an internet website, and therefore we have been able to check the
detector condition any time.

5. Analyses
The $2\nu2\beta$ candidate events are selected by eye scanning. Then we analyze each candidate to obtain
the single electron energy, the sum energy of the two electrons, the angle between the two electrons,
and the vertex points of the two electrons on the source plate.

5.1. Scanning
An event candidate consists of two circular tracks starting from one point of the central source plate:
one track is on the right-hand side chamber and the other is on the left. Since about 99% of triggered
events are straight tracks due to cosmic rays, it takes a long time to select the candidates with a careful
eye-scan by physicists. However, the process itself is technically not so difficult, so an automatic
scanning method is now under development.
A typical $2
\nu
2\beta$ event candidate is shown in Fig. 6. In the figure, the $X$-axis shows time counts in units of 10 ns, being digitized by a 100 MHz FADC. The data during a period of 40 $\mu$s are read out from the FADC memory, where the stop pulse is at 4000 counts. Positive and negative counts in the $X$-axis stand for the coordinates in the right-hand side chamber and in the left-hand side one, respectively. The upper part is the display in the $X$–$Y$ plane, and the lower one is in the $X$–$Z$ plane. The $Y$ and $Z$ axes show the anode and pickup wire positions, respectively. Since the magnetic field is in the $Z$ direction, the two tracks are counterclockwise circles in the $X$–$Y$ plane and sine curves in the $X$–$Z$ plane.

In order to obtain the vertex point on the source plate, we need the timing corresponding to the anode wire plane located 4 mm from the source plate, as described in Sect. 3.1. One can see in Fig. 6 that the earliest signals are produced at around ±500 counts for both the right- and left-hand side chambers. The earliest signal points correspond to the relative positions of the anode wires. In addition, other earliest signals, which are successively on the anode wires of 15–24 numbers in the left chamber, help determining the anode wire positions. These signals are considered to be a chain reaction of secondary avalanches caused by photons emitted by deexciting gas molecules around the earliest primary avalanche. Only the earliest avalanche can excite the gas molecules around the anode wires without obstruction from ions produced, and thus vertically successive signals correspond to the anode wire positions. Therefore, the gray area around the central region does not have a physical meaning.

Sometimes two circular tracks appear together with a straight track, as shown in Fig. 7(a). This is the event that we call a double knock-on electron by a muon; namely, the short circular track on the upper left is produced by the interaction of the muon with an electron in the chamber wall, and then the central long circular track is produced by the muon–electron interaction in the source plate.
The double knock-on electron is occasionally produced in the source plate with an extremely short distance, shown in Fig. 7(b). This event is so similar to Fig. 6 that we may easily make the mistake of selecting it as the $2\nu 2\beta$ event candidate. However, with careful observation of Fig. 7(b), we find that a muon comes in from the top near the left of the anode wire plane in the left chamber and goes down, crossing the source plate, and then goes out near the right-hand side of the anode wire plane in the right chamber.

5.2. Measurement

After the selection of $2\nu 2\beta$ event candidates, we need to determine the momentum and the starting position on the source plate, which we call the vertex position, for each helical track. As described in Eq. 2, the radius $r$ and the pitch angle $\lambda$ of the helical track should be measured to obtain the momentum. In order to measure the parameters of $r$, $\lambda$, and the vertex positions, an analysis program has been developed to depict 2D displays, as shown in Fig. 8. The upper and lower displays show the $X$–$Y$ and $X$–$Z$ projection planes, respectively, and the left-hand side is for the left chamber and the right-hand side is for the right one.

The depicted event is the same one as shown in Fig. 6. As described in Fig. 6, the $X$-axis in this figure also stands for the time count of FADC in units of 10 ns. The numbers in the $Y$-axis (upper display) are the anode wire numbers, and the ones in the $Z$-axis (lower display) are the pickup wire numbers. The wire pitch of both the anode and pickup planes is 6 mm, as previously described.

Track points are selected manually by clicking the display. By selecting points with the same $X$ position in the $X$–$Y$ and $X$–$Z$ planes, we can assign the 3D position. Since the manual selection of track points causes bias in the momentum measurement, careful evaluation will be made by simulation studies and repeating selections.

One can see that the numbers along the tracks in Fig. 8 correspond to each other in the upper and lower displays at the same $X$ point. This means that each number point has the 3D coordinate of the helical track. Circular lines in the upper right and left displays and sine curves in the lower right and left ones are obtained by fitting these position data with the least-$\chi^2$ method. After the measurement, the 3D display is reconstructed as shown in Fig. 9 to intuitively understand the event candidate.

In Figs. 8 and 9, $\beta_1$ and $\beta_2$ stand for the beta-rays in the right and left chambers, respectively. The measured kinetic energy of $\beta_1$ is 1.40 MeV and that of $\beta_2$ is 0.57 MeV. The differences between the start points of $\beta_1$ and $\beta_2$, which are expressed as $\Delta Y$ in the $Y$-direction and $\Delta Z$ in the $Z$-direction,
Fig. 8. 2D displays for measuring the momenta and vertex point of the event candidate depicted in Fig. 6. $\beta_1$ and $\beta_2$ stand for the beta-rays. The two black vertical lines around $\pm 500$ counts show the positions of the anode wire planes. The two red vertical lines around $\pm 400$ counts show the position of the source plate.

Fig. 9. 3D displays of the event candidate. $\beta_1$ and $\beta_2$ stand for the beta-rays.

are $\Delta Y = 4.1$ mm and $\Delta Z = 4.9$ mm. The angle $\theta$ between $\beta_1$ and $\beta_2$ at their vertex point is determined as $\cos \theta = 0.24$.

The half-life of $^{100}\text{Mo}$ $2\nu2\beta$ will finally be obtained from a comparison of the energy spectrum of the event data selected as mentioned above with the results of simulation studies based on the event production probability. The event detection efficiency is one of the most important parts in
Fig. 10. Background event with a sum energy of the $Q$-value of $^{100}$Mo (3.03 MeV). $e_1$ and $e_2$ stand for electron tracks, and $\Delta Y$ and $\Delta Z$ mean their start point difference on the source plate.

the simulation studies, depending on the magnetic flux density and the fiducial volume in tracking detectors. Though precise studies should be made in the final stage of obtaining the half-life, a preliminary result of about 5% at 0.8 kG has been found by using the detector simulator called Geant4.

6. Discussions

We took data intermittently from July 2011 to July 2016 and obtained about $8 \times 10^6$ triggered events to measure the half-life of $2\nu 2\beta$ from $^{100}$Mo. The tracking detection capability has made it possible to select two electron events from as many as $8 \times 10^6$ triggered events because almost all triggered events are straight tracks from cosmic rays crossing the source plate. Though the selection process itself is very simple, it has taken a long time with eye scanning to find event candidates such as that shown in Fig. 6. We have been trying automatic scanning, but that is still being developed.

There are rare backgrounds with the sum energy near to the $Q$-value of $^{100}$Mo (3.03 MeV). An example of such background is shown in Fig. 10. The kinetic energy of the electron $e_1$ in the right chamber is 2.19 MeV and that of the other one, $e_2$, in the left chamber is 0.85 MeV. However, their start points are quite different from each other as $\Delta Y = 24$ mm and $\Delta Z = 26$ mm. We can see that this is a double Compton event, as mentioned in Sect. 2.1.

In the final stage of deciding the half-life, the estimation of the ratio $(S/N)$ will be important, where $S$ is the true event number and $N$ the background event one. As described in Sect. 2.1, background events come from double Compton scattering and Compton scattering followed by Möller scattering. We have been trying to build up the method to get $S/N$. Although a very preliminary result of $S/N \simeq 2$ has been obtained in the region of $\Delta Y \leq 6$ mm and $\Delta Z \leq 12$ mm by using the event candidates obtained so far, this is expected to be improved with the accumulation of candidates.

Other interesting backgrounds are BiPo events, also mentioned in Sect. 2.1. Typical BiPo events are shown in Fig. 11. One can clearly see the difference between electron tracks in (a) and an alpha track in (b). The event shown in (a) looks like it comes from a double beta decay. However, the double
Fig. 11. Two-electron event followed by an alpha-ray. The event in (a) seems to be composed of a beta-ray from $^{214}$Bi and a recoil electron of Compton scattering due to a gamma-ray from the daughter nucleus $^{214}$Po. The event in (b) is certainly an alpha-ray from the decay process of $^{214}$Po to $^{210}$Pb. The event data in (b) were taken 186 $\mu$s later than those in (a). Red points indicate the starting positions of tracks, being the same position in the $Y$- and $Z$-coordinates in both (a) and (b). Blue parts of tracks mean higher pulse signals and green ones lower pulse signals.

buffer system described in Sect. 3.5 has caught the alpha-particle event shown in (b) 186 $\mu$s later than the event in (a). This means that the event in (a) consists of a single beta decay of $^{214}$Bi and a recoil electron of Compton scattering due to a gamma-ray from the excited state of the daughter nucleus $^{214}$Po. We have roughly measured the half-life of $^{214}$Po from 39 sets of BiPo events, which include not only two-electron events like (a) but also single beta decay events followed by alpha-particle emissions. A preliminary result of $T_{1/2} = 144 \pm 46 \mu$s has been obtained, which is consistent with the half-life of $^{214}$Po (162.3 $\mu$s) [20].

For future experiments searching for $0\nu 2\beta$ and $0\nu 4\beta$ events, we have to improve the energy resolution from that in the present experiment. Since all other double beta decay experiments do not measure beta-ray momenta, discussions with other experimental groups are usually about energy resolutions. Therefore, we briefly describe here the relation between the energy and momentum resolutions. From Eq. 1, we obtain the relation between the momentum resolution $\Delta p$ (FWHM) and the energy resolution $\Delta T$ (FWHM) as

$$\Delta T = \beta \Delta p,$$

where $\beta (= p/E)$ is the beta-ray velocity in units of light velocity. Since the position resolution of tracks is almost the same in the momentum region around 1–2 MeV/c, $\Delta p$ is constant in that region.

In DCBA-T2 operated with a magnetic flux density of 0.8 kG, we have measured the energy resolution using the internal conversion electron of 0.98 MeV energy ($\beta = 0.94$) from $^{207}$Bi, and obtained $\Delta T$ (FWHM) $\simeq$ 0.15 MeV [14]. According to the theory of neutrino mass dominance [8], the most probable energy of one beta-ray in $0\nu 2\beta$ is half of the $Q$-value. This is 1.69 MeV ($\beta = 0.97$) in the case of $^{150}$Nd, so the energy resolution is obtained as $\Delta T$ (FWHM) $\simeq$ 0.155 MeV. Thus the relative energy resolution at the $Q$-value (3.37 MeV) of $^{150}$Nd finally becomes 6.5% (FWHM) from the result of $\sqrt{2} \times 0.155/3.37$. We have to make a lot of effort to improve the energy resolution, because an energy resolution better than 5% (FWHM) is commonly recognized as a requirement in order to find the energy spike at the $Q$-value when the neutrino mass is assumed to be around 50 meV.
The next step is to operate DCBA-T3 with a better energy resolution and more massive Nd source than DCBA-T2.5. It aims to measure the half-life of $2\nu 2\beta$ from $^{150}$Nd and determine the lower limit of that of $0\nu 2\beta$. Since the drift chambers of DCBA-T3 will be operated in the 2–2.4 kG magnetic field density provided by SCSM, a beta-ray makes a helical track with a smaller radius than the one in the present experiment. A smaller pitch of 3 mm for the anode and pickup wires in the T3 chamber makes it possible to measure smaller-radius tracks, which receive smaller effects from multiple scattering in the chamber gas. We have been studying the energy resolution by using Geant4, obtaining a preliminary result of about 3% (FWHM) at 3.37 MeV.

A momentum analyzer has generally powerful abilities to eliminate backgrounds, as mentioned above; on the other hand, it has the disadvantage of having a small amount of source. The source plate should be thin to reduce the effects of energy loss and multiple scattering on beta-rays. A large amount of decay source is of course required to search for both the $0\nu 2\beta$ and $0\nu 4\beta$ events. We have been making efforts to solve this problem with R&D studies for a large-size analyzer called a magnetic tracking detector (MTD). One module of MTD will have a source plate area of about 80 m$^2$, which means 40 kg/module for 50 mg/cm$^2$ thick source material, as a typical example.

7. Conclusions

Momentum analyzers called DCBAs are tracking detectors operated in a uniform magnetic field. The advantage of DCBAs is that they selectively measure the momentum of each electron in a limited region between 0.5–3.5 MeV/c. Another advantage is the ability to determine the start point of an electron track on the source plate. These abilities are very useful to eliminate backgrounds.

In order to measure the half-life of $2\nu 2\beta$ from $^{100}$Mo, we have constructed and operated DCBA-T2.5, which is a combination facility with the DCBA-T2 chambers and the T3 SCSM. About $8 \times 10^6$ triggered events have been obtained over the last five years, and it was found that most events were due to cosmic rays. Nevertheless, we have been able to select $2\nu 2\beta$ event candidates and measure the momenta of their beta-rays continuously.

The present article has concretely shown that we have been able to select $2\nu 2\beta$ event candidates and eliminate backgrounds not only by cosmic rays escaping through veto counters but also by double Compton scatterings and BiPo processes.

Developing the DCBA series is an important R&D element of the future MTD project to search for $0\nu 2\beta$ and $0\nu 4\beta$ in order to answer the question of whether neutrinos are Majorana particles or Dirac ones.

Acknowledgements

The authors would like to thank Dr A. Suzuki, former Director of KEK, for his continuous support and encouragement on the DCBA project. DCBA-T2.5 could not have been realized without a lot of help from KEK mechanical engineering group members. This work was partly supported by the Yamada science program and Grants-in-aid Nos. 13440081, 18540299, 26287048, and 15K05112 from JSPS.

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