Magnetic tracking detector DCBA/MTD for neutrinoless double beta decay experiments

Nobuhiro Ishihara1, 2, for the DCBA collaboration
1 High Energy Accelerator Research Organization,
1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
2 The Graduate University for Advanced Studies,
Shonan Village, Hayama, Kanagawa 240-0193, Japan
Nobuhiro.ishihara@kek.jp

Abstract. Magnetic tracking detector is being developed at KEK for neutrinoless double beta decay experiments. Drift Chamber Beta-ray Analyzer (DCBA) is an R&D program to confirm the detection principle of the magnetic tracking detector. A prototype called DCBA-T2 has been constructed and operated to investigate its energy resolution and operation problems. Another new prototype DCBA-T3 is now under construction to improve the energy resolution and the amount of decay source. On the basis on DCBA-T2&T3, we have designed a future project temporarily called Magnetic Tracking Detector (MTD). One module of MTD will be able to accommodate a lot of decay source, so that several ten modules will give us a chance to investigate the effective neutrino mass down to 30 meV.

1. Introduction

Only the neutrinoless double beta decay (0νββ) experiment can realistically give us the solution of the problem whether neutrinos have the Majorana nature or not. The observation of 0νββ strongly supports the so-called Seesaw mechanism [1,2], which is based on Majorana neutrinos. The Seesaw mechanism is well-known as the most natural theory that describes the reason why existing neutrinos are so light in comparison with other leptons and quarks. According to the early universe theory called Leptogenesis [3], heavy Majorana neutrinos play important roles to produce the present universe, namely the advantage of materials over anti-materials. The Leptogenesis is based on the Seesaw mechanism. Therefore the Majorana nature is essential for understanding the early universe.

In addition, if we measure the half-life of 0νββ, absolute mass scale called the effective neutrino mass (<mββ>) is obtained with the help of nuclear matrix element. Oscillation experiments have measured neutrino oscillation parameters. Though they cannot directly have the information of absolute mass scale, mass spectra are theoretically predicted from their results. One spectrum is that three mass eigenstates (m1, m2, m3) are almost same, which is called Quasi-Degenerate (QD) spectrum. Another spectrum is in the case of m3>>m2> m1, which is called inverted-hierarchy (IH) spectrum. The last one is in the case of m1< m2< m3, which is called normal hierarchy (NH) spectrum. The <mββ> of 100-500 meV, 10-50 meV and 1-5 meV are predicted from QD, IH and NH spectra, respectively.

Several 0νββ experiments have been carried out so far, no observation of the phenomenon has been reported, except for the paper from Klapdor-Kleingrothaus et al. We need more experiments to judge the results of Klapdor-Kleingrothaus et al., which insist (0.69-4.18)×10^25 y for the 0νββ half-life of 76Ge, and the <mββ> range of (240-580) meV with the best fit value of 440 meV [4].

2. Magnetic tracking detector

Almost all the detectors of existing and future experiments for the 0νββ search use calorimeters to measure the energy of beta ray. We have developed a magnetic tracking detector called Drift Chamber Beta-ray Analyzer (DCBA), which essentially consists of tracking detectors and a solenoid magnet [5].
DCBA can determine the momentum of each beta ray by measuring its trajectory in a uniform magnetic field. Therefore angular correlation between two beta rays can also be obtained. The angular correlation and the energy spectrum of single beta ray in $0\nu\beta\beta$ will present the information for studying the origin of $0\nu\beta\beta$ [6]. The DCBA experiment is an R&D program for constructing future Magnetic Tracking Detector (MTD), which is a temporary name. Final name will be given by a new collaboration to be internationally organized in future. Followings are the present status of DCBA program continued at KEK, and the conceptual design of MTD based on DCBA.

2. DCBA experiment

DCBA has a uniform magnetic field where drift chambers holding decay source plates are installed. The direction of magnetic field is parallel to the source plate. Therefore a beta ray perpendicularly emitted from the source plate is most effectively measurable because of the small effect of multiple scattering in the source plate. This permits DCBA having thick source plate. According to simulation studies using Geant4, a source plate of 40 mg/cm$^2$ thick is available to search for $0\nu\beta\beta$ down to $<m_{\beta\beta}>\sim 30$ meV.

2.1.1. DCBA-T2. A prototype called DCBA-T2 has been constructed and operated at KEK. The energy resolution has been obtained to be about 150 keV (FWHM) using internal conversion electrons of 976 keV from $^{207}$Bi [7]. Engineering run has been carried out for studying operation problems in future. In the run, natural Mo plate of 45 mg/cm$^2$ thick, which contains 9.6% $^{100}$Mo (Q=3.03 MeV), has been used because the plate is commercially available. We had 21 candidates of $2\nu\beta\beta$ in 2010. An example of event is shown in figure 1. Figure 2 is the energy spectrum of single beta ray for 21 candidates.

In the figure 1, upper parts of right and left mean X-Y projection planes of right and left drift chambers, respectively. Lower parts show X-Z projection planes in both chambers. A Mo thin plate is interleaved between right and left drift chambers. These chambers are installed in a uniform magnetic field of 0.8 kG. One can see two beta-ray tracks come from the same vertex (VTX) point back to back. Though the scales in X, Y and Z are not adjusted, both the curves in X-Y are circles, and those in X-Z are sine curves. A momentum $p$ (MeV/c) of each beta ray is obtained from the equation of $p\cos\lambda=0.3rB$, where $r$ (cm) is the radius of helical track, $B$ (kG) the magnetic flux density and $\lambda$ the pitch angle of the helix. And then, the kinetic energy $T$ (MeV) is given by the equation of $T=(p^2+m_e^2)^{1/2}-m_e$, where $m_e$ (MeV/c$^2$) is electron mass. Therefore we don’t need energy calibration runs. The energy spectrum shown in figure 2 has been obtained by this method. Figure 3 shows the energy sum spectrum of two beta rays in the candidates.
Figure 4 shows the distribution of alpha decay time from $^{214}$Po. The source plate contains a small amount of $^{214}$Bi, which takes place beta decay and becomes $^{214}$Po, and then the $^{214}$Po produces an alpha with the half-life of 164 $\mu$sec. We have measured the time between a single electron event and an alpha event, and obtained the results shown in figure 4. A two-electron event followed by an alpha has been also observed as shown in figure 5. This is considered as that one electron comes from $^{214}$Bi beta decay and the other electron comes from Compton scattering due to a gamma-ray from the excited state of $^{214}$Po. Of course, these kind events are also included in figure 4. We have obtained the half-life of alpha decay from $^{214}$Po to be $144 \pm 46.1$ $\mu$sec from figure 4. This means DCBA-T2 works well.

Figure 5. Example of a two-electron event followed by an alpha ray from $^{214}$Po.

2.1.2. DCBA-T3. In order to improve the energy resolution in DCBA, a new prototype called DCBA-T3 (T3, hereafter) is under construction at KEK. Main different points from DCBA-T2 (T2, hereafter) are magnetic flux density, wire pitch and source plate. In the case of T2, they are 0.8 kG, 6 mm and single plate of 24×24 cm$^2$ Mo, respectively. In T3, they are 3 kG (max.), 3 mm and multi plates of 45×45 cm$^2$ Nd, which includes 5.6% $^{150}$Nd (Q=3.37 MeV). Shorter track length in stronger magnetic field reduces multiple scattering effects and will produce better energy resolution as less than 100 keV (FWHM) in whole energy range of 0.5-3.0 MeV. This means the relative energy resolution is better than 5% (FWHM) at 3.37 MeV. Figure 6 is a photo of the super-conducting solenoid magnet for T3, in which new drift chambers of T3 will be installed soon.
2.2. Future project MTD (temporary name)

In order to search for $0\nu\beta\beta$ up to the order of $10^{26}$ y half-life, we need 1000 mol of decay source at least. If 100% enriched source of $^{150}$Nd is available, the total weight of the source plate is about 150 kg for 1000 mol. On the basis of DCBA-T2 and T3, we have designed a large scale detector module temporarily called Magnetic Tracking Detector (MTD) as depicted in figure 7. MTD has 2,600 mm outer diameter and 3,500 mm length and can accommodate source plates of about 80 m$^2$ area. If source plate thickness is 40 mg/cm$^2$, about 30 kg source will be able to be installed in a MTD module. This means 5 modules of MTD will give us the chance to search for $0\nu\beta\beta$ up to the order of $10^{26}$ y half-life, if we can use 100% enriched source of $^{150}$Nd. However, when we use natural Nd (5.6% $^{150}$Nd), 100 modules will be required to realize the installation of 1000 mol $^{150}$Nd into MTD. This is possible but not so easy. It is very important to develop the enrichment method for $^{150}$Nd.

3. Conclusions

A magnetic tracking detector presents a characteristic pattern for a double beta decay event. Momentum measurement of each beta ray is a powerful method to eliminate backgrounds and to obtain the kinetic energy of beta ray. We are constructing DCBA-T3 to confirm its energy resolution better than 5% (FWHM) at the Q-value of $^{150}$Nd. On the basis of DCBA-T2 and T3, we have conceptually designed a future magnetic tracking detector, temporarily called MTD. Future international collaboration of MTD will be able to investigate $<m_{\beta\beta}>$ down to 30 meV, which will probably be corresponding to the $0\nu\beta\beta$ half-life of $10^{25}$-$10^{26}$ y for $^{150}$Nd.

Acknowledgment

The author thanks Dr A Suzuki (KEK director) for his encouragement to advance the DCBA experiment.

References

[1] Yanagida T 1979 Proc. of the Workshop on the Unified Theory and the Baryon Number in the Universe ed O Sawada and A Sugamoto (Tsukuba: KEK Report KEK-79-18) p 95
[2] Gell-Mann M, Ramond P and Slansky R 1979 Supergravity ed D Z Freedman and P van Nieuwenhuizen (North-Holland, Amsterdam) p 315
[3] Fukugita M and Yanagida T 1986 Phys. Lett. B 174, 45
[4] Klapdor-Kleingrothaus et al. 2004 Phys. Lett. B 586 198
[5] Ishihara N, Ohama T and Yamada Y 1996 Nucl. Instr. and Meth. Phys. Res. A 373 325
[6] Doi M, Kotani T and Takasugi E 1988 Prog. Theor. Phys. Suppl. 83 1
[7] Ishihara N for the DCBA collaboration 2010 Nucl. Instr. and Meth. Phys. Res. A 623 457