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N. Ishihara, T. Ohama and Y. Yamada

*KEK, National Laboratory for High Energy Physics
Tsukuba, Ibaraki, 305, Japan*

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Abstract

A magnetic tracking detector called DCBA (Drift Chamber Beta-ray Analyzer) is proposed for double beta decay experiments. The DCBA project is divided into two stages: DCBA-I and -II. DCBA-I will be able to measure the half life of the two-neutrino double beta decay of ^{150}Nd , though natural Nd is used as the decay source material. DCBA-II will make it possible to investigate the effective mass of the Majorana neutrino up to $0.1 - 0.5$ eV, since it is expected to have the ability to measure the half-life limit up to 4×10^{24} y using enriched ^{150}Nd . A fundamental strategy of the DCBA project and some details of DCBA-I are described.

1. Introduction

Zero neutrino double beta ($0\nu\beta\beta$) decay violates lepton-number conservation, and is therefore forbidden in standard electroweak theory. However, $0\nu\beta\beta$ decay is possible if at least one neutrino is a massive Majorana particle [1] [2] [3]. Recent experimental results concerning the solar neutrino [4], atmospheric neutrino [5] and neutrino oscillation [6] strongly suggest the existence of a neutrino mass. Theoretical studies, such as the so-called see-saw mechanism, also demand massive Majorana neutrinos [7] [8] [9]. The $0\nu\beta\beta$ decay experiments carried out so far using a calorimeter with ^{76}Ge have set the upper limit of the effective neutrino mass parameter $\langle m_\nu \rangle$ as 1.1 eV from the half-life lower limit of 1.9×10^{24} y [10]. It is notable that the half-life lower limit tends to be saturated, though the peak of the signal counts has not yet been observed at the Q-value, the end point of the kinetic energy sum spectrum[3].

In order to proceed to the next step of research concerning the neutrino mass, some

breakthroughs seem to be required in the detector technique. Tracking detectors operated in magnetic fields, such as TPC's of UCI [11] and ITEP [12], have some advantages over the calorimeter. A magnetic tracking detector can produce a high signal-to-background ratio, because its signature of $\beta\beta$ decay is two electrons, both negatively charged and coming from a common vertex. On the other hand, both TPC's mentioned above have the common disadvantage of a low detection efficiency due to the small spatial acceptance.

A magnetic tracking detector using a drift chamber is newly proposed, and is called DCBA (Drift Chamber Beta-ray Analyzer). The DCBA is based on the experience of the VENUS vertex detector at TRISTAN [13], and was designed under a philosophy in which (1) the vertex point should be efficiently determined by the three-dimensional track reconstruction and (2) a large amount of the source should be contained. As for the decay source, any isotope is available for the DCBA if the isotope is only fabricated to the shape of a thin plate. From the viewpoint of the neutrino mass sensitivity, ^{150}Nd is the most advantageous source, because its calculated value of $T_{1/2}^{0\nu} < m_\nu >^2$ is as small as 3.37×10^{22} y·eV² [14] or 1.05×10^{24} y·eV² [15], where $T_{1/2}^{0\nu}$ is the half life of the $0\nu\beta\beta$ decay mode and $\langle m_\nu \rangle$ is the neutrino effective mass.

2. DCBA project

The DCBA project is divided into two stages: DCBA-I and DCBA-II, as shown in Table 1 and Fig.1. We now consider the so-called detector sensitivity (S_D), which is defined as

$$S_D = \frac{kN_0}{\sqrt{N_{BG}\Delta E}}, \quad (1)$$

where k is the detection efficiency, N_0 the number of nucleus, N_{BG} the number of background events in (keV⁻¹·y⁻¹) and ΔE the FWHM energy resolution at the measured energy in (keV) [16]. Using the detector sensitivity, the measurable half-life limit ($T_{1/2}^{lim}$) is expressed as

$$T_{1/2}^{lim} = (\ln 2) S_D \sqrt{t}, \quad (2)$$

where t is the measurement time in (y). $T_{1/2}^{lim}$ with a 1 year measurement is estimated in Table 1 along with other estimated parameters.

DCBA-I comprises a drift-chamber module, nuclear source plates (SP's) of natural Nd (5.6% abundance of ^{150}Nd), a solenoidal magnet and plastic scintillation veto-counters against the cosmic ray background, as illustrated in Fig.1(a). The measurable half-life limit with a 1-year measurement is estimated to be 3×10^{21} y, as described in Table 1. This is much longer than the calculated half life of two-neutrino double beta ($2\nu\beta\beta$) decay of ^{150}Nd , 7.37×10^{18} y [14] or 6.0×10^{18} y [17]. The DCBA capability concerning the detection efficiency, the background reduction and the energy resolution will probably make it possible to measure the half life of the $2\nu\beta\beta$ decay without dummy-source subtraction.

If the DCBA capability is confirmed by the results of DCBA-I, it is possible to start aiming at DCBA-II. DCBA-II comprises 60 modules of the drift chamber containing source plates of Nd_2O_3 enriched to about 90% ^{150}Nd , a large aperture solenoidal magnet of 3 m diameter $\times$ 5 m length and scintillation veto-counters, as shown in Fig.1 (b). Since the best quality region in the drift-chamber module is in the direction perpendicular to the SP

with respect to the energy resolution and the detection efficiency, relatively thick SP as 50 mg/cm² will be usable, even taking account of multiple scattering in the SP. If Nd₂O₃ of 50 mg/cm² containing ¹⁵⁰Nd enriched to 90% is available as the SP, about 4.5×10^{25} of ¹⁵⁰Nd (about 14.4 kg of Nd₂O₃) will be prepared. The DCBA-II will reach a half-life limit up to 4×10^{24} y if a detection efficiency of 0.7, a background rate of 0.1 (keV·y)⁻¹ and an energy resolution of 200 keV are achieved. This corresponds to an effective neutrino mass of 0.1 to 0.5 eV, depending on the nuclear matrix element [14] [15].

3. Energy Resolution

The momentum (p) of a single electron and its resolution (σ_p/p) in the DCBA are expressed as

$$p = 0.3 \frac{B}{\gamma \cos \omega} \quad (3)$$

and

$$\left(\frac{\sigma_p}{p}\right)^2 = \left(\frac{\sigma_\gamma}{\gamma}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2 + \tan^2 \omega \sigma_\omega^2, \quad (4)$$

where p is in units of MeV/c, and B is the magnetic-flux density in (kG), γ the curvature of the helical track in (cm⁻¹) and ω the pitch angle of the track.

The errors in the curvature and pitch angle are obtained as follows [18]:

$$\sigma_\gamma^2 \simeq \frac{720}{N+5} \frac{\epsilon^2}{(L \cos \omega)^4} + \left(\frac{16}{L p \beta \cos^2 \omega}\right)^2 \frac{L}{X_0} \quad (5)$$

and

$$\sigma_\omega^2 \simeq \frac{12N}{(N+1)(N+2)} \frac{\delta^2}{L^2} + \left(\frac{8}{p \beta}\right)^2 \frac{L}{X_0}, \quad (6)$$

where N is the number of measured points, ϵ the position error in the projected x-y plane, β the electron velocity in the unit of light velocity, δ the position error in three-dimensional space, L the measured track length and X_0 the radiation length of the material in the chamber. The second terms of the equations are due to multiple scattering. The kinetic energy resolution (σ_T/T) is related to the momentum resolution (σ_p/p) by

$$\left(\frac{\sigma_T}{T}\right) = \frac{\beta p}{T} \left(\frac{\sigma_p}{p}\right). \quad (7)$$

The error in the energy measurement is mainly due to multiple scattering in the chamber gas, and significantly depends on the emitted angle of the helical track.

The specific energy resolution is defined as the kinetic-energy resolution of the single electron emitted in the direction perpendicular to the SP. Such electrons suffer only a small multiple-scattering effect in the SP, and, thus, provide good results with respect to the energy resolution and the angular correlation between two electrons. In general, the specific energy resolution becomes smaller as the kinetic energy becomes higher. However, the finite tracking space (as described in section 5) limits L and N in eqs.5 and 6 to the peculiar values concerning the helical radius; thus, the specific energy resolution becomes

worse in a low magnetic field as the kinetic energy becomes higher. For example, as for an electron of 1 MeV kinetic energy, the specific energy resolution is 3.5% at a magnetic field of 0.6 kG, where L and N are 24.8 cm and 26, respectively. On the other hand, for a 2 MeV electron, the specific energy resolution is 6.1% at the same magnetic field. This is because the tracking space with a maximum drift length of 99 mm limits L and N to 12.0 cm and 8, respectively.

Figure 2 shows the calculated specific energy resolution for the various electron energies as a function of the magnetic field. It is found in Fig.2 that a higher magnetic field is suitable for research on the $\beta\beta$ decay from the viewpoint of energy resolution. However, as described in the next section, since a higher magnetic field decrease the detection efficiency, there will be an optimal magnetic field.

4. Detection efficiency

The detection efficiency has been roughly estimated using a Monte-Carlo simulation program. The program comprises a collisional energy-loss process, a multiple-scattering process, the spatial resolution of the chamber, the energy distribution of a single electron and an angular correlation of the electron pair. Good events have been selected by eye-scan with criteria in which the decay vertex is clearly identified and both electron tracks are long enough to be measured for those momenta. The results for $0\nu\beta\beta$ and $2\nu\beta\beta$ are shown in Fig.3 as a function of the magnetic field. Though the detector size is not considered, the present result seems to be realistic if a fiducial volume is reasonably defined.

A simulation study of the event topology has also shown that the true events seem to be easily distinguished from the background events. Figures 4 (a),(b) and (c) show examples of the simulated event display: (a) $0\nu\beta\beta$ event emitted back to back, (b) $2\nu\beta\beta$ event emitted to the same side and (c) the background event of e^+e^- pair creation. The event topology from single beta decay, which is, of course, a single spiral, is quite different from that from the $\beta\beta$ decay, which is double spirals, as shown in Fig.4 (a) or (b). The event of electron-positron pair creation (as shown in Fig.4 (c)) is easily distinguished from the events shown in Figs.4 (a) and (b). A one- or two-prong event by Møller scattering is also distinguishable because the track of the incident electron is similar to the track of the positron. Events from double Compton scatterings in the SP are not rejected by the eye-scan if two interaction points are close to each other with a distance less than the vertex resolution. Events from Compton-Møller scatterings in the SP are also hard to be rejected by the eye-scan. However, it is not difficult to distinguish these background events from the $0\nu\beta\beta$ decay event, because the sum kinetic energies of these events are generally much lower than the Q value of the $\beta\beta$ decay, while that of the $0\nu\beta\beta$ event shows a sharp peak energy at the Q value, if it exists. The backgrounds from the natural decay chain, such as the U and Th series, are also hard to be distinguished in the event topology. In this case hot spots will be found in the SP.

As for the $2\nu\beta\beta$ decay, from the estimated numbers of DCBA-I shown in Table 1 and the theoretical calculations of the half life [14] [17], the event rate is roughly estimated to be about 2000 y⁻¹. Though it is very difficult to estimate the background rate in the present stage, the signal-to-background ratio is expected to be around 5, as obtained in other magnetic tracking detectors [19].

5. Design of DCBA-I

All fundamental techniques should be established and confirmed at the stage of DCBA-I, so that no technical problems will remain in the DCBA-II, except for the mass production of the chamber modules and veto-counters, and the construction of a large-size solenoidal magnet. The designed parameters of DCBA-I are described in Table 2.

The configurations of the wires and the SP's in the drift-chamber module are shown in Fig.5. The accommodated 8 SP's have dimensions of $10 \times 60 \text{ cm}^2$ each, so that the total area is 4800 cm^2 . Since the source thickness is 35 mg/cm^2 (about $50 \mu\text{m}$), the total weight of the SP is 168 g.

There are four tracking spaces, each of which has dimensions of 105 mm in the x direction, perpendicular to both the SP and MF (Magnetic Field), 486 mm in y, parallel to the SP and perpendicular to the MF and 600 mm in z, parallel to both the SP and MF. The tracking space is surrounded by an anode-potential plane, a cathode plane and four field shaping planes. All of the planes, but two field planes, consist of metal wires of 610 mm length. The wires and the magnetic field are in the same direction, namely z.

The anode-potential plane, which is located at each side of the SP with a distance of 6 mm, comprises 80 anode wires of $20 \mu\text{m}$ diameter stainless steel. In other words, one tracking space contains 80 anode wires. The potential wires of 81 are $80 \mu\text{m}$ diameter aluminum. The anode and potential wires are alternately arrayed with a pitch of 3 mm. The cathode plane comprises 159 cathode wires. The cathode plane located at the central part is common to the two tracking spaces adjoining each other. Two field-shaping planes comprise 34 field wires each. Two other field-shaping planes consist of wire-printed film, mounted on the insides of the endplates. All of the wires of the cathode and field shaping are aluminum of $80 \mu\text{m}$ diameter.

The decay electron emitted from the SP makes electron-ion pairs along its trajectory in the chamber gas of He(95%) and C_2H_6 (5%) at 1 atm. Electrons produced by the ionization process drift to anode wires along the uniform electric field in the x direction with a maximum drift length of 99 mm. The x position of the track is determined by the product of the measured drift time and the electron drift velocity, which should be previously confirmed. Here, the first anode signal gives the initial time for the drift-time measurement. Since the electric field is different between both sides of the anode-potential plane, the drift electron velocity in one side is different from that in the other side, as shown in the drift-distance-to-time relation (x-t relation) of Fig.6, where the drift paths along the electric field lines are also depicted. When the electric field is 500 V/cm at the cathode side, the drift velocity is estimated to be $8 \text{ mm}/\mu\text{sec}$ [20]; also, under the condition of 2 kV anode potential, the electric field at the SP side is calculated to be around 1000 V/cm , in which the drift velocity is estimated as about $16 \text{ mm}/\mu\text{sec}$. To be more precise, the electric field close to the potential wire is different from that in the middle part of the tracking space, as shown in Fig.6. A track reconstruction from the detector signals should be corrected using the x-t relation [21]. The y position of the track is considered to be the same as the potential wire position. All of the wires must be strung so that their sagittas due to gravity and the electrostatic force are less than their own diameters. The z position is obtained by the so-called charge division method using the signals from the pre-amplifiers located at both sides of the anode wire.

The anode signals are read out by a system comprising pre-amplifiers, shaping amplifiers, FADC's (Flash Analog to Digital Converter), memories and a CPU as shown in Fig.7. Using the readout system, the two track separation capability is expected to be about 2 mm. The event to be triggered is selected by a TDM (Trigger Decision Module), which produce a trigger signal when several adjoining anode wires are simultaneously hit during about $5 \mu\text{sec}$. The TDM covers 80 channels for each tracking space.

The momentum of each decay electron is obtained by measuring the curvature and the pitch angle of the helical track so that the energy and the angular correlation of the event can be confirmed one by one. The track position will be able to be determined within errors of less than 0.2 mm in both the x and y directions, and of about 2 mm in the z direction. The vertex point determined with an accuracy of about 2 mm is extremely useful for rejecting background events, especially the ones from the natural decay chain such as the U and Th series.

6. Concluding remarks

Recent results of the neutrino experiments and of theoretical studies strongly suggest the existence of a massive Majorana neutrino. It is notable that a $\beta\beta$ decay experiment using the calorimeter of ^{76}Ge shows the saturation tendency for a half-life lower limit of around $2 \times 10^{24} \text{ y}$ [10]. In order to investigate whether the event count is excessive at the Q-value or not, it seems essential to efficiently detect the vertex point of the event one by one with a sufficiently large amount of isotope source. The DCBA is a newly proposed magnetic detector using a drift chamber, which can satisfy these conditions. The DCBA-I will provide the chance to solve the technical problems and to measure the half life of the $2\nu\beta\beta$ decay of ^{150}Nd . The DCBA-II will have a half-life sensitivity of $4 \times 10^{24} \text{ y}$, which corresponds to the sensitivity of an effective neutrino mass of $0.1 - 0.5 \text{ eV}$, depending on the calculation of the nuclear matrix element. A fundamental strategy of the DCBA project and some details of DCBA-I have been described.

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Table.1 Specifications of DCBA-I and DCBA-II.

	DCBA-I	DCBA-II
k	0.4 ($2\nu\beta\beta$)	0.7 ($0\nu\beta\beta$)
N_0	3.8×10^{22} Natural Nd (5.6% ^{150}Nd)	4.5×10^{25} Nd_2O_3 ($\sim 90\%$ ^{150}Nd)
$N_{BG} \text{ (keV}^{-1}\cdot\text{y}^{-1}\text{)}$	$\sim 10^{-1}$	$\sim 10^{-1}$
$\Delta E \text{ (keV)}$	~ 100	~ 200
$T_{1/2}^{lim} \text{ (y)}$	3×10^{21}	4×10^{24}

Table 2. Designed parameters of DCBA-I.

Dimension	$464(x) \times 524(y) \times 680(z)$ mm ³
Tracking space	4 tracking spaces $105(x) \times 486(y) \times 610(z)$ mm ³ /tracking space
Anode wire	80 wires/tracking space, total 320 wires 20 μ m diam. stainless steel
Potential wire	81 wires/tracking space, total 324 wires 80 μ m diam. aluminum
Cathode wire	161 wires/tracking space, total 483 wires 80 μ m diam. aluminum
Field wire	2 layers/tracking space, 34 wires/layer, total 272 wires 80 μ m diam. aluminum
Gas	He(95%) + C ₂ H ₆ (5%), 1 atm
Drift field	500 V/cm
Drift velocity	8×10^6 mm/s/atm
Magnetic field	0.4 – 1.2 kG by solenoid coil
Readout	Pre-amplifier + shaping amplifier + FADC 80 channels $\times$ 2/tracking space, total 640 chs.
z-position	Charge division
Resolution	$\sigma_x \leq 0.2$ mm, $\sigma_y \leq 0.2$ mm, $\sigma_z \leq 2$ mm $\sigma_{VTX} \leq 2$ mm
Source	8 plates of natural Nd (5.6% ¹⁵⁰ Nd, Q = 3.367 MeV) 10 $\times$ 60 cm ² and 50 μ m thick (35 mg/cm ²)/plate
Veto counter	Plastic scintillator

Fig.1 Conceptual drawings of DCBA: (a) DCBA-I and (b) DCBA-II.

Fig.2 Specific energy resolution for the various electron energies as a function of the magnetic field.

Fig.3 Detection efficiency for $0\nu\beta\beta$ and $2\nu\beta\beta$ decay modes as a function of the magnetic field.

Fig.4(a) Example of the simulated $0\nu\beta\beta$ event emitted back to back.

Fig.4(b) Example of the simulated $2\nu\beta\beta$ event emitted to the same side.

Fig.6 Drift-distance-to-time relation (x-t relation) and the drift paths along the electric field lines around the anode-potential plane.

Fig.7 Schematic diagram of the read-out system. TDM and TDC stand for the trigger decision module and the time-to-digital converter, respectively.