Session IV

Double beta decay experiments: future II
Neutrinoless double beta decay experiment with DCBA

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Abstract
A magnetic momentum analyzer, called DCBA (Drift Chamber Beta-ray Analyzer), is being developed at KEK in order to search for neutrinoless double beta decay events. Since DCBA includes new techniques, a test apparatus, DCBA-T, has been constructed and operated for confirming technical feasibility. Preliminary results of the test operation are described together with future prospects.

1 Introduction

The existence of neutrino mass has been confirmed by the observation of neutrino oscillations [1][2][3][4][5], as pointed out by Maki, Nakagawa and Sakata [6]. The next major matter of concern is to measure the absolute neutrino mass. Because the small neutrino mass is naturally explained by the so-called see-saw mechanism [7][8][9], the possibility of a Majorana-type neutrino mass becomes large. If neutrinos are Majorana particles, neutrinoless double beta decay (NDBD) takes place [10][11][12][13][14].

Though evidence of NDBD was reported at the end of 2001 [15] using the data of ⁷⁶Ge [16], there are some objections against the analysis method in the derivation process [17][18]. One reason for this confused situation is that the Q-value of ⁷⁶Ge is as low as 2039 keV. A Ge-detector is sensitive to both electrons and gamma-rays, and measures only the total energy. It is well-known that there are many background events in energy measurement around 2 MeV due to alpha, beta and gamma decays in the source contamination. Other background events are external gamma rays from the surroundings. While a Ge-detector has excellent energy resolution, very careful attention is required to the energy calibration of the detector.

Calorimeter-type detectors, such as Ge, Xe, bolometer and scintillator, including source materials, have been well-investigated so far, because their detection efficiencies are very high. However, these detectors are usually sensitive to gamma rays, and easily suffer background. For a future calorimeter-type detector, some efforts are required to distinguish electron signals from gamma signals and/or to identify the daughter nucleus.

For searching for NDBD events, experiments using the decay sources of high Q-value, such as ⁴⁸Ca, ¹⁰⁰Mo and ¹⁵⁰Nd, the Q-values of which are 4.27 MeV, 3.03 MeV and 3.37 MeV, respectively, have advantages, because the number of background events is extremely lowered at an energy region higher than 3 MeV. In these cases, however, we need a detector surrounding sources in order to observe NDBD events. If we can measure the momentum of each electron from its trajectory, the electron kinetic energy is obtained by a calculation, and the decay vertex position is also determined. Information concerning the decay vertex position is very useful for eliminating background events.

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²N. Ishihara, T. Inagaki, T. Ohama, S. Takeda, Y. Yamada (KEK), K. Terada, Y. Teramoto (Osaka City University), Y. Sakamoto (Rikkyo University), I. Nakano (Okayama University), S. Kitamura (Tokyo Metropolitan University of Health Sciences), T. Emura (Tokyo University of Agriculture and Technology), N. Tamura (Niigata University) and Y. Nagasaka (Hiroshima Institute of Technology).
A magnetic tracking detector, called Drift Chamber Beta-ray Analyzer (DCBA), is being developed at KEK, using a decay source of $^{150}$Nd [19][20]. Since new techniques are adopted in DCBA, a test apparatus, called DCBA-T, has been constructed and operated in order to confirm its technical feasibility [21]. In this report, an outline of the DCBA experiment and the present status of DCBA-T are described together with future prospects.

2 Outline of the DCBA experiment

DCBA is a momentum analyzer consisting of a drift chamber, a solenoid magnet and cosmic ray veto-counters. DCBA-T is illustrated in Fig. 1, where a simulated NDBD is also shown. The end plates of the magnet and veto-counters surrounding the magnet are not illustrated for clarity. Thin source plates made of Nd$_2$O$_3$ are installed in a drift chamber located in a solenoid magnet. A simulated event in the figure shows that two beta rays, $\beta_1$ and $\beta_2$, are emitted back-to-back from a source plate, and make helical trajectories in a magnetic field. Of course, when two beta rays are emitted from the same side of source plate, it is also possible to detect them.

The momentum of each beta ray is obtained by measuring the radius and pitch angle of the helical track. Since the energy of a beta ray is calculated from the momentum, the detection efficiency of DCBA is larger than that of a hybrid detector, which consists of trackers and calorimeters, for example NEMO [22] and ELEGANT V [23]. In the case of a hybrid detector, the long distance between a source plate and a calorimeter makes the spatial acceptance small.

From the viewpoint of background elimination, DCBA completely rejects gamma rays, because the DCBA drift chamber is insensitive to gamma rays. Therefore, accidental coincidence due to a gamma ray, which is a serious problem in the case of a calorimeter, is intrinsically avoidable in the energy derivation for an NDBD event.

Since the magnetic-field direction of DCBA is parallel to the source plates, a beta ray perpendicular...
Figure 2: Comparison of $<m_\nu>_\text{sns}$ for various detectors. The horizontal axis is the product of the amount of source nucleus (mol) and the measuring time (yr).

ularly emitted to the source plate has the best quality because of the minimum effect from multiple scattering and energy loss in the source plate. This makes it possible that DCBA contains a thicker source plate than that of UCI-TPC, the magnetic field of which is perpendicular to the source plate [24]. Compared with UCI-TPC, other advantageous points are a larger spatial acceptance, and possible mass production because of the simple DCBA structure.

The DCBA experiment is divided into 4 steps: DCBA-T, -I, -II(1) and -II(2). The 1st step is the R&D stage comprising the construction and operation of DCBA-T. The 2nd step is the construction and tuning of a standard module, DCBA-I, which has a 4 times larger volume than DCBA-T. The 3rd step is the mass-production stage, called DCBA-II(1), where 100 modules of DCBA-I are constructed and operated. Up to this step, the source plates are made of natural Nd, which includes about 5.6% $^{150}$Nd. The 4th step is the final stage, called DCBA-II(2), where natural Nd source plates are replaced by enriched $^{150}$Nd source plates.

Under the assumption of mass mechanism dominance, the half-life of NDBD, $T_{1/2}^{0\nu}$, is related to the effective neutrino mass, $<m_\nu>$, by the following equation:

$$T_{1/2}^{0\nu} = (G^{0\nu}|M^{0\nu}|^2 <m_\nu>^2)^{-1},$$

(1)

where $G^{0\nu}$ is the phase-space factor and $M^{0\nu}$ the nuclear matrix element. The sensitivity to the effective neutrino mass, $<m_\nu>_\text{sns}$ (eV), has been estimated for the DCBA series and other experiments [20], using

$$<m_\nu>_\text{sns} = \left( \frac{C\sqrt{BG}}{(\ln 2)kN_0} \right)^{1/2} t^{-1/4},$$

(2)

where $C$ (yr·eV²) is the product of the half-life and the neutrino mass square, which is equal to $(G^{0\nu}|M^{0\nu}|^2)^{-1}$, calculated by A. Staudt et al. [25], $BG$ (yr⁻¹) the background event rate, $k$ the
detection efficiency, $N_0$ the number of source nuclei and $t$ (yr) the measuring time. The results of the estimation are shown in Fig. 2 [20]. In this figure, the left-side of the parallelogram stands for the sensitivity obtained by a one-year measurement, the right-side means that by a 10-year measurement, and the height shows the calculation ambiguity. The mass sensitivities calculated from the half-life limits measured so far by experimental groups were obtained by using the nuclear matrix elements of A. Staudt et al. [25], and shown in the figure with several marks. All of the marks are in good agreement with the estimated results. In the case of a shorter measuring time than one year, a dashed parallelogram is drawn for a comparison. One can see that the series of DCBA has the best sensitivity under the conditions of the same product of nuclear quantity and measuring time. This is because of three features of the DCBA detector: (i) the high nuclear matrix element of $^{150}$Nd, (ii) the high detection efficiency and (iii) the good background-elimination capability.

3 Present status of DCBA-T

DCBA-T consists of a drift chamber, a solenoid magnet and veto-counters, shown in Fig. 3. One can see the iron end cap and the flux return iron yoke of the solenoid magnet, hollow conductors used for current supply and water cooling to the magnet coils, and cables from pre-amplifiers connected to the drift chamber, which is installed in the magnet. The diameter and the length of the magnet are 65 cm and 104 cm, respectively.

The specifications of DCBA-T are described in Table 1. The wire configuration of the drift chamber is depicted in Fig. 4. Anode and potential wires, which are alternately aligned with 3 mm pitch, are located at both sides of the central source plate. There are cathode wires 99 mm apart from the anode and potential wire plane. Field wire planes are used to compensate the electric field uniformity. A region surrounded by two cathode wire planes and field wire planes is a sensitive volume. It is important that a small region between the source plate and the anode and potential wire plane is also sensitive, because the signal in the region provides information about the anode wire position in a drift-time space.

The principle of electron track detection is illustrated in Fig. 5. There exist a thin source plate, an anode and potential wire plane, and a cathode wire plane in a uniform magnetic field of the wire direction. The chamber is filled with a light gas mixture, such as 80% helium and 20% ethane. When an electron is emitted from a source plate, the electron ionizes the chamber gas, and the electrons produced by the ionization drift to anode wires along electric force lines, while ions drift to the cathode.
Figure 4: Wire configuration of the DCBA-T drift chamber.

Figure 5: Principle of track detection of an electron in the DCBA chamber installed in a uniform magnetic field. Only one part of a sensitive volume is illustrated.
Table 1: Specifications of DCBA-T.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift chamber</td>
<td>Multi-track capability</td>
</tr>
<tr>
<td>Decay source</td>
<td>Nd$_2$O$_3$, ($^{150}$Nd = 0.015 mol, 40 mg/cm$^2$)</td>
</tr>
<tr>
<td>Sensitive volume</td>
<td>21 (X) × 24 (Y) × 60 (Z) cm$^3$</td>
</tr>
<tr>
<td>Anode wire</td>
<td>80 wires of 25 µm diameter Nichrome, 1.2 kΩ each</td>
</tr>
<tr>
<td>Potential wire</td>
<td>82 wires of 80 µm diameter aluminum</td>
</tr>
<tr>
<td>Cathode wire</td>
<td>162 wires of 80 µm diameter aluminum</td>
</tr>
<tr>
<td>Signal readout</td>
<td>Flash ADC, 160 ch</td>
</tr>
<tr>
<td>X-position</td>
<td>Drift velocity × Drift time ($\sigma \sim 0.5$ mm)</td>
</tr>
<tr>
<td>Y-position</td>
<td>Wire position ($\sigma \sim 0.05$ mm)</td>
</tr>
<tr>
<td>Z-position</td>
<td>Charge division ($\sigma \sim 6$ mm)</td>
</tr>
<tr>
<td>Magnet</td>
<td>Solenoid coil + Flux return yoke</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>0.8 kG (max.)</td>
</tr>
<tr>
<td>Uniform volume</td>
<td>40 dia. × 70 cm$^3$ (&lt; ± 1% error)</td>
</tr>
<tr>
<td>Veto-counters</td>
<td>Scintillation counters</td>
</tr>
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wires. We can measure the drift time of the drift electrons ($t_e$) by using a Flash Analog to Digital Converter (FADC). Since we previously know the velocity of the drift electrons ($v_e$), $t_e \times v_e$ means the drift length between the ionization point and the corresponding anode wire. At the same time, each FADC channel, which is connected to a pre-amplifier from each side of an anode wire, reads out the charge information of the so-called electron avalanche produced on the anode wire surface by drift electrons. By comparing the charge information of both sides of the wire, the position in the wire direction, at which drift electrons arrive, is determined. This method is called charge division.

As shown in Figs. 1 and 5, the space coordinates are defined as the X-direction of the electric field ($E$), the Z-direction of the magnetic field ($B$) and the Y-direction of $B \times E$. From a three-dimensional reconstruction of the electron helical trajectory, we can measure the radius and the pitch angle, which is defined as the angle between the electron track and the X-Y plane. The electron momentum is obtained from

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

where $p$ is the momentum in MeV/c, $\lambda$ the pitch angle, $r$ the radius in cm and $B$ the magnetic flux density in kG. We usually discuss the kinetic energy of an electron ($T$), which is expressed by the relation

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

with the electron rest mass ($m_e$).

A data acquisition (DAQ) system is one of the main parts in this experiment. While the development of a new DAQ system is in progress, as described later, the DAQ-system of DCBA-T temporarily consists of TKO-FADC’s, which were used at the VENUS vertex detector [26], VME-bus containing memory circuits, and UNIX-CPU, as shown in Fig. 6. A TKO-FADC board has 8 channels with 8-bit resolution and 1 k-word memory, each. Since the present condition of event trigger requires a memory time of 20 µsec for one event, a sampling rate of 50 MHz has been selected.
Figure 6: DAQ system temporarily used for the DCBA-T.

Figure 7: Preliminary result of the spatial resolution at the X-position.
4 Preliminary results from DCBA-T

In order to investigate the spatial resolutions in the X- and Z-positions, cosmic rays of relatively high energies have been taken without a magnetic field. Straight tracks of cosmic rays have been reconstructed in the X-Y and Y-Z projection planes. A linear fit was made for each straight track with the least-squares method, and then the residual of every wire data from the fit point of corresponding Y-position was measured. The preliminary results of spatial-resolution studies are partly shown as residual distributions for a wire in Figs. 7 and 8, for the X- and Z-positions, respectively. These resolutions will be improved by developing chamber techniques, such as an ingenious method for high-voltage supply to the anode wires, the new DAQ system and contrived analysis methods for deriving accurate position.

The Z-position resolution will especially be improved by reducing the electrical noise coming from accelerator equipment at KEK. The noise level of the anode signal is always changing, and also individually different among signal channels, depending on the accelerator condition. The noise deforms an anode signal and disturbs the charge derivation. This makes it difficult to obtain an accurate Z-position of a particle track, because the Z-position is determined by the so-called charge-division method. We need to operate DCBA-T in a low-noise environment in order to obtain the actual Z-position resolution.

As for the sensitivity to electrons of the energy region of NDBD, internal conversion electrons from $^{207}$Bi, the kinetic energy of which are 0.5, 1.0 and 1.7 MeV, have been used. Two isotopes of $^{207}$Bi, each intensity of which is estimated to be less than 0.1 Bq, have been mounted on the support frame of a source plate. It is well known that a 1.0 MeV electron is relatively intense. A typical electron track is shown in Fig. 9. In the figure, the horizontal axis is a time count of FADC, corresponding to the X-position, and the vertical axis is a wire number, corresponding to the Y-position. One can see that an electron curls counter-clockwise in a magnetic field of the Z-direction, this side. Using the events of the internal-conversion electron of 1 MeV, a temporary energy resolution of 220 keV (rms) was obtained so far. The main reason for this worse resolution is bad Z-position resolution, as previously described.
Figure 9: Track of an internal-conversion electron from $^{207}$Bi.

Figure 10: Dependence of the energy resolution on the Z-position resolution. The inverse triangle line shows the case of only energy loss considered in the chamber gas. The open circle line means the case where both the multiple scattering and the energy loss are considered.
The dependence of the energy resolution on the Z-position resolution has been studied using a Monte-Carlo simulation program developed by our group, and its result is shown in Fig. 10. The expected Z-position resolution is 6 mm, which is 1% of the wire length. After the expected value is achieved, the energy resolution of less than 6% is obtained.

In DCBA, only two-track events become background events. It has been demonstrated that we can easily eliminate a knock-on electron event caused by a cosmic ray and an \(e^+e^-\) pair creation event, using a track-pattern analysis [21].

5 Future prospects

In the near future, a new DAQ system will be completed with FADC based on a compact PCI (CPCI) bus, being controlled by board computers with Linux OS [27]. A CPCI-FADC board contains 8 channels of 6U size by a single slot. Each channel consists of a 100 MHz FADC chip with 8-bit resolution and a high-speed double-buffered memory (\(2 \times 4\) k-words: 1 word = 8-bits). The memory has a two-times larger capacity than the required memory size in the present wire configuration of the chamber, so as to have redundancy with respect to the drift electron velocity, depending on the gas mixture and the electric field. This is useful to improve the X-position resolution.

The CPCI-FADC can take data without any dead time. This is very useful for eliminating background events, according to the following description. Events of NDBD are generally very rare, because the half-life is expected to be longer than \(10^{24}\) yr [25]. On the other hand, the \(^{238}\)U natural decay chain produces background events, the most serious one of which is from \(^{214}\)Bi. The beta decay of \(^{214}\)Bi to \(^{214}\)Po is sometimes followed by the emission of an internal-conversion electron. This two-electron event resembles an NDBD event of \(^{150}\)Nd, because the mass difference between \(^{214}\)Bi and
$^{214}\text{Po}$ is 3.27 MeV, while the Q-value of $^{150}\text{Nd}$ is 3.37 MeV. If an alpha particle emitted by the alpha decay of $^{214}\text{Po}$ with a half-life of 164 µsec can be caught, the background event is easily eliminated, as performed by TPC-UCI [28] and NEMO [22] groups.

In CPCI-FADC, operation without a dead time is performed as shown in Fig. 11. When the first event occurs, the data are recorded into memory bank-1 together with their address, and are then read out by a computer. If the second event comes during the time of computer reading out, the second data are recorded into memory bank-2. A time counter in a sequence controller measures the time interval between both STOPs of the first and second events with a 20 ns resolution.

After the new DAQ system with CPCI-FADC is installed in DCBA-T, full operation will be performed in an electrically low-noise environment in order to investigate the position and energy resolutions. DCBA-I will start after that the technical confirmation is successfully finished with DCBA-T.

6 Concluding remarks

Though NDBD is forbidden by the standard theory of the weak interaction, it takes place when a Majorana neutrino exists. From the results of neutrino-oscillation experiments, $\langle m_\nu \rangle$ is predicted to be around 0.05 eV by the model of inverted hierarchy mass [10][13]. The final stage of the DCBA experiment will have an effective mass sensitivity of less than 0.05 eV. If a statistically meaningful number of events is obtained, the study of a right-handed lepton current will be available by investigating the angular correlation between two beta rays [29].

As the first stage of the DCBA experiment, DCBA-T has been constructed, and now in the operation for engineering runs. Using internal-conversion electrons emitted from $^{207}\text{Bi}$, it has been confirmed that the helical tracks of low-energy electrons around 1 MeV can be obtained by a drift chamber located in a uniform magnetic field. Straight tracks of cosmic rays are also obtained in order to study the spatial resolution of the chamber. The spatial resolutions in both directions, X and Z, have been temporarily obtained. However, they have to be improved in order to achieve good energy resolution. To do this, we have a plan to operate DCBA-T with a newly developed DAQ system in an electrically low-noise environment. According to a simulation study, an energy resolution of 60 keV (rms) at 1 MeV is possible, if the designed spatial resolutions are achieved.

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References


Extrapolation of the NEMO technique for future generation 2$\beta$- decay experiments

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Abstract

The possibility of applying the NEMO experimental technique for a future neutrinoless double beta decay experiments is discussed. The main goal is to have an immediately realizable project with a planned sensitivity for the half-life at the level of $\sim (1.5 - 2) \times 10^{26}$ y (sensitivity to neutrino mass $\sim (0.04 - 0.1)$ eV). It is demonstrated that this can be achieved using the improved NEMO technique to investigate 100 kg of $^{82}$Se. Possible improvements of the NEMO technique and background conditions are discussed. A possible layout of the future SUPERNEMO detector and the main characteristics of the experiment are presented. Such a detector can also be used to investigate $0\nu\beta\beta$-decay in $^{100}$Mo, $^{130}$Te and $^{116}$Cd with a sensitivity of up to $\sim (2 - 5) \times 10^{25}$ y (or with sensitivity to neutrino mass of $\sim 0.1$ eV).

1 Introduction

The main goal of the NEMO experiment is to search for neutrinoless double beta decay ($0\nu\beta\beta$) in $^{100}$Mo with a sensitivity of $\sim 10^{25}$ y, which corresponds to a sensitivity for the effective neutrino mass $\langle m_\nu \rangle$ of the order of $\sim (0.1 - 0.3)$ eV. In 1988 the NEMO Collaboration started an R&D program in order to develop a detector for studying ($0\nu\beta\beta$) decay with such sensitivity. Two prototypes, NEMO-1 [1] and NEMO-2 [2] have proved the feasibility of this approach and have contributed to the background studies for the NEMO-3 project [3]. Furthermore, the NEMO-2 detector performances enabled the measurement of the half-lives of the allowed double beta decay ($2\nu\beta\beta$) of $^{100}$Mo [4], $^{116}$Cd [5], $^{82}$Se [6] and $^{96}$Zr [7]. The NEMO-3 detector is now operating at the Frejus Underground Laboratory (4800 m w.e.) and first results were presented at the NDM'03 Symposium by V. Vasiliev and H. Ohsumi.

In this paper we investigate the possibilities of using the NEMO technique for future, more sensitive neutrinoless double beta decay experiments.

2 Brief description of NEMO-2 and NEMO-3

A brief description of the NEMO-2 and NEMO-3 detectors is presented, because for future NEMO-4 or SUPERNEMO detector we will use essentially the same technique. For definiteness, we shall use the SUPERNEMO as name of the detector. The concept of SUPERNEMO was first presented in [8].

2.1 NEMO-2

NEMO-2 [2] consists of a 1m$^3$ tracking volume filled with helium gas and 4% ethyl alcohol (Fig. 1). Vertically bisecting the detector is the plane of the source foil (1m $\times$ 1m$^2$). The tracking portion of the detector is made of open Geiger cells with octagonal cross sections defined by 100$\mu$m nickel wires.

On each side of the source there are 10 planes of 32 cells which alternate between vertical and horizontal orientations. The cells provide three-dimensional tracking of charged particles by recording the drift time and two plasma propagation times in each cell.
A calorimeter made of scintillator blocks covers two opposing, vertical sides of the tracking volume. Two configurations of the calorimeter have been implemented. The first one consisted of 2 planes of 64 scintillators (12 cm×12 cm×2.25 cm$^3$) associated with “standard” photomultiplier tubes (PMTs). This configuration was used in the experiment with $^{100}$Mo. The other configuration consisted of 2 planes of 25 scintillators (19 cm×19 cm×10 cm$^3$) with PMTs made with low radioactive glass. The tracking volume and scintillators were surrounded by a lead (5 cm) and iron (20 cm) shield.

The performance and operating parameters were as follows: the threshold for the scintillators was set at 50 keV, the energy resolution (FWHM) was 18% at 1 MeV and the time resolution was 275 ps for a 1 MeV electron (550 ps at 0.2 MeV).

The NEMO-2 detector was operated in the Frejus Underground Laboratory (4800 m w.e.) from 1991 to 1997. During this period $\beta\beta$ decay processes in $^{100}$Mo, $^{116}$Cd, $^{82}$Se, $^{96}$Zr and $^{94}$Zr were investigated. Half-life values for 2$\nu\beta\beta$ decay and half-life limits on 0$\nu\beta\beta$, 0$\nu\beta\beta\chi^0$, and the 0$\nu\beta\beta$ transition to the 2$^+$ and 0$^+$ excited states have been extracted from the data [4, 5, 6, 7, 9].
2.2 NEMO-3

The NEMO experiment [3] uses a tracking detector which is not only able to measure the full energy released, but other parameters of the process such as the single electron energy, the angle between the electrons and the coordinates of event vertex. The optimal operating parameters of the detector were determined with the prototype NEMO-2 [2, 4, 5, 6, 7]. Currently the NEMO-3 detector is now operating and is able to accommodate up to 10 kg of various double beta decay candidates (\(^{100}\)Mo, \(^{116}\)Cd, \(^{82}\)Se, \(^{130}\)Te, \(^{96}\)Zr, \(^{150}\)Nd, etc). The sensitivity after 5 years of measurement will be at the level \(10^{21}\) y for 0\(\nu\)\(\beta\)\(\beta\) decay (\(\langle m_{\nu} \rangle \sim (0.1 - 0.3)\) eV), and \(10^{23}\) y for 0\(\nu\)\(\beta\)\(\beta\)\(X^0\) decay (\(\langle g_{ee} \rangle \sim 10^{-5}\)), and finally \(10^{22}\) y for 2\(\nu\)\(\beta\)\(\beta\) decay.

![Figure 2: Schematic view of the NEMO3 detector.](image)

A view of the detector’s cylindrically symmetric geometry is shown in Fig. 2. The detector consists of a tracking volume filled with helium gas, a thin (~ 50\(\mu\)m) source foil divides the tracking volume vertically into two concentric cylinders with a calorimeter at the inner and outer walls. The tracking system consists of 6180 2.7m long Geiger cells which are parallel to the detector’s vertical axis. The accuracy of the vertex reconstruction is on the level of 1 cm (\(\sigma\)). Energy and time-of-flight measurements are performed by the plastic scintillators covering the two concentric surfaces discussed above and their associated end caps. The total number of low radioactive photomultipliers is 1940. At 1 MeV, the energy resolution which depends on the scintillator shape and the associated PMT ranges from 13% to 16% (FWHM) and the time resolution is 250 ps (\(\sigma\)). The detection threshold is
30 keV. A magnetic field (\(\sim 25\) Gauss) is used to reject backgrounds connected with pair creation and incoming electrons. External shielding, made of 20 cm thick, low radioactivity iron, covers the detector in order to reduce \(\gamma\)-ray and thermal neutron external backgrounds coming from the LMS laboratory cave. Water tanks on the side walls and wood on the top and the bottom of the detector thermalize fast neutrons and constitute neutron shielding. In June 2002, all 20 sectors of NEMO-3, the magnetic field coil and the iron shield were installed. The detector began to take its first data, which allowed a preliminary analysis of \(0\nu\beta\beta\), \(2\nu\beta\beta\) and to start a background study. In the beginning of the year 2003 the final tuning of the detector, the laser system and neutron shielding construction were finished and from February 14 the detector started taking data with stable conditions.

Presently, the detector is operating with 6.9 kg of \(^{100}\text{Mo}\), 0.93 kg of \(^{82}\text{Se}\), 0.45 kg of \(^{116}\text{Cd}\), 0.6 kg of \(^{130}\text{Te}\), 37 g of \(^{150}\text{Nd}\), 9.4 g of \(^{96}\text{Zr}\), 7 g of \(^{48}\text{Ca}\) and with some sectors filled with foils especially designed to check background (0.6 kg of Cu and 0.6 kg of \(^{nat}\text{TeO}_2\)). The first results obtained with NEMO-3 are presented in [10].

3 SUPERNEMO - the next generation of experiment using the NEMO technique

3.1 Main ideas

![Plastic scintillator walls: 20 m x 3 m x 0.1 m](image)

Figure 3: The scheme of one SUPERNEMO module.

a) The main goal is to propose a realistic project, which can be achieved within a reasonable timescale. This is the motivation for using 1) the very well-known NEMO technique and 2) only 100 kg source which can be produced in a few years in Russia.

b) The next idea is to select the isotope for which maximal sensitivity can be reached and to this end we propose 100 kg of \(^{82}\text{Se}\), because of the high energy of the \(0\nu\beta\beta\)- transition (\(E_{2\beta} = 3\) MeV) and
a rather low probability of $2\nu$-decay which gives a small contribution to the $0\nu$-region. In addition, $^{82}\text{Se}$ can be produced using the centrifuge method - this is why we hope to produce 100 kg quite easily and with a reasonable cost.

c) Finally, we propose a modular scheme for the new detector - four identical modules with 25 kg of enriched source in each. It provides the possibility to start data taking quite soon (before finishing the entire construction).

The scheme for one module of the detector is shown in Fig. 3. The module consists of two plastic scintillator counter walls with the source between them. On each side of the source there are a few layers of Geiger cells. As in NEMO-2 and NEMO-3, the electron energy will be measured by plastic scintillator counters and tracks will be reconstructed using information from the Geiger cells. The new installation might be located at the Frejus Underground Laboratory (4800 m w.e.) or at some other Underground Laboratory (such as Gran Sasso, for example).

3.2 Main parameters of the installation

The main parameters of the installation are the following:
- 100 kg source of $^{82}\text{Se}$;
- planar geometry (4 modules);
- weight of plastic scintillator - 50 tons;
- $\sim$ 5000 low-background PMTs (for 30x30x10 cm$^3$ plastic scintillators);
- $\sim$ 30000 Geiger cells;
- passive shielding of 20 cm Fe and 20 cm borated polyethylene.

The planar geometry simplifies the construction and provides the possibility to use standard blocks and components. Notice that the number of PMTs is only a factor 2.5 higher than for NEMO-3 and the number of Geiger cells is only a factor 5 higher leading to the observation that one module of SUPERNEMO will be even simpler than the NEMO-3 detector.

3.3 Main characteristics of the detector

The main characteristics of the detector are the following:
- energy resolution of $10 \pm 12\%$ (FWHM) at 1 MeV;
- time resolution of 250 ps at 1 MeV;
- vertex resolution of 1 cm (1$\sigma$);
- efficiency ($0\nu$-decay) of $\sim$ 20$\%$;
- Purity of $^{82}\text{Se}$ is $< 0.05$ mBq/kg for $^{214}\text{Bi}$ and $< 0.005$ mBq/kg for $^{208}\text{Tl}$.

One can see that the main characteristics of SUPERNEMO are approximately the same as for NEMO-3. However, here we hope to obtain a better energy resolution ($10 \pm 12\%$ instead of $13 \pm 16\%$ in NEMO-3) and a higher efficiency (20$\%$ instead 12$\%$), and we are confident that these requirements can be realized. The reasons for this is that during production of the plastic scintillator counters for NEMO-3 many counters already had an intrinsic resolution of $\sim 10 \pm 12\%$. Furthermore, an improved selection efficiency can be achieved as a result of some improvements (no magnetic field, better geometry, decreasing the number the wires in the tracking volume, decreasing the diameter of wires, and improved selection of useful events).

3.4 Sensitivity of the experiment

3.4.1 External background

In [11], the external background in the NEMO-3 detector was estimated. One can extrapolate these results to SUPERNEMO and demonstrate that the external background in the energy interval (2.8-
3.2) MeV after 5 years of measurement will be smaller than one event in the case of $^{100}$Mo and $^{82}$Se. For $^{116}$Cd and $^{130}$Te the background was estimated as $\sim 10$ and $\sim 100$ events, respectively.

### 3.4.2 Internal background

There are two contributions to the internal background: 1) the radioactive impurities inside of the source, and 2) the tail from $2\nu$-decay. On the basis of experience which we now have, we believe that it is possible to reach SUPERNEMO requirements for the purity of the source and reach a level of 0 event contribution to background. Thus, the main internal background is associated with the tail from $2\nu$-decay. This contribution was estimated using expected parameters of SUPERNEMO for the four most prospective isotopes, $^{82}$Se, $^{100}$Mo, $^{116}$Cd and $^{130}$Te. The results are $\sim (1 - 2), \sim 20, \sim 5$ and $\sim 0$ background events, respectively.

### 3.4.3 Expected sensitivity

Using the background and efficiency estimations, one can obtain the expected sensitivity of the measurements with the various isotopes - see Table 1. The expected sensitivity is obtained for a 100-kg enriched source and for 5 years of measurement. Notice that all mentioned isotopes above can be produced in such quantities using the centrifuge method in Russia over a reasonable time. In the case of $^{130}$Te, even natural Te ($\sim 34\%$ of $^{130}$Te) can be used. The estimated sensitivity of SUPERNEMO with a natural Te source is $\sim (0.2 - 0.5)$ eV. Of course, other prospective isotopes (for example, $^{150}$Nd, $^{96}$Zr and $^{48}$Ca) could also be investigated. The main problem here is the difficulty in producing 100 kg of such isotopes at the present time.

Table 1: Best present limits at 90\% CL on $0\nu$-decay for $^{82}$Se, $^{100}$Mo, $^{116}$Cd, $^{130}$Te and expected sensitivity of NEMO-3 and SUPERNEMO. The last line shows the best present limits on the effective neutrino mass $\langle m_\nu \rangle$ of NEMO-3 and SUPERNEMO experiments (nuclear matrix element values from [16], [17], [18] and [19] were used).

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Best present limits</th>
<th>NEMO-3</th>
<th>NEMO-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{82}$Se</td>
<td>$&gt; 1.4 \cdot 10^{22}$ y [12]</td>
<td>$\sim 2 \cdot 10^{25}$ y</td>
<td>$\sim (1.5 - 2) \cdot 10^{26}$ y</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>$&gt; 5.5 \cdot 10^{22}$ y [13]</td>
<td>$\sim (5 - 8) \cdot 10^{24}$ y</td>
<td>$\sim 5 \cdot 10^{25}$ y</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>$&gt; 7 \cdot 10^{22}$ y [14]</td>
<td>$\sim 4 \cdot 10^{24}$ y</td>
<td>$\sim 4.6 \cdot 10^{25}$ y</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>$&gt; 2.1 \cdot 10^{23}$ y [15]</td>
<td>$\sim 1 \cdot 10^{24}$ y</td>
<td>$\sim 2 \cdot 10^{25}$ y</td>
</tr>
<tr>
<td>$\langle m_\nu \rangle$, eV</td>
<td>$&lt; 1.2 - 12$</td>
<td>$\sim 0.1 - 1.2$</td>
<td>$\sim 0.04 - 0.26$</td>
</tr>
</tbody>
</table>

### 4 Conclusion

It has been shown that the NEMO technique can be extrapolated to a larger SUPERNEMO detector with 100 kg of $^{82}$Se. The expected sensitivity for 5 years of measurement is estimated as $\sim (1.5 - 2) \cdot 10^{26}$ y, which corresponds to a sensitivity in $\langle m_\nu \rangle$ at the level of $\sim (0.04 - 0.1)$ eV. The same detector can be used to investigate $0\nu/3\beta$-decay in other prospective nuclei ($^{100}$Mo, $^{116}$Cd, and $^{130}$Te) with a sensitivity of $\sim (2 - 5) \cdot 10^{25}$ y.
The information from NEMO-3 will give us the possibility to improve our knowledge about, for example, external and internal backgrounds, the efficiency for $0\nu$- and $2\nu$- decays and the effect of magnetic field. We expect to start work on the proposal for SUPERNEMO very soon.

5 Acknowledgements

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References

Neutrino-less Double Electron Capture

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Abstract

Intensive search for neutrino-less double $\beta^-$ decay as a method to discover massive Majorana neutrinos is presently being conducted or planned. An alternative to this method is to observe the monoenergetic photon spectra due to radiative neutrino-less double electron capture. This recent proposition is presented and developed in some details. Strong rate enhancements are predicted at low decay energies. The enhancements are due to atomic resonances at photon energies equal to energy differences between the $1S$ and $2P$ atomic states. The phenomenon is particularly strong for high $Z$ atoms. Experimental advantages of the method are discussed for energies close to the resonance as well as outside the resonance region. The feasibility of experiments is considered and found encouraging.

1 Introduction

The oscillation experiments [1], [2], [3] indicate that the lepton flavour is not conserved and that at least one of the neutrino species has a finite rest mass. They also provide some constrains on the mass hierarchy. As a matter of principle, however, they can neither determine the mass values nor provide information on the properties of neutrino under charge conjugation. Phenomena of different kind have to be studied to meet these requirements. There are two kinds of experiments presently being pursued to achieve this goal: the direct measurement of the electron antineutrino mass from the end point of tritium $\beta^-$ spectrum [4] and the indirect determination from the rate of the neutrino-less double beta decay, $0\nu\beta^-\beta^-$ (see e.g. [5], [6] and [7] for recent reviews); both subjects have also been discussed at length at this NDM03 Conference (see this Proceedings). Constraints on the neutrino mass value can also be obtained from cosmological considerations (cf., e.g., [8] and this Proceedings).

Observing the double beta decay with no accompanying neutrino emission would mean much more than merely obtaining a measure of the neutrino mass, however important that is. Such an observation would also prove that not only the lepton flavour but also the lepton number is not conserved and, moreover, that neutrino is a Majorana (two spinor) and not a Dirac (four spinor) particle and thus that it is identical to its charge conjugate, i.e. that $\nu \equiv \bar{\nu}$. Both facts would have far reaching consequences for our understanding of weak interactions.

The double beta decay is a very slow process, unobservable practically in the presence of the single $\beta^-$ decay to the adjacent isobar. It may be observed, however, whenever the single beta decay of an even nucleus is energetically impossible while there is a positive mass difference for isobars with neutron or proton numbers differing by two units. Thus we may have processes

$$ (Z, N) \rightarrow (Z + 2, N - 2) + e^-_1 + e^-_2 + \bar{\nu}_e + \bar{\nu}_e \tag{1} $$

or

$$ (Z, N) \rightarrow (Z - 2, N + 2) + e^+_1 + e^+_2 + \nu_e + \nu_e \tag{2} $$

with the double electron capture alternative

$$ (Z, N) \rightarrow (Z - 2, N + 2) + \nu_e + \nu_e \tag{3} $$

\[\text{work done in collaboration with S. Wycech}\]
This is illustrated in Fig. 1 showing the mass parabolae for $A = 76, 92, 100, 144$ and $180$. There are two candidates shown for the $\beta^-\beta^-$ decay, namely $^{76}\text{Ge}$ and $^{100}\text{Mo}$, and three for the $\beta^+\beta^+$ or double electron capture transitions: $^{92}\text{Mo},^{144}\text{Sm}$, and $^{180}\text{W}$. The latter three concern physical processes which are usually considered as non-favourable for the neutrino-less double beta decay searches. The purpose of the present work is to show that there may exist situations in which these estimates are not justified and which, moreover, offer definite experimental advantages. Such situations are tentatively described in [9], where it is proposed to study the photon radiation accompanying the neutrino-less double electron capture. The present work extends the proposal of [9]. Particular attention is paid to the very special cases in which the decay energy corresponds to resonance conditions in the decaying atoms. Very strong enhancements of the process are predicted. Some nuclear species are considered as possible candidates exhibiting such enhancements. Very promising in this context are decays to excited states. These are favoured by the phase space considerations, very different from those for the "usual" neutrino-less double $\beta^-$ emission.

2 Neutrino-less double beta decay

The general features of the double beta decay have been described at this NDM03 conference in several contributions. Only some basic information needed specifically for the purpose of this article will be given here.

The Feynmann diagram for $0\nu\beta^-\beta^-$ Majorana decay is depicted in fig.2 (top). The left-handed neutrino, $\nu_L$, emitted by one neutron is absorbed by another with an amplitude proportional to the proper helicity admixture and thus to the neutrino mass. Only two electrons appear in the continuum in the final state. In the case of the Dirac neutrinos there would be two $\nu_L$ in the continuum in the final state, in addition to the two electrons. Fig.2 (bottom) shows a similar diagram for neutrino-less double electron capture transitions, $0\nu e^-e^-$. There is a unique experimental signature of the neutrino-less double $\beta^-$ decay, $0\nu\beta^-\beta^-$: the sum of the energies of the two correlated $\beta^-$ electrons is constant and equal to the total decay energy. This gives a chance to distinguish the effect from that of the dominating $2\nu\beta^-\beta^-$ process, in which the energy is statistically shared among the four particles emitted. Typically, the $2\nu\beta^-\beta^-$ process is $10^3 \div 10^4$ times faster than the $0\nu\beta^-\beta^-$ one.

As mentioned above, the rate of the double beta decay offers a sensitive measure of the neutrino mass. This is so under the assumption that the neutrino mass diagram of fig.2 dominates the $0\nu\beta\beta$ decay. There exist, however, many additional, non-neutrino diagrams (Higgs, supersymmetry, right handed neutrinos etc.) which also can generate the $0\nu\beta\beta$ decay. In the following we assume that the contributions of these processes, if any, are negligible. What is worth stressing at this point is that while the exact value of the neutrino mass deduced from a successful $0\nu\beta_2$ experiment can be subject to various corrections, the mere observation of the effect proves unambiguously the existence of a non-vanishing Majorana neutrino mass as well as the nonconservation of the lepton number. This remains true regardless of the mechanism causing the decay [10].

Crudely, the rate for the $0\nu\beta\beta$ processes can be factorized into the phase space factor, $G^{0\nu}(E,Z)$, and the nuclear matrix element, $M^{0\nu}$:

$$\Gamma(0\nu\beta\beta) = G^{0\nu}(E,Z)|M^{0\nu}(A, Z \rightarrow A, Z \pm 2)|^2 \chi^2$$

The $G^{0\nu}$ factor contains the leptonic contributions including the final state electron wave functions. The crucial $\chi$ factor is the effective neutrino mass

$$\chi = \langle m_{\nu_{ij}} \rangle = \sum_i |U_{ei}|^2 m^\nu_i \epsilon^\delta_{ei}$$

(5)
where $\delta_e$ are the Majorana phases, $U_{ei}$ are the mixing amplitudes and the masses are in units of the electron mass, $m_e$.

The nuclear matrix element is a combination of the Gamov-Teller and Fermi terms:

$$M^{0\nu} = M_{GT}^{0\nu} - \frac{gV}{gA} M_{F}^{0\nu}$$  \hfill (6)

From the oscillation experiments we can deduce the mixing angles and the mass square differences. The maximal and minimal values of $m_\nu$ are

$$\langle m_\nu \rangle_{\text{max}} = \sum_i |U_{ei}|^2 m_i$$  \hfill (7)

$$\langle m_\nu \rangle_{\text{min}} = \max[(2|U_{ei}|^2 m_i - \langle m_\nu \rangle_{\text{max}}, 0)] \hfill (8)

The $\langle m_\nu \rangle$ value, to be eventually deduced from the double $\beta$ decay, will fix the range of the neutrino masses!

The values of $M^{0\nu}$ for a large number of $\beta^-\beta^-$, $\beta^+\beta^+$ and $\beta^+EC$ processes are calculated and/or reviewed in [12], [13] and more recently in [5]. The straggling of these state-of-the-art values results occasionally in an order of magnitude differences in the lifetime expected. This reflects the uncertainties in the calculations. Extensive programs of improving this situation are in progress [14]. The two basic approaches are the quasiparticle random phase approximation, QRPA, and the shell model, SM.

3 The experimental quest

The major experiments and new experimental projects have been described in details at this Conference (see this Proceedings). Only some comments on the experimental challenges and difficulties are mentioned here.

The experiments searching for the $0\nu\beta^-\beta^-$ decay can be divided into two categories: the calorimetric experiments, in which the material of the source is usually identical with that of the detector, and the tracking experiments, in which the source and the detector are separate. The former automatically sum up the energies of the charged particles emitted. Large quantities of the material can be used. The main difficulty rests in suppressing the background. The only available means to do so are the shielding and the extreme purity of all the material of the detector housing and of the surroundings. The tracking detectors, counting the two electrons in coincidence, are somewhat less sensitive to the background. On the other hand, there are practical difficulties in using large amount of material, of the order of tons, in the form of thin sheets sandwiched between the detectors. The detectors in both kinds of experiment must fulfill the high resolution requirement. Otherwise the $0\nu\beta^-\beta^-$ peak in the sum spectrum will not be discernible from the dominating continuous physical background due to the $2\nu\beta^-\beta^-$ decay.

A coincidence trigger suppressing the background can be provided by the 511 KeV annihilation quanta in the case of $0\nu\beta^+\beta^+$ or $0\nu\beta^+EC$ decays. Likewise, decays to excited nuclear states can be observed in coincidence with the subsequent gamma rays. The practical limitation of these techniques rests in the very fast energy dependence of the phase space factor (roughly $\sim Q^5$, where Q is the available decay energy). This results in prohibitive enlargements of the lifetimes of the decaying species.
4 Neutrino-less double electron capture - an overlooked possibility

The neutrino-less double electron capture decay without additional radiation violates the energy conservation. There has to be a medium to carry away the excess energy. This can be a single photon, two photons, an electron or some more exotic particle like a majoron. Such higher order processes are usually strongly retarded. They have, therefore, been discarded as a practical way to search for the neutrino-less transitions [15, 16]. It has recently been pointed out [9], however, that there may exist situations in which this retardation is compensated by favourable phase space relationships. In addition, the spectrometry with monoenergetic photons offers important experimental advantages.

The Feynman diagram for the process with emission of a single monoenergetic photon is shown in fig. 2b. The radiation is attributed to one of the captured electrons. In the spirit of eq. 4 the rate for this process can be expressed as

\[ \Gamma(0^{\nu}\nu ee) = G^{0\nu}\gamma (A, Z - A, Z - 2)^2 (m_\nu/m_e)^2 |M^\gamma|^2 \]  

The photon emission probability estimated semi-classically is

\[ |M^\gamma|^2 = (e^2/2qm_e)f \]  

where \( e \) is the electron charge, \( q \) is the photon momentum (it is equal to the mass difference less the binding energies of the two electrons) and \( f \) is a factor which describes the propagation of the radiating electron. Assuming the nuclear matrix elements for double electron capture and double \( \beta^- \) transitions as being equal, one can roughly compare the rates for the \( 0^\nu\beta^-\beta^- \) and \( 0^{\nu}\nu ee\gamma \) processes. The retardation factor \( R(\gamma) \) can be defined as the ratio of these rates:

\[ R(\gamma) = \frac{\Gamma(0^{\nu}\nu ee\gamma)}{\Gamma(0^\nu\beta^-\beta^-)} \approx \frac{(m_e/Q_{\beta\beta})^5}{480\pi q^7 Z^6} \]  

This strongly favours high Z nuclei with low decay energy as candidates for the neutrino-less double electron capture search. The structure of the \( f \) factor is complex. It favours low \( q \) values, particularly for electric dipole transitions. These correspond to cases where the electrons are captured respectively from the 1S and 2P states. Crudely, \( f(\text{el.dip.}) \sim 1/q^4 \). Note that the radiative capture of two 1S electrons is not allowed for nuclear transitions of the \( 0^\nu \rightarrow 0^\nu \) type since the photon has to carry out at least one unit of angular momentum.

Table 1 presents estimates given in [9] of the \( (0^{\nu}\nu ee\gamma) \) process for a few selected nuclei. Very crude numbers taken for the nuclear matrix elements and the semi-classical, non-relativistic formulae used for the \( f \) factor result in one or even two orders of magnitude uncertainties. The life times given are those for \( m_\nu = 1eV \). They scale with \( (m_\nu)^2 \). The more accurate calculation [17] of \( f \) tends to yield larger lifetime values, corresponding to the upper limits of table 1. Even so, the estimates are highly encouraging, suggesting feasible experiments.

<table>
<thead>
<tr>
<th>Atom</th>
<th>abundance %</th>
<th>( \Delta M(\text{EC, EC}), \text{keV} )</th>
<th>( T_{1/2}(y), m_\nu = 1\text{eV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{92}\text{Mo})</td>
<td>15.84</td>
<td>1648.6</td>
<td>( 10^{31.7\pm1} )</td>
</tr>
<tr>
<td>(^{108}\text{Cd})</td>
<td>0.875</td>
<td>262</td>
<td>( 10^{28\pm1} )</td>
</tr>
<tr>
<td>(^{128}\text{W})</td>
<td>0.12</td>
<td>145</td>
<td>( 2.5 \times 10^{25\pm2} )</td>
</tr>
<tr>
<td>(^{196}\text{Hg})</td>
<td>0.146</td>
<td>820</td>
<td>( 2 \times 10^{28\pm1} )</td>
</tr>
</tbody>
</table>
5 Resonances in Radiative Electron Capture

It has been recognised already in the 50-ties by Glauber and Martin, [18], [19], that there is a pole in the expression for photon spectrum for radiative single electron capture energy corresponding to the energy difference of atomic 1S and 2P states. These authors have found the proper Green’s function for the Dirac electron in the external Coulomb field of the nucleus, relevant for the amplitude for the electron radiation and propagation from the initial atomic state $n_{int}$ towards the nucleus. The idea has later been used to propose a measurement of neutrino mass from the end point of the internal bremsstrahlung spectrum accompanying electron capture [20]. The argument remains true also for the radiative double electron capture even though for neutrino-less decays the photon spectrum is monoenergetic rather than continuous (cf. [21]).

Fig.3 shows the Feynmann diagram for double electron capture in the resonance situation. The transition involves three bound electrons: two 1S and one 2P. In the final state there are one 1S and one 2P vacancies in the atom. The amplitude can be written as

$$A \equiv \frac{H_w H_{\gamma}}{E_i - E_{int}} \approx \frac{H_w H_{\gamma}}{E_{\gamma} + E_{1S} - E_{2P}}$$  \hspace{0.5cm} (12)

The radiative factor in the resonant region can thus be written [17]:

$$| M_{\gamma} |^2 \sim \frac{Z^3 Q}{| Q - Q_{res} |^2 + (\Gamma_{atomic})^2},$$  \hspace{0.5cm} (13)

where $Q$ is the photon energy.

Table 2 shows the rate enhancements in the resonance region for tungsten atom ($Z = 74$). The enhancement at the resonance is determined by the natural width of the atomic states involved, $\Gamma_{atomic}$. In the case considered it amounts to the factor of about $10^6$. The rate values are indicative only, with the nuclear matrix elements estimated crudely, with the neutrino mass $m_{\nu} = 1$ eV and with $\Gamma_{atomic} = 150$ eV. The resonance energy is 59.32 keV $m_{\nu} = 1$ eV.

<table>
<thead>
<tr>
<th>$Q$ (keV)</th>
<th>$\Gamma(0\nu 2e\gamma)$</th>
<th>$10^{39} (1/y)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>59.0</td>
<td>$5 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td>59.32</td>
<td>$10^6$</td>
<td></td>
</tr>
<tr>
<td>59.64</td>
<td>$5 \times 10^4$</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>$10^4$</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>$1.6 \times 10^2$</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>$5$</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>$1.5$</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>$0.8$</td>
<td></td>
</tr>
</tbody>
</table>

Several candidates can be found for resonance-like decays to excited states, such as, e.g., $^{162}Er$ ($1^+ \text{ state at } Q - Q_{res} = -11 \pm 8 \text{keV}$) or $^{130}Ce$ ($0^+ \text{ state at } Q - Q_{res} = 8 \pm 50 \text{ keV}$). Close to the resonance is the ground-to-ground state decay of $^{174}W$ with $Q - Q_{res} = 11 \pm 5 \text{keV}$. In view of the sharp energy dependence of the rate in the resonance region it would be highly desireable to improve the accuracy of the mass values for the nuclei in question.
6 Experimental advantages

From the experimental point of view there are several advantages of the radiative electron capture process as compared to the double $\beta^{-}$-emission:

- the monoenergetic photon escapes easily from fairly thick layers of the source material without energy degradation;
- the source can be separate from the detector;
- the physical background due to the competing $2\nu\nu e\gamma$ process is low;
- the photon emission is followed by that of the K X-ray. Note that the energy of these X-rays in heavy atoms such as W or Hg is of the order of 60 - 70 keV. This provides a precious coincidence trigger to combat the random background;
- the phase space arguments make it feasible and even advantageous to study decays to excited states. These are followed by nuclear gamma emission providing yet another valuable coincidence trigger with unique identification of the emitting species.

The two last mentioned advantages are presumably of the ultimate importance. To quote ref. [5]: "the study of double $\beta$ decay is about suppressing backgrounds". The calorimetric experiments for the $\beta^{-}\beta^{-}$ emitters have no trigger to select the wanted events from the overwhelming background radiation. Extreme purity of all the material is required.

The experimental feasibility arguments have to include the decay rate and the cost estimates. Leaving the cost arguments aside and assuming 1 ton of the source material and the correspondingly larger amount of the high resolution detector (be it high purity Ge or a large bolometer) it seems to be feasible to design experiments for the $0\nu$ double electron capture process in $^{180}$W with the count rates of the order of a few counts per year and with the $\gamma$ – K X-ray coincidence requirement to reduce the random background to a tolerable level. Prior to proper calculations of the nuclear matrix elements and the reduction of the present uncertainty factor, this estimate can be considered as encouraging.

7 Summary and Outlook

There is a major challenge for the particle and nuclear physics community: to study the lepton sector, to determine the basic properties of one of the most important and certainly the least known unbound elementary particle: the neutrino, to make the next step beyond the Standard Model following the neutrino oscillation discovery. The best chances to make such a major step are offered by studying the neutrino-less double beta decay. A successful result of such an endeavour would not only supply an accurate value of the effective electron neutrino mass and permit to fix the range of the neutrino masses. This effective neutrino mass would be the Majorana mass, proving unambiguously the Majorana nature of neutrino and the lepton number non-conservation at the same time.

There are several medium scale projects going and/or planned for double $\beta^{-}$ emitters such as $^{76}$Ge, $^{100}$Mo or $^{130}$Te. The recent suggestion of looking for the radiative double electron capture decay may provide a viable alternative. The technique offers several definite experimental advantages. Of particular interest is the resonance effect strongly enhancing the rates at low decay energies, particularly for high $Z$ atoms. This favours decays leading to excited states in the final nuclei. Several candidates for such decays can be found in nature. More accurate rate and cost estimates and a realistic experimental design have yet to be made before embarking on the experiment. Still, the preliminary estimates are encouraging.
References

Figure 1: Mass parabolae for selected isobar chains.
Figure 2: Feynman diagram for neutrino-less double $\beta^-$ decay (top) and for radiative neutrino-less double electron capture (bottom).
THE RESONANT SITUATION

\[ A = \frac{H_w H_\gamma}{E_i - E_{\text{int}}} \approx \frac{H_w H_\gamma}{E_\gamma + E_{1s} - E_{2p}} \]

Figure 3: Feynmann diagram for resonant radiative neutrino-less double electron capture.
Dark matter search with ELEGANT VI CaF$_2$ detector

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Abstract

A CaF$_2$ scintillation detector system (ELEGANT VI) is developed to search for the spin coupled dark matter (WIMPs) and study the neutrino-less double beta decay ($0\nu\beta\beta$) of $^{48}$Ca. CsI(Tl) scintillators and active lightguides (pure CaF$_2$ crystals) which are on both sides of the central CaF$_2$(Eu) crystal act as $4\pi$ active shields. The whole system is in operation at the underground laboratory located in Nara (Oto Cosmo Observatory) which has effectively 1.4 km water equivalent shield. In this article our current status of the investigation is described.

1 Introduction

Weakly interacting massive particles (WIMPs) are one of the strongest candidates of the non-baryonic cold dark matter. Search for WIMPs is one of the most challenging issues related to recent particle physics and cosmology. Among them particles that have axial vector coupling with matter (spin coupled dark matter) are unexplored due to small cross sections with matter. The lightest neutral super partners (neutralino) are the most promising candidates since supersymmetry seems to be the theory beyond the standard model [1].

Our strategy is the direct detection of spin coupled dark matter by elastic nuclear recoils. The dark matter is drifting in a galaxy with a velocity of $\beta \sim 10^{-3}$. The signals are expected to be of low energy and rare, so one has to develop a detector that can sense such weak signals.

2 Detector system

We developed a CaF$_2$ scintillation detector system [9, 10, 11, 12] to search for WIMPs [13, 14, 15] and study the DBD of $^{48}$Ca [17, 18]. For the spin coupled dark matter search, $^{19}$F nucleus has the best figure of merit, represented by the product of cross section and natural abundance (100 % $^{19}$F) [13]. The $^{48}$Ca isotope in CaF$_2$ crystals serve as a source for double beta decay with highest Q-values of 4.27 MeV (“active source” experiment). The detector system consists of 25 CaF$_2$ scintillator complexes surrounded by 38 CsI(Tl) veto scintillators and passive shields. A total weight of the $^{19}$F ($J = 1/2$) is about 3.5 kg.
2.1 CaF$_2$ scintillator complex

The CaF$_2$ scintillator complex consists of central CaF$_2$(Eu) cubic crystal ($45 \times 45 \times 45$ mm$^3$), pure CaF$_2$ crystals ($45 \times 45 \times 200$ mm$^3$) on both sides as light guides which are also sensitive to gamma rays and 2 PMTs with quartz window (sensitive to both ultra-violet (UV) and visible light). Scintillation light of the pure CaF$_2$ is dominantly in the UV region (peak emission at $\sim 275$ nm), although CaF$_2$(Eu) emits normal visible light ($\sim 420$ nm) (Figure 1). Transmittance of CaF$_2$(Eu) is limited only for visible light, while pure ones are able to transmit UV light in addition to visible one. The CaF$_2$(Eu) crystal acts as a filter against the scintillation light from pure CaF$_2$ crystals. Thus the events occurred at pure crystals, which are mostly generated by the background gamma rays, can be rejected by setting a proper window on the asymmetry parameter (roll-off-ratio) between the signals from 2 PMTs. The roll-off-ratio ($R$) is defined to be,

$$R = \frac{V_R - V_L}{V_R + V_L}$$  \hspace{1cm} (1)

where $V_R, V_L$ are the charges from right and left PMTs, respectively. Figure 2 shows a typical roll-off-ratio spectrum with $^{60}$Co source.

The response of the detector to a nuclear recoil, so-called $f$-value, was measured by the $^{19}$F($n, n'$) reaction for our crystal [16]. The experiment was carried out using a pulsed neutron beam generated from the $d(d, n)^3$He reaction at the PELLETRON accelerator of Tokyo Institute of Technology. The $\sim 3.7$ MeV neutron gives similar energy to a $^{19}$F nucleus as the scattering by the dark matter. The obtained $f$-value is a little larger especially at low energy region than that has been measured for other detectors which makes total detection efficiency large.

WIMPs are thought to give a quite low energy deposit to the detector. Thus it is important to treat properly the signals and to evaluate the detection efficiency in the low energy region. The low energy signal like a few keV from CaF$_2$ scintillators looks like a bundle of many one photon signals in a long decay time ($\sim 1$ $\mu$sec). To treat such signals, we developed high gain amplifiers with integration circuit and low noise discriminators. A timing filter amplifier gives good timing signal even for such low energy signals which is essential to have good energy resolution as well as efficiency.
Figure 2: (LEFT) A typical roll-off-ratio spectrum of the CaF$_2$ scintillator complex with $^{60}$Co. (RIGHT) Two dimensional plot of light outputs from 2 PMTs.

We measured the efficiency of the low energy signal by using light from a LED. We generated the similar pulse shape as the real gamma ray signal by the LED in the low energy region. We found that the detector system is sensitive to 2 keV signal with 40% efficiency. The system achieved effectively 2 keV energy threshold.

2.2 Flash scaler

Further to separate the events occurred at CaF$_2$(Eu) crystal from CaF$_2$(pure) ones, we developed a Flash scaler which measures time distribution of one photon signals and installed it for single CaF$_2$ scintillator complex in the ELEGANT VI. In the low energy region we are interested for WIMPs search, the energy resolution is worse than in higher energy region so that the separation of the events in the roll-off-ratio spectrum is not so clear like shown in Figure 2. Instead of measuring charges from PMTs by ADCs, direct counting of the number of photoelectrons enables us to be free from the fluctuation on the pulse height of one photoelectron.

We can re-define the roll-off-ratio as

$$ r = \frac{N_r - N_l}{N_{tot}} $$

(2)

$$ N_{tot} = N_r + N_l, $$

(3)

where $N_l, N_r$ are number of photoelectrons from left and right PMTs, respectively. This makes it possible to reproduce the roll-off-ratio spectrum of flash scaler data for each $N_{tot}$

$$ F(N_{tot}, r) = n_l B^*(N_{tot}, P_l, r) + n_{Eu} B^*(N_{tot}, P_{Eu}, r) + n_r B^*(N_{tot}, P_r, r), $$

(4)

using modified binomial distribution function $B^*(N, P, r)$ concerning with trigger efficiency of coincidence (Figure 3),

$$ B^*(N, P, r) = \frac{B(N, P, r)}{\sum_{r_i = \lfloor\frac{N}{P}\rfloor}^{N} B(N, P, r_i)}. $$

(5)
Figure 3: A typical roll-off-ratio spectrum generated from the flash scaler. Total number of photo-electrons is 20. The solid line shows the fitted spectrum from binominal distribution.

Thus we can statistically estimate the number of events \((n_{\text{Eu}}, n_l, n_r)\) occurred at \(\text{CaF}_2(\text{Eu})\), left \(\text{CaF}_2(\text{pure})\) and right \(\text{CaF}_2(\text{pure})\) crystal separately.

2.3 Active and Passive shields

The schematic drawing of the detector is shown in Figure 4. Segmentation of the \(\text{CaF}_2\) detector enables us to reduce the background events which are supposed to be spread in space, while a true event is confined to a small region. Non-hygroscopic features of both \(\text{CaF}_2\) and \(\text{CsI(Tl)}\) crystals enables us to reduce the housing materials near the detectors. This becomes the advantage of low

Figure 4: Schematic drawing of detector system. (A)25 segmented \(\text{CaF}_2\) scintillator complexes. (B)38 \(\text{CsI(Tl)}\) veto detector. (C)Cd sheet. (D)\(\text{Pb}\) shield. (E)\(\text{OFHC Cu}\) shield. (F)\(\text{LiH}\) loaded paraffin. (G)\(\text{air-tight box}\). The whole system is surrounded by \(\text{H}_3\text{BO}_3\)-loaded water tanks (not shown).
background measurement originate from the housing material and 4π active shield even for X-rays. The materials used in the detector have been carefully selected for low radioactivity. The scintillators are in the airtight box inside of which is purged by pure N₂ gas to remove Rn gas in the air. As conventional passive shields, OFHC copper of 5 cm thick and lead of 10 cm shields are used to reduce the radioactive backgrounds from surroundings. Additional three kinds of shields (LiH-loaded paraffin, Cd sheet and H₃BO₃-loaded water tank moderator) for neutron background are prepared. About factor 3–5 reduction was achieved in the neutron flux with these shields. The whole system is in operation at the underground laboratory (Oto Cosmo Observatory) located in Nara, Japan which has effectively 1.4 km water equivalent shield to suppress the background originated from cosmic rays.

3 Contamination measurement

After the event selections by the active shields, the remaining backgrounds are come from internal radioactive contamination. To estimate the effects from the residual radioactivities on the data taken at this experiment, delayed coincidence methods were used to measure the contamination density inside the CaF₂(Eu) crystals. Our detector system has ‘delayed-α trigger’ to record a sequential second signal coming within 500 µsec after the main (first) trigger. Using this trigger system, we estimated the contamination density of the uranium and actinium daughters. The sequential decays we measured are,

\[
\begin{align*}
214^\text{Bi} & \rightarrow 214^\text{Po}(T_{1/2} = 164.3 \ \mu\text{sec}) \rightarrow 210^\text{Pb}, \\
219^\text{Rn} & \rightarrow 215^\text{Po}(T_{1/2} = 1.781 \ \text{msec}) \rightarrow 211^\text{Pb}.
\end{align*}
\]

In the thorium series, we can used the time stamp of each events for the analysis with setting the software time window to be 0.5 or 1.0 sec by using this sequence,

\[
226^\text{Rn} \rightarrow 216^\text{Po}(T_{1/2} = 0.145 \ \text{sec}) \rightarrow 212^\text{Pb}.
\]

The obtained value for each crystals are listed in Table 1. As can be seen, two crystals (#1 & #25) have much higher contaminations, then we decided not to use these crystals in the following analysis.

Table 1: Measured values of radioactive contamination for each crystal. The unit is ×10⁻⁵ Bq/kg.

<table>
<thead>
<tr>
<th>crystal #</th>
<th>214Bi</th>
<th>219Rn</th>
<th>220Rn</th>
<th>crystal #</th>
<th>214Bi</th>
<th>219Rn</th>
<th>220Rn</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4554 ± 33</td>
<td>148 ± 24</td>
<td>2952 ± 11</td>
<td>14</td>
<td>159.9 ± 7.9</td>
<td>13.8 ± 6.5</td>
<td>13.4 ± 0.9</td>
</tr>
<tr>
<td>2</td>
<td>209.8 ± 7.7</td>
<td>8.6 ± 6.0</td>
<td>8.5 ± 0.6</td>
<td>15</td>
<td>401.8 ± 9.8</td>
<td>10.3 ± 7.5</td>
<td>16.7 ± 0.9</td>
</tr>
<tr>
<td>3</td>
<td>5.2 ± 2.3</td>
<td>1.2 ± 2.1</td>
<td>11.7 ± 0.8</td>
<td>16</td>
<td>60.7 ± 7.8</td>
<td>18.7 ± 7.2</td>
<td>24.7 ± 1.1</td>
</tr>
<tr>
<td>4</td>
<td>59.4 ± 4.9</td>
<td>5.1 ± 4.0</td>
<td>3.6 ± 0.4</td>
<td>17</td>
<td>97.3 ± 6.2</td>
<td>7.1 ± 5.3</td>
<td>6.1 ± 0.7</td>
</tr>
<tr>
<td>5</td>
<td>154.2 ± 7.9</td>
<td>12.6 ± 6.7</td>
<td>9.6 ± 0.7</td>
<td>18</td>
<td>39.2 ± 6.4</td>
<td>10.1 ± 5.7</td>
<td>13.7 ± 0.9</td>
</tr>
<tr>
<td>6</td>
<td>153.2 ± 7.5</td>
<td>12.8 ± 6.2</td>
<td>13.3 ± 0.7</td>
<td>19</td>
<td>151.0 ± 7.0</td>
<td>9.2 ± 5.6</td>
<td>15.1 ± 0.9</td>
</tr>
<tr>
<td>7</td>
<td>152.5 ± 6.5</td>
<td>5.6 ± 5.0</td>
<td>7.9 ± 0.7</td>
<td>20</td>
<td>16.1 ± 3.8</td>
<td>4.5 ± 3.4</td>
<td>12.0 ± 0.8</td>
</tr>
<tr>
<td>8</td>
<td>61.1 ± 5.2</td>
<td>5.9 ± 4.4</td>
<td>4.6 ± 0.5</td>
<td>21</td>
<td>36.4 ± 3.9</td>
<td>5.4 ± 3.6</td>
<td>4.4 ± 0.4</td>
</tr>
<tr>
<td>9</td>
<td>136.5 ± 6.3</td>
<td>5.4 ± 4.8</td>
<td>4.9 ± 0.6</td>
<td>22</td>
<td>32.6 ± 5.3</td>
<td>10.9 ± 4.8</td>
<td>12.4 ± 0.8</td>
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<tr>
<td>10</td>
<td>235.1 ± 8.0</td>
<td>7.8 ± 6.3</td>
<td>9.6 ± 0.7</td>
<td>23</td>
<td>55.3 ± 5.0</td>
<td>5.7 ± 4.3</td>
<td>7.0 ± 0.7</td>
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<tr>
<td>11</td>
<td>67.4 ± 5.0</td>
<td>6.2 ± 4.1</td>
<td>4.4 ± 0.5</td>
<td>24</td>
<td>41.9 ± 4.9</td>
<td>5.6 ± 4.3</td>
<td>4.3 ± 0.6</td>
</tr>
<tr>
<td>12</td>
<td>154.6 ± 7.1</td>
<td>10.0 ± 5.7</td>
<td>13.8 ± 0.9</td>
<td>25</td>
<td>7529 ± 40</td>
<td>205 ± 31</td>
<td>4072 ± 12</td>
</tr>
<tr>
<td>13</td>
<td>71.0 ± 5.3</td>
<td>6.0 ± 4.4</td>
<td>3.9 ± 0.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Total radioactive contaminations in the 23 CaF$_2$(Eu) crystals are $^{214}$Bi — $(1.11 \pm 0.01) \times 10^{-3}$ Bq/kg, $^{220}$Rn — $(9.81 \pm 0.15) \times 10^{-5}$ Bq/kg and $^{219}$Rn — $(8.2 \pm 1.1) \times 10^{-5}$ Bq/kg.

4 Preliminary Results

![Figure 5: Roll-off spectrum for each $N_{\text{tot}}$ obtained by using flash scaler. Filled circle indicates experimental value. Lines shows fitted function – blue for CaF$_2$(pure), green for CaF$_2$(Eu) and black for their sum.]

We used single CaF$_2$ scintillator complex of which PMTs’ outputs are connected to the flash scaler for following analysis. Total live time is 71.12 days. Off-line analysis to suppress the background and select the local events occurred at the CaF$_2$(Eu) crystal are done by setting the conditions; i) no events in CsI(Tl) veto detectors; ii) only one CaF$_2$ scintillator complex have recorded the event; iii) no following event recorded by ‘delayed-α’ trigger; Finally, we extracted the number of events occurred at CaF$_2$(Eu) crystal by fitting the function (4) to the roll-off-ratio spectra for each $N_{\text{tot}}$ (Figure 5). The obtained energy spectrum is shown in Figure 6 (left). The exclusion plot for the WIMP-proton cross section on spin-dependent coupled DM by the present measurement are shown in Figure 6 (right).

5 Pulse shape analysis

Figure 6 shows that our detector’s sensitivity is not enough to reach the expected regions from certain supersymmetric model. For further rejection of the backgrounds, we demonstrated the pulse shape analysis (PSA) by using the time distribution of photoelectrons obtained by flash scalers to separate the nuclear recoil signals from electron recoils due to γ-rays which are dominant. At higher energies, the difference in scintillation time constant has been utilized for many years as a means of discriminating between γ and α particles. But at lower energies, discrimination becomes more difficult due to an increasing spread in the measured values. This is because the number of photoelectron (p.e.) from PMTs is very small (a few p.e./keV). Thus at low energies, the time distributions overlap
and individual pulses can no longer be uniquely assigned. Nevertheless, if a sufficient large number of events are analyzed, and compared with calibration distributions from gamma and neutron scattering, a small nuclear recoil fraction can be extracted statistically.

Figure 6: Obtained energy spectrum (left) and exclusion plots for the WIMP-proton cross section on spin-dependent (RIGHT) coupled DM. (preliminary)

Figure 7: Mean pulse shape obtained from CaF$_2$ (pure) (left) and CaF$_2$(Eu) (right) scintillators. The measurement was done by using flash scaler. Black line indicate the pulse shape obtained from $^{60}$Co source and red line from $^{252}$Cf.
To check the difference in decay time of CaF$_2$, we used a $^{60}$Co gamma source to provide populations of low energy Compton scatter electrons and a $^{252}$Cf neutron source to produce nuclear recoil events. Observed pulse shape from CaF$_2$(pure) and CaF$_2$(Eu) by flash scalers are shown in Figure 7. Extracted mean $\tau$ distributions are plotted in Figure 8, where $\tau = \sum n_i t_i / (N_{\text{tot}} - 1)$ and $n_i$ is the number of counts in each time bin which central value is $t_i$. In case of CaF$_2$(pure) crystal, clear difference between two sources was seen. The decay time constants of scintillation light of CaF$_2$(pure) crystal for neutrons and $\gamma$-rays were obtained by fitting the $\tau$ distribution. Energy dependence of the decay time constants are plotted in Fig. 9. We extracted the Q-value [19]

$$Q \equiv \frac{\beta(1-\beta)}{(\alpha-\beta)^2}$$

for CaF$_2$(pure) crystal, where $\alpha$ and $\beta$ are cut efficiencies for neutron and $\gamma$-ray, respectively. The Energy dependence of Q-value is plotted in Figure 10. From these results, PSA is possible in case of CaF$_2$(pure) and the sensitivity of experiment of dark matter search will be increasing by the rejection of gamma backgrounds.

![Figure 8: Mean $\tau$ distribution of pulse shape from CaF$_2$(pure) (left) and CaF$_2$(Eu) (right) scintillators.](image)

**References**


Figure 9: Energy dependence of the decay time of scintillation signal from CaF$_2$ (pure) crystal. Black line is for $\gamma$-rays and red line shows for nuclear recoil.

Figure 10: Energy dependence of Q-value for CaF$_2$ (pure) crystal.