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KEK-P 94-4

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KEK Preprint 94-4
April 1994
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Submitted to Phys. Lett. B.

National Laboratory for High Energy Physics, 1994

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Neutrinoless Double Beta Decay of ^{160}Gd

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Abstract

A measurement of the neutrinoless double beta decay of ^{160}Gd was carried out using a large (353 cm³) GSO:Ce scintillating crystal as an active source-detector. The obtained lower limit of the half life ($T_{1/2}(0\nu)$) was 3.0×10^{20} y (68% CL). This gives an effective Majorana neutrino mass ($\langle m_{\nu} \rangle$) lower than 53 eV (68% CL), when the calculated value of $T_{1/2}(0\nu) \langle m_{\nu} \rangle^2 = 8.56 \times 10^{23}$ y eV² is used while ignoring the right-handed weak currents.

1. Introduction

Neutrinoless double beta ($0\nu\beta\beta$) decay, which is one of the typical processes involving lepton-number nonconservation, has attracted great interest in both particle and nuclear physics. The finite occurrence of this decay should imply[1] the existence of Majorana neutrinos ($\nu = \bar{\nu}$) with non-vanishing masses and/or finite right-handed currents; both of them are beyond the standard model [2] of the electroweak interaction. Since most of the grand unified theories [3], which are typical theories beyond the standard model, naturally predict massive Majorana neutrinos, it is very important to experimentally determine the types of neutrinos (Majorana or Dirac). In this respect, $0\nu\beta\beta$ decay is especially interesting since it is considered to be the most sensitive test for determining the types of neutrinos as well as the mechanism of lepton-number nonconservation.

The inverse half-life of the $0\nu\beta\beta$ decay, $0_1^- \rightarrow 0_1^-$, can be written as[4]

$$[T_{1/2}(0\nu)]^{-1} = C_{mm}(\langle m_{\nu} \rangle / m_e)^2 + \text{terms from right-handed currents},$$

where $\langle m_{\nu} \rangle$ is the effective value of the Majorana neutrino mass, and m_e is the electron rest mass. The coefficient C_{mm} depends on the nuclear matrix elements. The nuclear matrix elements for $0\nu\beta\beta$ decay, however, are considered not to be sensitive [4] to any details concerning the nuclear structure, in contrast to $2\nu\beta\beta$ decay. The half-lives were calculated [5] for various candidate nuclei in the proton-neutron quasiparticle random-phase approximation (QRPA).

The detection of $0\nu\beta\beta$ decay has been pursued for various candidate nuclei[6]. Experimental data concerning $0\nu\beta\beta$ decay from direct counting

as well as from geochemical measurements have been accumulated for various nuclei [6], including ^{48}Ca , ^{46}Ca , ^{70}Zn , ^{76}Ge , ^{82}Se , ^{96}Zr , ^{100}Mo , ^{110}Pd , ^{114}Cd , ^{116}Cd , ^{124}Sn , ^{128}Te , ^{130}Te , ^{134}Xe , ^{136}Xe , ^{148}Nd , ^{150}Nd , ^{186}W , ^{192}Os and ^{198}Pt . No finite occurrence of $0\nu\beta\beta$ decay, however, has yet been confirmed. The most stringent limit was obtained for ^{76}Ge with $T_{1/2}(0) > 2.5 \times 10^{24}$ y and $\langle m \rangle < 1.1$ eV (68% CL) [7]. This result was obtained using a direct detection method along with an enriched HP Ge-detector. Since the geochemical method, which detects the amount of $(A, Z+2)$ nuclei in rocks containing (A, Z) nuclei, cannot tell the difference between $0\nu\beta\beta$ and $2\nu\beta\beta$ decay, direct detection using scintillation detectors has been given much attention in recent years.

Most direct counting methods use a thin passive source with a separate detector. The detectors have been mostly a semiconductor Ge detector at low temperature. Several measurements[6], however, have been carried out using active sources. In this scheme, the source simultaneously constitutes the detector, itself. Measurements involving this scheme have been carried out[6] on ^{48}Ca using CaF_2 crystals, ^{76}Ge using Ge-detectors, ^{116}Cd using CdWO_4 crystals, ^{130}Te using a cryogenic thermal ^{130}Te detector, and ^{136}Xe using a high-pressure Xe ionization chamber. Some of the measurements employed scintillating crystals having a large light output: $\text{CaF}_2:\text{Eu}$ [8] or undoped CaF_2 [9] for studying ^{48}Ca and CdWO_4 [10] for studying ^{116}Cd .

In addition to the above-mentioned nuclei, ^{160}Gd has also been considered [5] to be an excellent candidate nucleus for studying $0\nu\beta\beta$ decay. Although the abundance of this element in naturally occurring Gd is as

large as 21.8%, no measurement has ever been published. In $0\nu\beta\beta$ decay, $^{160}\text{Gd} \rightarrow ^{160}\text{Dy} + e^- + e^-$, two electrons are produced with an energy sum of 1730 keV (see Fig. 1). Both ^{160}Gd and ^{160}Dy are stable and have ground states of $J^\pi = 0^+$. In recent years, an efficient, high-quality crystal scintillator, cerium-doped gadolinium silicate $\text{Gd}_2\text{SiO}_5:\text{Ce}$ (simply $\text{GSO}:\text{Ce}$), has been developed [11-14]. This scintillator has a large density (6.71 g/cm³), fast response (exponential decay constant $\tau \sim 40\text{-}60$ ns) and a large light output (20% of $\text{NaI}:\text{Tl}$). $0\nu\beta\beta$ decay should show up as a monochromatic line at 1730 keV on the background energy spectrum in a $\text{GSO}:\text{Ce}$ scintillator. $\text{GSO}:\text{Ce}$ is an excellent source material, which serves as a detector at the same time.

We recently carried out at KEK a measurement of $0\nu\beta\beta$ decay of ^{160}Gd using an active source-detector of $\text{GSO}:\text{Ce}$. It is the aim of the present paper to present the results concerning the above-mentioned measurement.

2. Experiment

A $\text{GSO}:\text{Ce}$ crystal of 5 cm in diameter and 18 cm in length was viewed by a 2-inch photomultiplier (PMT) having a bi-alkali photocathode (Hamamatsu R329) from one of the end faces. For the later half of the accumulated statistics, the crystal was directly coupled to a photomultiplier with silicone-epoxy-type optical grease (OKEN 6262). For the former half of the statistics, however, a light guide of acrylicite (5 cm in diameter and 10 cm long) was inserted between the PMT and the $\text{GSO}:\text{Ce}$. The light guide was removed after finding that it did not help. The use of a light guide in the former half was the result of optimization of the length of the light guide for a small-

size GSO:Ce crystal (5 cm in diameter and 3 cm in length) so as to reduce the background coming from the PMT, while maintaining a large light output. The background at around 1730 keV decreased by half, and the energy resolution was degraded by a factor of 1.3 upon the addition of a 10 cm long light guide. For the larger crystal mentioned above, however, the background above 500 keV was almost independent of the light guide within 20%. After discovering this, the rest of the measurement was carried out without using the light guide, since the energy resolution was much better without it than with it. The longitudinal uniformity, measured by moving a γ -emitting isotope along the crystal length, was confirmed to be excellent; the pulse height was constant within $\pm 2\%$ [15] for both cases, with and without the light guide.

The GSO:Ce source-detector was mounted in a box of 5 cm thick OFHC (oxygen-free high-conductivity) copper inside 10-cm thick lead (see Fig. 2). The output was fed to a spectroscopy amplifier (ORTEC 571) with a shaping time constant of 3 μ s, and was finally analyzed using a pulse-height analyzer (ORTEC 917) in the pulse-height mode. Each measurement run took almost one week; the energy calibration was usually carried out at both the beginning and the end of each run using γ -emitting isotopes (^{22}Na , ^{60}Co and ^{137}Cs). The energy resolution at the full-width at half-maximum (FWHM) was 19.6% (24.1%), 11.1% (13.8%), 7.8% (10.1%) at 662, 1275 and 1786 keV, respectively, without (with) the light guide.

3. Result

The sum of the crystal weight times the measurement time was $(MT)_1 =$

$4.42 \cdot 10^{10} \text{ g} \cdot \text{s}$ for GSO:Ce with the light guide and $(MT)_2 = 3.36 \cdot 10^{10} \text{ g} \cdot \text{s}$ without the light guide, respectively. Figure 3 gives the spectrum, summed for all the runs, of the energy deposit in the GSO:Ce without the light guide. There are two broad maxima below 1 MeV. That at around 0.38 MeV can be assigned to the 2.14 MeV α 's from ^{152}Gd (the isotopic abundance = 0.20%, half life = $1.1 \cdot 10^{14} \text{ y}$), since the pulse-height ratio of α - and γ -rays with the same energy is about 0.21, as was calibrated with 5.49 MeV α -rays from ^{241}Am . The other one at around 1 MeV can be interpreted [16] in terms of α 's with energies in the range of 4.1-8.9 MeV (mostly below 6 MeV) coming from uranium and thorium decay chains.

A part of the spectrum (Fig. 3) at around 1730 keV is shown in Fig. 4. In order to detect the monochromatic line at around 1730 keV from $0\nu\beta\beta$ decay, the spectrum was fitted with a polynomial background plus a Gaussian peak sitting at around 1730 keV with a width of less than the instrumental value (the FWHM, $\Delta E = 137 \text{ keV}$ (176 keV) without (with) the light guide). No finite peak was observed with any meaningful statistical significance. When the obtained energy spectrum given in Fig. 4 was fitted in a range of 1555-1905 keV with a polynomial of the order 2 (or 3), the χ^2/DF (degree of freedom) was 540/67 (46/66), indicating a sufficient fit with a polynomial of order 3 without any additional Gaussian peaks. The fit is also shown in Fig. 4. The residue, which is the difference between the original spectrum minus the fit, is plotted in Fig. 5. For a measurement with the light guide, a fit to the obtained energy spectrum in 1500-1960 keV with a polynomial of order 2 (or 3) gave $\chi^2/\text{DF} = 85/89$ (82/88), again indicating no need for additional Gaussian peaks.

One standard deviation (σ) of the background events is given by

$$\sigma_{bg} \sim [n_{bg} M T \Delta E]^{1/2}, \quad (1)$$

where n_{bg} is the background intensity per unit weight, time and energy; M is the crystal weight; T is the measurement time; and ΔE is the FWHM width of the instrumental energy resolution at 1730 keV. The result mentioned above means that the number of $0\nu\beta\beta$ decay events $N_{0\nu\beta\beta}$ at 1730 keV should be less than the statistical fluctuation of the background; we obtain

$$N_{0\nu\beta\beta}(\text{at } 1730 \text{ keV}) < \sigma_{bg} \text{ (at 68\% CL)}. \quad (2)$$

Here, $N_{0\nu\beta\beta}$ should be related to the half-life of $0\nu\beta\beta$ decay $T_{1/2}(0\nu)$ by the following equation:

$$N_{0\nu\beta\beta}(\text{at } 1730 \text{ keV}) = \varepsilon n(^{150}\text{Gd})M [1 - \exp(-T \cdot \ln 2 / T_{1/2}(0\nu))], \quad (3)$$

where ε is the detection efficiency and $n(^{150}\text{Gd})$ is the number density of ^{150}Gd nuclei per unit weight of the crystal.

From Eqs. 1-3, we obtain

$$T_{1/2}(0\nu) > (\ln 2) n(^{150}\text{Gd}) [MT / n_{bg} \Delta E]^{1/2} \text{ (68\% CL)}. \quad (4)$$

Here, $n(^{150}\text{Gd}) = 6.19 \times 10^{20} \text{ }^{150}\text{Gd/g}$. $M = 2.371 \text{ kg}$ for most of the total statistics. The acceptance (ε) can be taken as a product of the area factor of 0.76 (=the fraction of the area of the Gaussian lying in the FWHM) and A_{eff} , which is the efficiency that both electrons should stop inside the crystal. A_{eff} was found to be larger than 99% from an estimate based on the range of electrons with a maximum energy of 1730 keV. For runs with the light guide, $MT = (MT)_1 = 4.42 \times 10^{10} \text{ g} \cdot \text{s}$, $\Delta E = 176 \text{ keV}$, and $n_{bg} = 0.60 \times 10^{-6}$ events/g/s/keV at 1730 keV give $T_{1/2}(0\nu) \geq 2.10 \times 10^{20} \text{ y}$ (68% CL). For runs without the light guide, $MT = (MT)_2 = 3.36 \times 10^{10} \text{ g} \cdot \text{s}$, $\Delta E = 137 \text{ keV}$, and $n_{bg} = 0.551 \times 10^{-6}$ events/g/s/keV at 1730 keV give $T_{1/2}(0\nu) \geq 2.16 \times 10^{20} \text{ y}$ (68%

CL). Combining both results, by taking the root-mean square, we obtain

$$T_{1/2}(0\nu) \geq 3.01 \times 10^{20} \text{ y (68\% CL)}.$$

4. Summary and discussions

Using a large GSO:Ce scintillator crystal with a volume of 353 cm³, neutrinoless double beta decay was measured inside a box shielded by copper and lead. No finite amount of $0\nu\beta\beta$ events was observed, leading to a lower limit on the lifetime ($T_{1/2}(0\nu)$) of $3.0 \times 10^{20} \text{ y}$ (68% CL). This result gives an effective Majorana neutrino mass ($\langle m\nu \rangle$) smaller than 53 eV (68% CL) when the calculated value of $T_{1/2}(0\nu) \langle m\nu \rangle^2 = 8.56 \times 10^{23} \text{ y eV}^2$ [5] is used while ignoring the right-handed weak currents. The same limit was also obtained for the $0\nu\beta\beta$ decay of ^{150}Gd to the 1-st excited state of ^{150}Dy ($J^\pi = 2^+, \tau_{1/2} = 2.0 \text{ ns}$), since the energy difference of 87 keV between this state and the ground state (see Fig. 1) could not be detected within the present energy and time resolutions of the detector, when it was emitted as another γ -ray.

It is usually expected that the background level could be reduced if it were measured in an underground laboratory. However, the background level in a small GSO:Ce crystal measured in an underground laboratory [17] did not differ much from the present background in a shielded box on the ground level. The difference was only a factor of two to three for a crystal grown by the same company (Hitachi Chem.) from the raw material of the same grade as for the present crystal. This indicates that the intrinsic background, itself, in the GSO:Ce crystal essentially limits the sensitivity of the present measurement. A reduction in the intrinsic radioactive back-

ground is vitally important before GSO:Ce crystals are brought into an underground laboratory. A reduction in the intrinsic background by more than an order of magnitude is progressing. The use of GSO:Ce single crystals as the source-detector has several advantages: it is not difficult to increase the weight, the energy resolution is reasonably good, and the crystal is very stable and easy to handle.

Acknowledgements

The authors would like to express deep thanks to Yu. Zdesenko (INR, Kiev) for information concerning their intrinsic background level of GSO:Ce in their underground laboratory and for a critical reading of the manuscript, K. Nakai of KEK for his support of the present work, M. Taino for constructing the shielded box, T. Kamae (Univ. of Tokyo) and H. Ishibashi (Hitachi Chem.) for their help in reducing the background level of the GSO:Ce, and H. Ejiri (Osaka Univ.) and S. Sugimoto (INS, Univ. Tokyo) for their interest in the present work as well as helpful discussions. This work was supported in part by a Grant in Aid of Scientific Research, Ministry of Education, Science and Culture, Japan.

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Figure captions

Fig. 1 $0\nu\beta\beta$ decay scheme of ^{160}Gd .

Fig. 2 Sketch of the experimental setup.

Fig. 3 Energy deposit spectrum summed over all runs for GS0:Ce without a light guide (LG). The position (1730 keV) of $0\nu\beta\beta$ decay and the instrumental energy resolution (FWHM) are also indicated.

Fig. 4 Fit of the energy deposit spectrum (see Fig. 3) around 1730 keV with a Gaussian peak plus polynomial background in the GS0:Ce without the light guide. The bin width is 5 keV. The position (1730 keV) corresponding to the $0\nu\beta\beta$ decay and the instrumental energy resolution are also indicated.

Fig. 5 Residue of the obtained energy spectrum (Fig. 4) minus the fit with a polynomial background (see the text) for the GS0:Ce. The position (1730 keV) corresponding to the $0\nu\beta\beta$ decay and the instrumental energy resolution (FWHM) are also indicated.

Fig. 1

Fig. 3

Fig. 2

Fig. 5

Fig. 4