

OBSERVATION OF TWO NEUTRINO DOUBLE BETA DECAY
OF ^{116}Cd WITH THE TRACKING DETECTOR NEMO-2

NEMO Collaboration

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The two neutrino double beta decay of ^{116}Cd has been detected using a 152 g source of enriched cadmium. A signal-to-background ratio of 2.8 was achieved in a 2460 h run with the NEMO-2 detector. The corresponding half-life is $T_{1/2}^{2\nu} = [3.6^{+0.6(stat)}_{-0.5(stat)} \pm 0.3(sys)] \cdot 10^{19}$ y.

Neutrinoless double beta ($\beta\beta 0\nu$) decay is one of the best probes for physics beyond the standard model of electroweak interactions. Up to now only lower limits on the half-life ($T_{1/2}^{0\nu}$) of different nuclei have been obtained experimentally. These limits are used to deduce upper limits on the Majorana neutrino mass, the right-handed current admixture parameter, the majoron-Majorana neutrino coupling constant, etc. (see reviews [1-5]). The reliability of these estimates is directly connected to uncertainties in nuclear matrix element (NME) calculations. Unfortunately the accuracy of NME calculations remains one of the main problems for $\beta\beta$ decay theory. At the moment $\beta\beta 2\nu$ decay NME for only a few nuclei [4, 5], are experimentally known. These experimentally determined values improve the

nuclear structure description of $\beta\beta$ decay. One can expect that the accumulation of experimental information on the $\beta\beta 2\nu$ processes such as the half-lives for a large set of nuclei with high accuracy, the detection of other types of $\beta\beta$ transitions ($\beta^+\beta^+$, electron capture(EC)- β^+ and ECEC processes) and the developments in the $\beta\beta$ theory will aid in solving the NME problem. It is especially worth while to note that the NME for $\beta\beta 0\nu$ decay cannot be measured independently, and a precise investigation of the $\beta\beta 2\nu$ processes is one of the means, and maybe the only one, which can provide information to test the correctness of NME calculations for the 0ν decay mode.

The NEMO collaboration has already investigated the $\beta\beta 2\nu$ decay of ^{100}Mo with high statistical accuracy and analysed details of the $\beta\beta$ process (angular distribution and single electron energy distribution) with the tracking detector NEMO-2 [6, 7]. This detector was built as the prototype of the future NEMO-3 detector which will study $\beta\beta 0\nu$ decay of ^{100}Mo and other nuclei with a sensitivity up to $\sim 10^{25}$ y (that corresponds to a sensitivity to the neutrino mass of 0.1 – 0.3 eV)[8].

In this paper the detection of $\beta\beta 2\nu$ decay of ^{116}Cd ($Q = 2802$ keV) is reported with the upgraded NEMO-2 detector that has run in its current mode for 2460 h. The improvements entail replacement of the original plastic scintillators and photomultiplier tubes. The new scintillator blocks are thicker (10 cm instead of 2 cm) which increases the probability of γ -ray detection. The new photomultiplier tubes (EMI 9822B53) which were especially developed for this experiment reduce the background of the external photon flux associated with the tubes.

The active part of the detector consists of a 1 m³ tracking volume filled with a mixture of helium gas and 4% ethyl alcohol. Two arrays of scintillators sandwich/ the cubic tracking volume. Bisecting the detector is the source foil plane (1 m \times 1 m). The source consists of two nearly symmetric halves. The first half is a 152 g foil of enriched cadmium (93.2% is ^{116}Cd) with a thickness of 40 μm . The second part is a 143 g foil of natural cadmium which has a ^{116}Cd isotopic abundance of 7.58% and a thickness of 37 μm . To record events initiated in the central source plane there are 5 frames (1 m \times 1 m with 32 horizontal and 32 vertical Geiger cells in each frame) to track charged particles while the five-by-five array of plastic scintillators (20 cm \times 20 cm \times 10 cm) provide energy and timing measurements. The distance between the foil and each of the two scintillator arrays is 0.5 m. Other performance and operating parameters for the detector are: the threshold of the scintillation counters is 50 keV, the measured energy resolution (FWHM) is 18% at 1 MeV, and the time resolution is equal to 275 ps for 1 MeV electrons and increases up to 550 ps at 0.2 MeV. A more detailed description of the NEMO-2 detector is given in [7–9]. The trigger requires the firing of at least two scintillation counters within 50 ns followed by four Geiger cells firing within 2.5 μs . Charged particle trajectories are reconstructed off-line and time and energy calibrations are checked daily.

The NEMO-2 detector is able to measure the internal radioactive contaminations of the foils by using the electron-gamma ($e\gamma$) channel. Analysis of $e\gamma$ events gives an upper limit on the ^{208}Tl contamination in the enriched and natural cadmium of 1 mBq/kg and 1.5 mBq/kg respectively. This level of contamination in both foils produces very few electron-electron ($2e$) events. Specifically, the effect of 1 mBq/kg would give 1.5 $2e$ events of background in the accumulated data. So the background induced by ^{208}Tl contamination has been neglected.

In the case of the ^{214}Bi an upper limit in the difference of contamination between the natural and the enriched cadmium foils is 2.5 mBq/kg (90% C.L.). The quantity of interest here is the 2e background estimate which corresponds to 2.3 2e events. Thus the ^{214}Bi contribution has also been neglected. Upper limits (90% C.L.) of ^{214}Bi contamination in each foil are 8.3 mBq/kg for natural and 7.5 mBq/kg for enriched cadmium.

In the data collection process one-electron events are recorded simultaneously. This channel is used to measure the contribution to 2e events from pure β -emitters (like ^{90}Sr and ^{234m}Pa) by the Möller effect. An analysis of the one-electron energy spectra for $E_e > 1.4$ MeV leads to a level of contamination for such beta emitters which is less than 44 mBq/kg in both foils. This is determined by fitting the experimental spectra to a simulated ^{234m}Pa energy spectrum. The contamination difference between the two foils is < 6 mBq/kg which corresponds to less than 1.5 2e events. These results have shown that the internal radioactive impurities do not contribute significantly to the $\beta\beta$ events and they will be taken into account in the calculations of the 2e channel systematic error.

Radioactive impurities in both foils have been measured with HPGe detectors in the Fréjus Underground Laboratory before installation in the NEMO-2 detector. The upper limits (90% C.L.) on contamination obtained in the enriched cadmium¹⁾ for the three isotopes ^{214}Bi , ^{208}Tl and ^{234m}Pa are respectively 5, 2.5, and 66 mBq/kg, and in natural cadmium these limits are 5, 1.7, and 33 mBq/kg. These results are close to those obtained with the NEMO-2 detector.

The 2e background in the enriched cadmium foil due to the external photon flux (Compton + Möller effects) has been evaluated using the 2e events in the natural cadmium foil (^{116}Cd contribution subtracted). Most of the $e\gamma$ events are due to the external photon flux and an analysis of these events shows that the photon flux ratio corrected for the thickness ratio of the foils is compatible with one. This result indicates that the 2e background is the same in both foils.

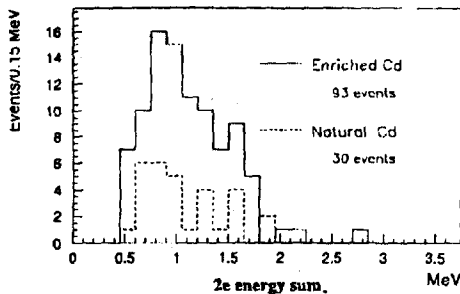


Fig. 1

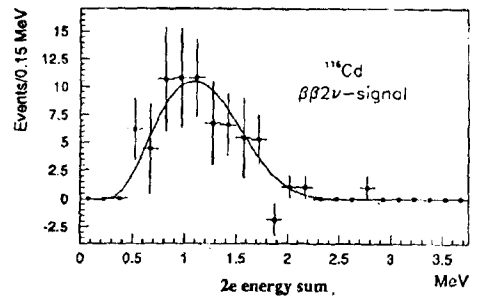


Fig. 2

Fig. 1. The raw data energy spectra in enriched cadmium (solid line) and in natural cadmium (dotted line) correspond to 2460 h of data collection

Fig. 2. Energy sum spectrum of $\beta\beta$ events in ^{116}Cd (background subtracted). Solid line is the calculated spectrum for $\beta\beta 2\nu$ decay with a half-life of $3.6 \cdot 10^{19}$ y

¹⁾ Before production of the foil, enriched Cd (metallic pieces of different shape and weight) was used in an experiment to search for $\beta\beta$ decay of ^{116}Cd to excited states of ^{116}Sn [10]. In this experiment the limits on ^{214}Bi , ^{208}Tl and ^{234m}Pa in the enriched Cd were found to be < 0.4 , < 0.25 and < 15 mBq/kg, respectively.

In the $2e$ event analysis electrons are defined by tracks linking the source foil and a scintillator. Both tracks must have their vertex position within 5 cm. As a cut in the data the maximum scattering angle along the track was taken to be less than 20° . Also in the data the cosine distribution of the angle (α) between tracks showed that the external background was peaked in the forward direction, so a $\cos\alpha < 0.6$ cut was applied which increased the signal-to-background ratio to 2.8. Fig. 1 shows the energy spectra of $2e$ events in enriched and natural cadmium foils (respectively 93 and 30 events). In Fig. 2 the $\beta\beta$ energy spectrum in enriched cadmium (69 events) is shown after background subtraction (24 events). Using the calculated detection efficiency of the $\beta\beta 2\nu$ decay of ^{116}Cd ($\epsilon = 1.73\%$) one gets,

$$T_{1/2}^{2\nu} = [3.6_{-0.5}^{+0.6}(\text{stat}) \pm 0.3(\text{syst})] \cdot 10^{19} \text{ y.}$$

The main contributions to the systematic error are due to efficiency calculations (3%), energy calibrations (3.5%), internal background subtraction (4.5%) and external background subtraction (5%).

Using values of $T_{1/2}^{2\nu} = 3.6 \cdot 10^{19}$ y and the phase space factor $G^{2\nu} = 8 \cdot 10^{-18}$ y^{-1} [11] one gets the NME for ^{116}Cd : $M^{2\nu} = 0.059$. This value may be compared with theoretical ones: $M^{2\nu} = 0.03 - 0.08$ [12] and $M^{2\nu} = 0.1$ [10] for QRPA model calculations.

The $\beta\beta 2\nu$ decay of ^{116}Cd has been investigated by others recently. The limit $T_{1/2}^{2\nu} > 3 \cdot 10^{19}$ y (90% c.l.) [13] was obtained using scintillator crystals. In the Osaka symposium in March of 1994 H. Ejiri et al. [14] (ELEGANT-V experiment) reported a half-life $T_{1/2}^{2\nu} = 2.6_{-0.5}^{+0.9} \cdot 10^{19}$ y.

The operation of the cadmium-source filled NEMO-2 experiment will continue with the intention of lowering the statistical errors to the level of the systematic errors ($\sim 10\%$).

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