Observation of two neutrino double beta decay of ^{116}Cd with the tracking detector NEMO-2

NEMO Collaboration

R. Arnold, E. Caurier, J. L. Guyonnet, I. Linck, and F. Scheibling
Centre de Recherches Nucléaires, IN2P3-CNRS et Université Louis Pasteur, 67037 Strasbourg, France

C. Augier, D. Blum, J. E. Campagne, S. Jullian, D. Lalanne, F. Laplanche, and G. Szklarz
Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS et Univerité de Paris-Sud, 91405 Orsay, France

A. S. Barabash, V. N. Kornoukhov, Yu. B. Lepikhin, V. I. Umatov, and I. A. Vanushin
Institute of Theoretical and Experimental Physics, 117259 Moscow, Russia

V. Brudanin, V. Egorov, O. Kochetov, V. Kovalenko, A. Nozdrin, and Ts. Vylov
Joint Institute for Nuclear Research, 141980 Dubna, Russia

D. Dassié, R. Eschbach, F. Hubert, Ph. Hubert, F. Leccia, P. Mennrath, F. Piquemal, and A. Vareille
Centre d'Études Nucléaires, IN2P3-CNRS et Université de Bordeaux, 33170 Gradignan, France

C. Longuemare and F. Mauger
Laboratoire de Physique Corpusculaire, IN2P3-CNRS et Université de Caen, 14032 Caen, France

H. W. Nicholson and C. S. Sutton
Mount Holyoke College, South Hadley, MA 01075, USA

V. I. Tretyak, Yu. Vassilyev, and V. Zerkin
Institute for Nuclear Research of the Ukrainian Academy of Sciences, 252028 Kiev, Ukraine

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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 $T_{1/2}^{2\nu} = [3.6^{+0.6(\mathrm{stat})}_{-0.5(\mathrm{stat})} \pm 0.3(\mathrm{syst})] \times 10^{19}$ y. © *1995 American Institute of Physics.*

Neutrinoless double beta ($\beta\beta0\nu$) decay is one of the best probes for physics beyond the standard model of electroweak interactions. Until 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, on the right-handed current admixture parameter, on the majoron–Majorana neutrino coupling constant, etc. (see the 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 of $\beta\beta$ decay theory. At this time, the $\beta\beta2\nu$ decay NME is experimentally known for only a few nuclei.[4,5] These experimentally determined values improve the nuclear structure description of the $\beta\beta$ decay. It is expected that the accumulation of experimental information on the $\beta\beta2\nu$ processes such as the half-lives of a large number 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 help the solution of the NME problem. It is especially worthwhile to note that the NME for $\beta\beta0\nu$ decay cannot be measured independently, and a precise investigation of the $\beta\beta2\nu$ processes is one of the means, and possibly 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 $\beta\beta2\nu$ decay of ^{100}Mo with high statistical accuracy and analyzed details of the $\beta\beta$ process (angular distribution and single-electron energy distribution) with the tracking detector[6,7] NEMO-2. This detector was built as the prototype of the future NEMO-3 detector, which will study $\beta\beta0\nu$ 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[8] 0.1–0.3 eV).

In this paper the detection of the $\beta\beta2\nu$ decay of ^{116}Cd ($Q=2802$ keV) is reported with the upgraded NEMO-2 detector which 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 the γ-ray detection. The new photomultiplier tubes (EMI 9822B53), which were specially designed 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-m^3 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$1 m). The source consists of two nearly symmetric halves. The first half is a 152-g foil of enriched cadmium (93.2% of ^{116}Cd) with a thickness of 40 μm. The second part is a 143-g foil of natural cadmium, which has a ^{116}Cd isotopic abundance of 7.58% and a thickness of 37 μm. To record events initiated in the central source plane there are 5 frames (1 m$\times$1 m with 32 horizontal and 32 vertical Geiger cells in each frame) to track charged particles, while the 5$\times$5 array of plastic scintillators (20 cm$\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 of the detector are as follows: 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 Refs. 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. The background induced by ^{208}Tl contamination has therefore been ignored.

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. The upper limits (90% C. L.) of ^{214}Bi contamination in each foil are 8.3 mBq/kg for natural cadmium 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 the 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/kb in each foil. This value 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.

The radioactive impurities in each foil have been measured with HPGe detectors in the Fréjus Underground Laboratory before installation of the NEMO-2 detector. The upper limits (90% C. L.) on contamination obtained in the enriched cadmium[1] 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 eγ 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.

In the 2e event analysis electrons are defined by tracks linking the source foil and a

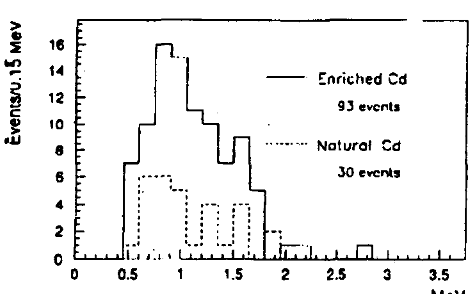

FIG. 1. The raw data energy spectra in enriched cadmium (solid line) and in natural cadmium (dotted line) correspond to 2460 h of data collection.

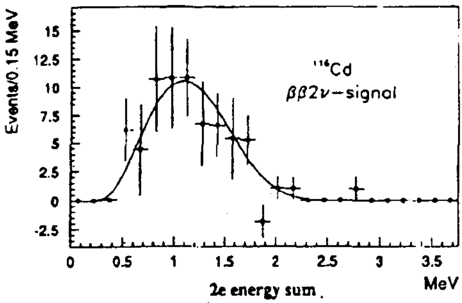

FIG. 2. Energy sum spectrum of $\beta\beta$ events in ^{116}Cd (background subtracted). Solid line is the calculated spectrum for the $\beta\beta 2\nu$ decay with a half-life of 3.6×10^{19} y.

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 assumed to be less than 20°. In the data the cosine distribution of the angle (α) between tracks showed that the external background peaked in the forward direction, so a cos $\alpha<0.6$ cut was applied. This increased the signal-to-background ratio to 2.8. Figure 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 ($\varepsilon=1.73\%$), we find

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

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

Using the values of $T_{1/2}^{2\nu}=3.6\times 10^{19}$ y and the phase space factor[11] $G^{2\nu}=8\times 10^{-18}\mathrm{y}^{-1}$, we find the NME for ^{116}Cd: $M^{2\nu}=0.059$. This value can be compared with the theoretical values: $M^{2\nu}=0.03$–0.08 (Ref. 12) and $M^{2\nu}=0.1$ (Ref. 10) for the QRPA model calculations.

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

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[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.

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