Double beta decay of ^{116}Cd

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Abstract

The NEMO-2 tracking detector located in the Fréjus Underground Laboratory was designed as a prototype of the detector NEMO-3 to study 0ν and 2ν double-beta decay ($\beta\beta$) physics. A $\beta\beta 2\nu$ half-life of $T_{1/2} = (3.75\pm0.35(stat)\pm0.21(syst))\cdot 10^{19}$ y was measured with an enriched cadmium source (0.92 mol· y of ^{116}Cd). Limits on half-lives of $6.2\cdot 10^{21}$ y for $\beta\beta 0\nu$ and $1.2\cdot 10^{21}$ y for $\beta\beta 0\nu\chi^0$ decays of ^{116}Cd were obtained (CL=90%).

1 Introduction

$\beta\beta 0\nu$ decay is rare a second-order weak transition from nuclei (A,Z) to the (A,Z+2) ones, where A is a mass number, Z - proton number. It can occur if the neutrino is a Majorana particle and if the lepton number is not conserving. Majorana mass term can flip the chirality of the emitted left-handed virtual neutrino to a right-handed one which is absorbed. Neutrinoless decay could be driven also by right-handed weak currents or the exchange of supersymmetric particles. All these decay processes are beyond the Standard Model.

The reliable value for the effective Majorana neutrino mass $\langle m_\nu \rangle$ (or its upper limit) could be extracted from the experimental data analysis using the equation

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} \mid M^{0\nu} \mid^2 \langle m_\nu \rangle^2,$$

where $G^{0\nu}$ is the well calculable phase space factor, and $\mid M^{0\nu} \mid$ is the nuclear matrix element (NME). The NME for neutrinoless double beta decay are difficult to calculate precisely by nuclear theory. Similarly, the neutrino-Majoron coupling constant $\langle g_{\nu,M} \rangle$ is related to the $[T_{1/2}^{0\nu,M}]$ half-life as

$$[T_{1/2}^{0\nu,M}]^{-1} = G^{0\nu,M} \mid M^{0\nu} \mid^2 \langle g_{\nu,M} \rangle^2$$

On the other side the $\beta\beta 2\nu$ decay NME could be measured experimentally:

$$[T_{1/2}^{2\nu}]^{-1} = G^{2\nu} \mid M^{2\nu} \mid^2,$$

and improve the nuclear structure description of $\beta\beta2\nu$ decay. A precise investigation of $\beta\beta2\nu$ processes for different nuclei will provide information to the correctness of the NME calculations for the $\beta\beta2\nu$ decay mode and, probably, for the $\beta\beta0\nu$ mode.

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, two and one electron energy distributions) with the tracking detector NEMO-2 [1].

2 NEMO-2 detector

NEMO-2 detector [2] consist of a $1m^3$ tracking volume filled qwith helium gas and 4% ethyl alcohol (Fig. 1). Vertically bisecting the detector is the plane of the source foil (1m×1m). Tracking is accomplished with the long open Geiger cells with an octagonal cross section defined by 100 μm nickel wires. On each side of the source foil there are 10 planes of 32 cells which alternate between vertical and horizontal orientations. The cells provide three-dimensional tracking of charged particles.

A calorimeter made of 25 scintillators ($19cm \times 19cm \times 10cm$) with PMT made of low radioactivity glass covers two vertical opposing sides of the tracking volume. The tracking volume and scintillators are surrounded with a lead (5 cm) and iron (20 cm) shield.

2.1 Cadmium sources

The source plane is divided into two halves, the first is a 152 g isotopically enriched cadmium foil (93.2% is ^{116}Cd) with a thickness of 40μm. The second half is a 143 g foil of natural cadmium of which 7.58% is ^{116}Cd.

2.2 Backgrounds

The most important "external" background is due to photons originating from outside of the detector and interacting with the source foils or with the scintillators. Compton electrons produced in the scintillators and crossing the tracking device are rejected by time-of-flight analysis.

Radioactive pollution of the source foils is a background identified as "internal". A beta electron which gives rise to the Möller effect or is associated with an internal conversion electron or with a Compton electron can produce 2e background events. Another source of background originates from neutron capture in natural cadmium which produces photon and conversion electron emissions. All these backgrounds have been studied and their contributions to the $e\gamma$ and 2e channels are identified. The internal radioactive contamination limits, if taken as levels, will only produce a very few "two-electron" events in each foil.

3 Results

3.1 $\beta\beta 2\nu$ signal

The 2e events are defined by two tracks with a common vertex associated with two fired scintillators and a deposited energy of at least 200 keV in each one. The 2e events are selected by the time-of-flight analysis. The complete cadmium data set (6588 h of running time) is presented here.

The distribution of the angle between the two emitted electrons in enriched cadmium with background subtracted and in natural cadmium (Fig. 2) are rather different. In order to improve the signal to background ratio the cut $\cos\alpha \leq 0.6$ is applied in the selection of 2e events. The row data energy spectrum in enriched cadmium and in natural one are shown in Fig.3.

The $\beta\beta$ energy spectrum in enriched cadmium is obtained after background subtraction and compared to the simulation in Fig.4. With Monte-Carlo calculated detection efficiency for the $\beta\beta 2\nu$ decay of ^{116}Cd (ε=1.73%) one gets,

$$T_{1/2}^{2\nu} = [3.75 \pm 0.35(stat) \pm 0.21(syst)] \cdot 10^{19} y.$$

The main contributions to the systematic error are due to the Monte-Carlo calculations, energy calibration, thermal neutron flux, internal and external background subtractions.

This experimental result can be compared with some theoretical predictions have been made for the $\beta\beta 2\nu$ decay half-life with $T_{1/2}$ in the range of $1.2 \cdot 10^{19}$ to $1.2 \cdot 10^{20}$ y [9, 8].

3.2 Limits on 0ν modes

Half-life limits extracted from the data are given in Table 1. The energy windows, number of events and efficiencies are also given. Limits are computed with the formula for Poisson processes with background [3].

Channel	$0^+_{g.s.}$	Majoron	2^+
Window (MeV)	[2.3,2.8]	[1.8,2.5]	[1.2,1.5]
Number of events	0	8	41
Background ($\beta\beta 2\nu$)	0.2	8.4	46
Efficiency (%)	3.7	1.8	1.8
$T_{1/2}(10^{21}$ y)	>6.2	>1.2	>0.7

Using the NME calculation [4] and the experimental half-life limit, $T_{1/2}^{0\nu} > 6.2 \cdot 10^{21}$ y, the following upper limits for the effective neutrino mass and right-handed coupling strengths: $|\langle m_\nu \rangle| < 8.82$ eV, $|\langle \eta \rangle| < 9.30 \cdot 10^{-8}$, $|\langle \lambda \rangle| < 1.02 \cdot 10^{-5}$ were derived. Using the experimental half-life limit, $T_{1/2}^{0\nu,M} > 1.2 \cdot 10^{21}$ y, and half-life formula [5], one deduces the upper limit $|\langle g_M \rangle| < 1.2 \cdot 10^{-4}$ for the Majoron-Majorana neutrino coupling.

Some recent results are recalled here for comparison. Using an enriched crystal scintillator [6] a half-life $T_{1/2} = [2.7^{+0.5}_{-0.4}(stat)^{+0.9}_{-0.6}(syst)] \cdot 10^{19}$ y was published with the restriction that ^{90}Sr impurities imitating the effect cannot be excluded. Another result from the ELEGANT V detector [7] gives the half-life $T_{1/2} = [2.6^{+0.9}_{-0.5}] \cdot 10^{19}$ y which is very close to the previous one. But in this experiment one also cannot exclude the effect of ^{90}Sr.

4 Conclusion

After the first experiment with enriched molybdenum which showed the capabilities of the NEMO-2 detector, a second experiment with an improved calorimeter (low background PMTs and thicker scintillators) has generated double-beta decay measurement of an enriched cadmium source. The systematic error on the $\beta\beta 2\nu$ half-life was 9.5% in the first experiment and was lowered to the 5.5% in the present one. In both experiments a very low background is measured in the expected $\beta\beta 0\nu$ decay energy region. New sources of enriched selenium and zirconium were installed in NEMO-2 (autumn 1995) and data collection has started. The NEMO-3 detector is currently under construction and will be installed in the Fréjus Underground Laboratory in 1998.

References

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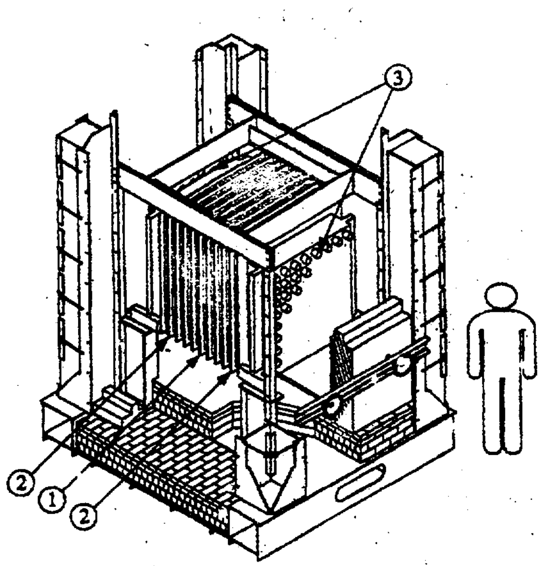

Figure 1: The NEMO-2 detector without shielding. (1) Central frame with the source plane capable of supporting plural source foils. (2) Tracking device of 10 frames, each consisting of two perpendicular planes of 32 Geiger cells. (3) Two scintillator arrays each consisting of 5 by 5 counters. In the earlier experiment with molybdenum sources the scintillator arrays were 8 by 8 counters as depicted here.

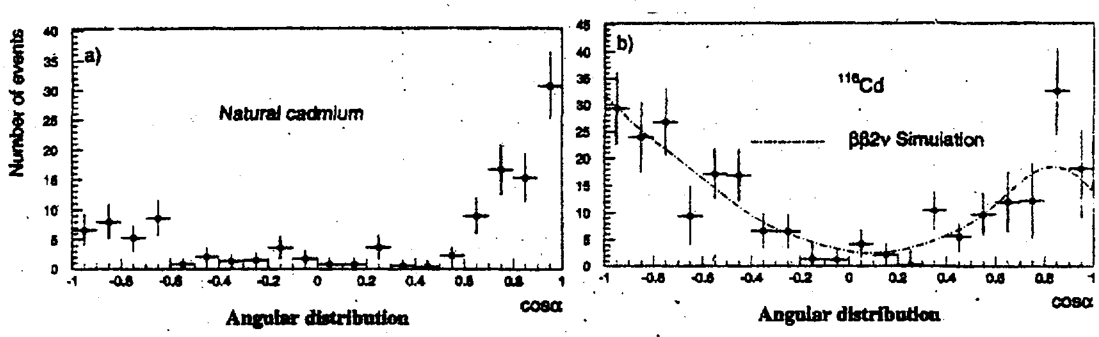

Figure 2: The angular distribution in the natural cadmium foil (a), where α is the angle between the two electron tracks, is peaked in the forward direction as expected from the external photon flux. A scaled estimate of the $\beta\beta 2\nu$ decay contribution, in accordance with the ^{116}Cd abundance in natural Cd has been subtracted. The angular distribution in enriched cadmium (b) after background subtraction is in good agreement with the simulation.

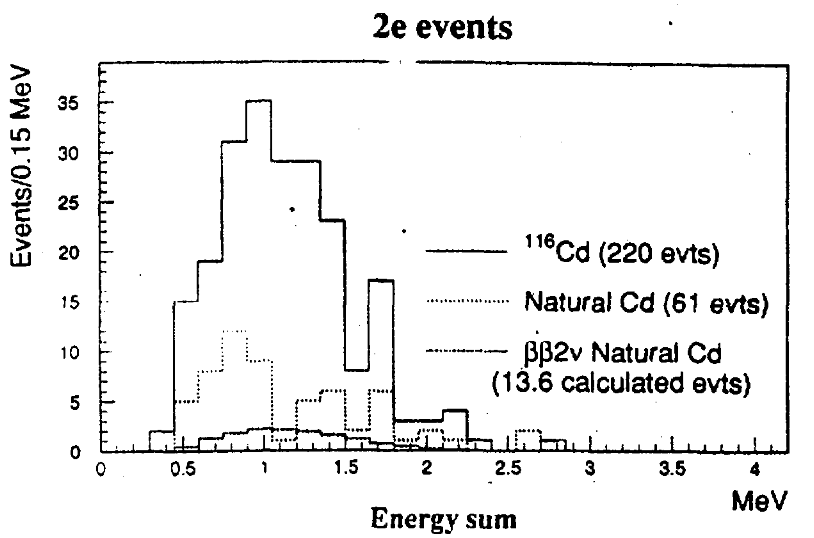

Figure 3: The raw data energy spectrum before background subtraction in enriched cadmium (solid line) and in naturel cadmium (dotted line) are shown here. The corresponding $\beta\beta 2\nu$ spectrum contribution in natural cadmium is also represented (dashed-dotted line). Only one event in enriched cadmium is found in the 2.5-3 MeV energy range. Recollect that Q= 2802 MeV.

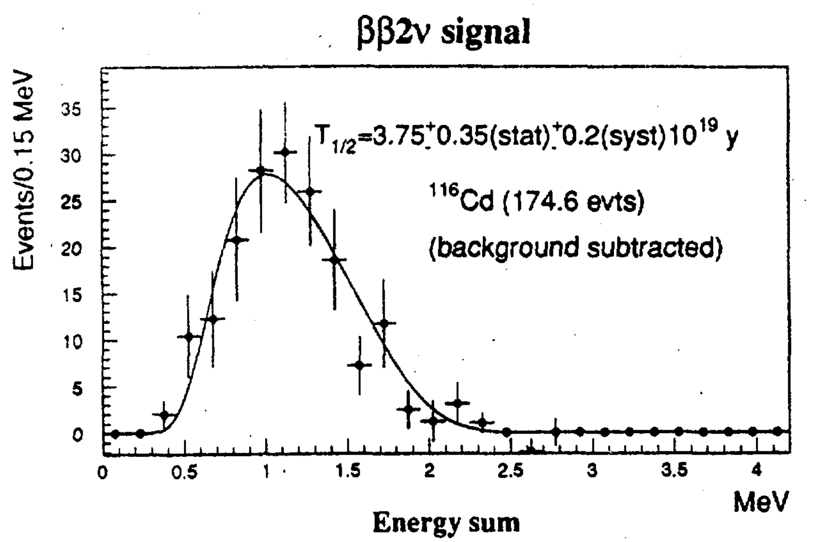

Figure 4: Energy sum spectrum of $\beta\beta 2\nu$ events in ^{116}Cd. The solid line represents the simulated spectrum for a half-life of $3.75 \cdot 10^{19}$ y.