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COBRA – A new approach to double beta decay

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Abstract. The COBRA experiment is going to use a large amount of CdZnTe semiconductor detectors to perform a search for various double beta decay modes. The current status of the experiment is presented as well as first results. A short outlook on future activities is presented.

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1 Introduction

The lepton number violating process of neutrinoless double beta decay

$$(Z,A) \rightarrow (Z+2,A) + 2e^- \quad (0\nu\beta\beta\text{-decay}) \tag{1}$$

is not allowed in the Standard Model and therefore implies New Physics. In contrast to neutrino oscillations which violate flavour lepton number, but keeps total lepton number conserved, $0\nu\beta\beta$-decay violates total lepton number by two units. It is generally considered as 'gold plated' channel to probe the fundamental character of neutrinos, whether being Dirac (like all other fundamental fermions) or Majorana particles. $0\nu\beta\beta$-decay is only possible if neutrinso are massive Majorana particles. The Majorana character of neutrinos restricts theoretical redefinitions of the particle fields which results in the occurence of two additional CP-violating phases, which can only be explored by neutrinoless double beta decay. These phases might be crucial for the creation of a baryon asymmetry in the early Universe with the help of leptogenesis.

The experimental signal of $0\nu\beta\beta$-decay is two electrons in the final state, whose energy add up to the Q-value of the nuclear transition. Being a rare nuclear decay the experimental quantity to be measured is a half-life, which depends in the background limited case on experimental quantities as

$$T^{0\nu}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot B}} \tag{2}$$

with a the natural abundance of the isotope of interest, ϵ the efficiency, M the used mass, t the measuring time, ΔE the energy resolution and B the background index, typically quoted in events/yr/keV/kg. The measured half-life can be converted into a neutrino mass

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \mid M^{0\nu}_{GT} \mid^2 (\frac{\langle m_{ee} \rangle}{m_e^2}^2) \tag{3}$$

where $G^{0\nu}$ is the exactly calculable phase space integral of the decay and $\mid M^{0\nu}_{GT} \mid$ is the involved nuclear matrix element (NME) of the transition. The deduced quantity of importance $\langle m_{ee} \rangle$, called effective Majorana neutrino mass, is given by

$$\langle m_{ee} \rangle \; = \mid \sum_i U_{ei}^2 m_i \mid \tag{4}$$

with U_{ei} as the complex PMNS mixing matrix elements and m_i as the corresponding mass eigenvalues.

Even if really observed, the underlying physics process mediating $0\nu\beta\beta$-decay remains unknown. In addition to the popular light Majorana neutrino exchange, other possibilities are discussed in the literature like the exchange of heavy Majorana neutrinos, double charged Higgs bosons, leptoquarks or right handed weak currents and R-parity violating SUSY couplings. Thus, to disentangle the underlying mechanisms it is necessary to explore other processes. One option is the investigation of transitions into excited states or double positron decay and double electron capture. Three different decay channels can be considered for the latter

$$\begin{aligned} (Z,A) &\rightarrow (Z-2,A) + 2e^+ + (2\nu_e) \quad (\beta^+\beta^+\,) \\ e^- + (Z,A) &\rightarrow (Z-2,A) + e^+ + (2\nu_e) \quad (\beta^+/EC\,) \\ 2e^- + (Z,A) &\rightarrow (Z-2,A) + (2\nu_e) \quad (EC/EC\,) \end{aligned} \tag{5}$$

where the last two cases involve electron capture (EC). These modes are mainly driven by right handed weak currents instead of light Majorana neutrinos.

In addition, it is an important aspect to measure the $2\nu\beta\beta$-decay

$$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}_e \quad (2\nu\beta\beta\text{-decay}) \tag{6}$$

allowed as higher order process in the Standard Model. Its measurement is important to check the reliability of the NME calculations.

2 COBRA

The idea is to use a large array of CdTe (CdZnTe, both will be called CdTe unless stated otherwise) semiconductor crystals [1]. CdTe contains 7 (9) double beta isotopes, 5 in the form of $\beta^-\beta^-$–emitters. Among them are ^{130}Te and ^{116}Cd as the most promising ones for the neutrino mass search and ^{106}Cd as one of only six known $\beta^+\beta^+$ emitters in nature. Advantages of the COBRA project are:

- Source is equal to detector. The isotopes of interest are intrinsic to the detector itself. This is always the most preferred approach.
- Semiconductor. Semiconductors are well known to have excellent energy resolution and can be produced very clean.
- Room temperature detectors. For practical purposes this is an enormous advantage.
- Modular design. The modular design offers the chance for an easy upgrade. In addition, it will allow significant background reduction, because high energy photons will hit several detectors, while double beta decay is a single detector event.
- Two isotopes. The sensitivity in two isotopes will help to account partly for the NME uncertainties if $0\nu\beta\beta$ decay is observed.
- The Q-value of ^{116}Cd is beyond all gamma-lines from natural decay chains, resulting in a significant background reduction.
- Pixelisation. The very exciting option of pixelisation would offer additional information in form of tracking and vertex reconstruction. The device would act as a ”solid state TPC”.
- Ongoing industrial development. In addition, CdTe detectors have wide applications in other fields of physics like γ-astronomy, material science, medical physics and dosimetry, hence further improvements in detector size and performance might be expected.

3 Current status

Initial studies were performed with various commercial detectors, differing in size (0.5 and 1 cm^3) and composition (CdTe and CdZnTe). None of them has been built under the special request of low background. In addition to studies on energy resolution and long term stability also first background measurements were performed. For the latter, a small shielding setup in form of a cube, consisting out of 10 cm thick electro-polished copper and 20 cm spectroscopy lead as shielding materials has been built at the University of Dortmund. This has been surrounded by plastic scintillators as active veto against cosmic rays and put into an airtight box flushed with nitrogen to avoid air. More than 1400 hours of measuring time were collected with the 0.5 cm^3 detector (Fig. 1). Another 397.5 g·d could be added to the analysis beyond 1 MeV using a 1 cm^3 detector. The presence of some impurities can be detected by their gamma lines, e.g. the 351 keV and 609 keV lines from the ^{238}U and 238.6 keV line from the ^{232}Th decay chains are visible. The 4-fold forbidden β-decay of ^{113}Cd with a half-life of around 10^{16} yrs is clearly visible as a shoulder in the low energy region. For the first time a direct limit on the $0\nu\beta\beta$-decay of ^{70}Zn has been obtained. Five word best limits, mainly involving EC-modes have been obtained, which are compiled in Table 1, for a complete listing of all results see [2]. In addition, a six orders of magnitude difference in the half-life of the second forbidden EC of ^{123}Te between the Table of Isotopes and a new measurement by the Milano double beta experiment, has been solved in strong favour of the latter result [3]. The setup has been transferred to Gran Sasso Laboratory in May 2003 to reduce background from cosmic rays. A first preliminary analysis using the 0.5 cm^3 detector showed an improvement by a factor three in the regionn 2.4-3 MeV. This implies that the major background is from components close the detector itself.

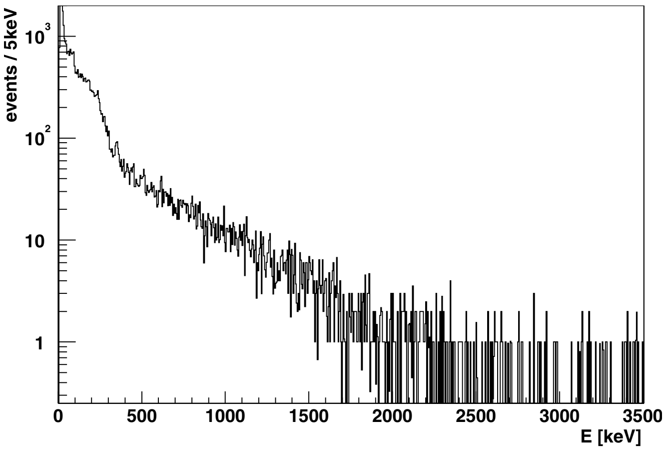

Fig. 1. Energy spectrum taken with a 0.5 cm^3 CdZnTe and a total measuring time of 1402 hours. Clearly visible is the low-energy shoulder from the 4-fold forbidden beta decay of ^{113}Cd. The peaks of the most relevant $0\nu\beta\beta$-decay are at 2530 keV (^{130}Te) and 2805 keV (^{116}Cd)

Thus, to improve on that in a next step, four naked 1 cm^3 CdTe crystals were bought and installed in a copper brick to form a 2×2 prototype. In addition, to the removal of material around the crystal also the concept of coincidences can now be explored. This device is running in Gran Sasso Laboratory since August 2003 and a first sum spectrum is shown in Fig. 2.

4 Outlook

In addition to an upgrade of the electronics and the installation of more detectors the major issue is a further reduction of background, especially in the region of the ^{116}Cd peak at 2.8 MeV. Being beyond all gamma-lines from the natural decay chains the major background from this source is the beta decay of ^{214}Bi, with an endpoint beyond 3 MeV. However, this can be vetoed by a coincidence with the subsequent 7.7 MeV α-particle produced with a $\tau = 164\mu s$. To reduce the background from the natural decay chains an increase of the lead shield and

Table 1. Limits on various decay modes improved by COBRA. The numbers obtained are from a measurement with a 0.5 cm^3 on the surface. For a full listing see [2]

Isotope	Level [keV]	$T_{1/2}$ [yrs]
^{70}Zn	(0^+) g.s.	1.3×10^{16}
^{120}Te	(0^+) g.s. $0\nu\beta^+$EC	2.2×10^{16}
	(0^+) g.s. 2νECEC	9.4×10^{15}
	(2_1^+) 1171 2νECEC	8.4×10^{15}
^{64}Zn	(0^+) g.s. 2νECEC	6.0×10^{16}
^{106,108}Cd	(0^+) g.s. 2νECEC	1.0×10^{18}

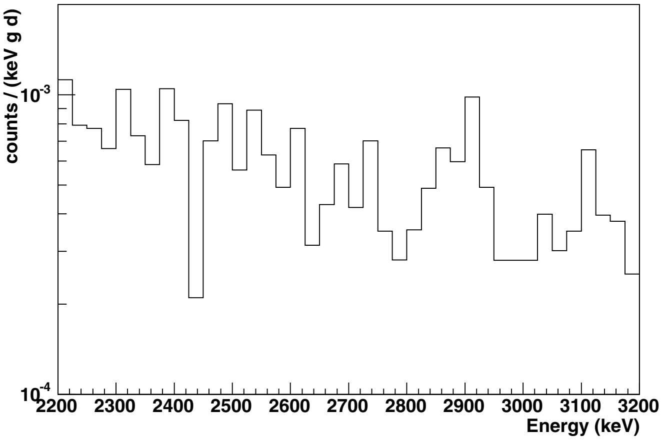

Fig. 2. Sum energy spectrum of the four prototype detectors in the region from 2.4-3 MeV. Statistics corresponds to 0.57 kg d

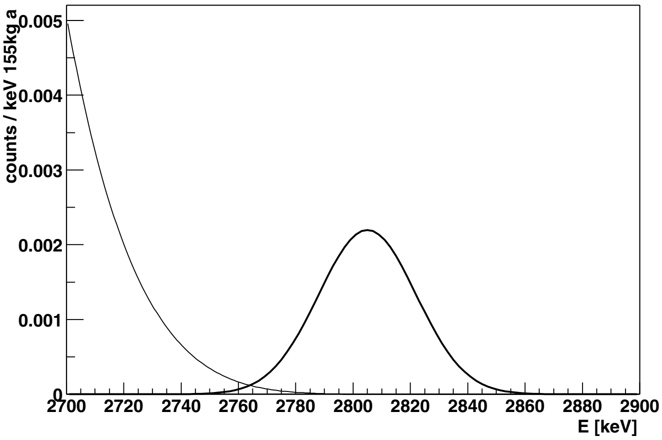

Fig. 3. Energy spectrum around the $0\nu\beta\beta$-decay peak of ^{106}Cd using the energy resolution of the currently used detectors. Shown is a peak assuming a half-life of $2 \cdot 10^{26}$ yrs and the expected background from the $2\nu\beta\beta$-decay of ^{106}Cd with an expected half-life of $3.2 \cdot 10^{19}$ yrs is showns as well. As can be seen , the very good signal-background ration can be obtained

a replacement using cleaner lead together with a more profound material selection is foreseen. In addition, the whole apparatus will be flushed with nitrogen to keep the air out. Another major background component is neutrons, especially because of the large cross-section of the $^{113}\mathrm{Cd}(n,\gamma)^{114}\mathrm{Cd}$ capture reaction producing gamma rays up to 8 MeV. However such an event would result in an energy deposition in various detectors and can be discriminated. To reduce the incoming neutrons a sophisticated neutron shield made out of boron-loaded polyethylene will be installed. A further source of background is cosmogenic radioisotopes, produced in the detector, while on the surface. These have been measured for the INTEGRAL mission using a 1.5 GeV proton beam at CERN [4]. An irreducible background is the $2\nu\beta\beta$-decay making the energy resolution of the detectors a crucial issue. Here COBRA profits from the effect of using a semiconductor. Figure 3 shows an expected peak of $0\nu\beta\beta$-decay with a half-life of about seven orders of magnitude longer than the one for $2\nu\beta\beta$-decay assuming the current energy resolution. Following [5] the number of $2\nu\beta\beta$-decay background events in the peak region is only

$$F = \frac{8Q(\Delta E/Q)^6}{m_e} = 3.7 \cdot 10^{-10} \qquad (7)$$

allowing a possible peak detection with a high signal-background ratio.

5 Summary

COBRA is a new experimental approach towards double beta decay searches. The usage of CdZnTe semiconductor offers a new handle on various decay modes, of special interest are the isotopes ^{116}Cd , ^{130}Te and ^{106}Cd . Already with a commercial small scale detector five world best limits have been obtained. Currently a prototype of four detectors is taking data in the Gran Sasso Underground Laboratory and detailed background studies are performed. The outcome from these measurements will lead to a design for a large scale experiment. As has been shown recently, on the very large scale even a real time detection of low energy solar neutrinos could be possible [6].

Evidently, an upgrade to a larger number of detectors and a new data acquisition system are foreseen.

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