COBRA - Double beta decay searches using CdTe detectors

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A new approach (called COBRA) for investigating double beta decay using CdTe semiconductor detectors is proposed. This will allow simultaneous measurements of $\beta^-\beta^-$- and $4\beta^+\beta^+$- emitters at once. Half-life limits for neutrinoless double beta decay of $^{116}\text{Cd}$ and $^{130}\text{Te}$ can be improved by more than one order of magnitude and sensitivities on the effective Majorana neutrino mass of less than 1 eV can be obtained. Furthermore, for the first time a realistic chance of observing double electron capture processes exists. Additional searches for rare processes like the 4-fold forbidden $^{113}\text{Cd}$ $\beta$-decay, the electron capture of $^{123}\text{Te}$ and dark matter detection can be performed. The achievable limits are evaluated for 10 kg of such detectors and can be scaled accordingly towards higher masses because of the modular design of the proposed experiment.

**Key words:** massive neutrinos, double beta decay

1 Introduction

The fundamental question whether neutrinos have a non-vanishing rest mass is still one of the big open problems of particle physics. In case of massive neutrinos a variety of new physical processes open up [1]. Over the last years evidence has grown for a non-vanishing mass by investigating solar and atmospheric neutrinos as well as by results coming from the LSND-experiment. They all can be explained within the framework of neutrino oscillations [2]. However oscillations only depend on the differences of squared masses and are therefore no absolute mass measurements. Besides, the question concerning the fundamental character of neutrinos, whether being Dirac- or Majorana
particles, is still unsolved. A process contributing information to both questions is neutrinoless double beta decay of a nucleus \((Z, A)\)

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

This process is violating lepton-number by two units and only allowed if neutrinos are massive Majorana particles. The quantity which can be extracted out of this is called effective Majorana neutrino mass \(\langle m_{ee} \rangle\) and given by

\[
\langle m_{ee} \rangle = \left| \sum_i U_{ei}^2 \eta_i m_i \right|
\] (2)

with the relative CP-phases \(\eta_i = \pm 1\), \(U_{ei}\) as the mixing matrix elements and \(m_i\) as the corresponding mass eigenvalues. Currently the best limit is given by investigating \(^{76}\text{Ge}\) resulting in an upper bound of \(\langle m_{ee} \rangle \lesssim 0.35\, \text{eV}\) [3]. Moreover the standard model process

\[
(Z, A) \rightarrow (Z + 2, A) + 2e^- + 2\bar{\nu}_e \quad (2\nu\beta\beta\text{-decay})
\] (3)

can be investigated as well. It is important to check the reliability of the calculated nuclear matrix elements.

The experiment proposed here utilizes Cd-based semiconductor detectors. A big benefit of this approach is, that the double beta emitters are part of the detectors itself. The detectors can be used either in the form of only measuring the sum energy of both electrons or in a modified way as pixelised detectors, which allows simultaneous tracking and energy measurement. CdTe and CdZnTe (CZT) detectors are used in several areas of X-ray physics, astrophysics and medical applications. All isotopes of interest for \(\beta^-\beta^-\) -decay searches which are intrinsic in these detectors are listed in Tab.1. A few observations exist for \(2\nu\beta\beta\)-decay of \(^{116}\text{Cd}\), most of them with very low statistics. The obtained half-lives center around \(3 \cdot 10^{19} \, \text{a}\) [5–7]. The \(2\nu\beta\beta\)-decay of \(^{130}\text{Te}\) was only measured by geochemical methods and found to be in a range of \(0.7 - 2.7 \cdot 10^{21} \, \text{a}\), therewith a spread of a factor four among different measurements exist [8–11]. Current lower limits on \(0\nu\beta\beta\)-decay half-lives for the two favourite isotopes \(^{116}\text{Cd}\) and \(^{130}\text{Te}\) are \(7 \cdot 10^{22} \, \text{a}\) and \(1.44 \cdot 10^{23} \, \text{a}\) (both 90 % CL) respectively [7,12]. Limits on the other mentioned isotopes are rather poor, a compilation can be found in [13].

In a more general scheme \(0\nu\beta\beta\)-decay can be realised by several lepton number violating mechanisms. Beside massive Majorana neutrino exchange, additional mechanisms like right-handed weak currents, R-parity violating supersymmetry, double charged Higgs bosons or leptoquarks have been proposed [14–16]. To obtain more information on the underlying physics process, it is worthwhile to look for transitions into excited states [17] and to investigate \(\beta^+\beta^-\) -decay.
Three different decay channels can be considered here

\[(Z, A) \rightarrow (Z - 2, A) + 2e^+ + (2\nu_e) \quad (\beta^+\beta^+) \]

\[e^- + (Z, A) \rightarrow (Z - 2, A) + e^+ + (2\nu_e) \quad (\beta^+/EC) \]

\[2e^- + (Z, A) \rightarrow (Z - 2, A) + (2\nu_e) \quad (EC/EC) \]

where the last two cases involve electron capture. The first two are the easiest to detect because of the annihilation photons of the positron(s) emitted. On the other hand they are largely suppressed by phase space reduction \((Q - 4m_e c^2)\) for \(\beta^+\beta^+\) and \(Q - 2m_e c^2\) for \(\beta^+/EC\) respectively). The one with the lowest expected half-life is \(EC/EC\) - decay, but difficult to detect because only X-rays are emitted. All \(\beta^+\beta^+\) -decays can occur as \(2\nu\beta\beta\)-decay or \(0\nu\beta\beta\)-decay. Current half-life limits for the decay modes involving at least one positron are of the order of \(10^{20}\) a \([19,20]\), far below theoretical expectation. The proposed experiment would for the first time allow the measurement of \(EC/EC\) -decay in the theoretically expected range because the isotopes are within the CdTe crystals (source equal to detector) and do not rely on external devices for detecting 511 keV photons. All isotopes of interest for such studies are given in Tab. 2. Moreover, transitions to excited final states for most of the above listed isotopes are possible. This includes basically \(\gamma\)-rays of 1.294 MeV and 1.757 MeV \((^{116}Cd\) ), 512 keV, 1.13 MeV and 1.56 MeV \((^{106}Cd\) ) for Cd-isotopes and 442.9 keV \((^{128}Te\) ), 536.1 keV \((^{130}Te\) ) and 1.171 MeV \((^{120}Te\) ) for tellurium. For a compilation of existing limits see \([13]\). A first small attempt to use CdTe for rare decay searches was done by \([21]\).

2 Experimental considerations

The proposed experiment, running under the name COBRA\[^1\], should consist in a first stage of 10 kg of material in form of either CdTe or CdZnTe detectors. For double beta decay searches especially two experimental parameters have to be primarily considered, namely energy resolution and the expected background. A possible setup is shown schematically in Fig.1. The central detector is an array of about 1600 CdTe crystals, because the largest available crystal size is of the order of 1 cm\(^3\). In case of a cubic arrangement it would have a size of 12×12×12 cm\(^3\). The detectors will be installed within a NaI detector for two reasons: First, it can act as an active veto against penetrating particles and secondly it can be used as a detector for \(\gamma\)-rays, coincidence measurements between a CdTe detector and the NaI can be done. It has been demonstrated by several dark matter groups that such detectors can be built as low-level

\[^1\] CdTe 0 neutrino double Beta Research Apparatus
devices [22,23]. Coincidences among the various CdTe crystals can be formed as well.

This inner part is surrounded by a shield of very clean oxygen free high conductivity (OFHC) copper in combination with low-level lead, a setup common to low-level experiments. The complete apparatus will be covered by an active veto against muons made out of high efficiency scintillators. Clearly the experiment should be located in one of the existing underground facilities. A further shielding against thermal neutrons might be necessary, because of the large cross section of $^{113}Cd(n, \gamma)^{114}Cd$ reactions.

Common background to all low level experiments are the uranium and thorium decay chains as well as $^{40}K$ contaminations. Some parts of the chains might be eliminated by subsequent detections within one crystal, clearly identifying the origin of the event. As an example take a sequence from the $^{226}Ra$ decay chain (from the $^{238}U$ decay):

$^{214}Bi(Q_\beta = 3.27 MeV, T_{1/2} = 19.9 min) \rightarrow ^{214}Po$

$^{214}Po(Q_\alpha = 7.83 MeV, T_{1/2} = 164.3 \mu s) \rightarrow ^{210}Pb$

This $\beta - \alpha$ coincidence within one crystal can be used to estimate this background contribution. Studies on radioisotope production in CdTe due to cosmic ray activation have been performed using proton beams [24].

The intrinsic background from $^{113}Cd$ -decay is of no concern because its endpoint is around 320 keV, much below the $0\nu\beta\beta$-decay lines. A measurement of the energy spectrum in the range 2-3 MeV obtained with a test setup using a conventional 1 cm$^3$ CdTe is shown in Fig.2. The smallness of the CdTe detectors makes it possible to construct the experiment in a modular design, making future upgrades easy.

The principle readout of one CdTe detector will focus on electron collection only, to avoid smearing in the energy because of the bad hole mobility in CdTe. Energy resolutions of about 1 % for the $^{137}Cs$ line at 662 keV have already been achieved [25]. This is sufficient to assure no overlap between the $0\nu$ region of $^{130}Te$ with possible background lines at 2447.7 keV ($^{214}Bi$) and 2614.4 keV ($^{208}Tl$). A further improvement of the energy resolution might be achieved by a slight cooling of the CdTe detectors to temperatures of roughly $-20$ degrees centigrade.

As a modification the usage of pixelized detectors is envisaged. In addition to an energy measurement this allows tracking of the two emitted electrons and therefore a handle on background reduction. However, it has to be investigated experimentally in more detail whether the additional pixel bonds are not causing relatively more impurities. On the other hand this is a very attractive method to search for transitions to final states using separate pixels within one crystal. Pulse shape analysis techniques might be performed as well for background subtraction. A more detailed treatment of experimental details and simulation studies can be found in [26].
3 Expected sensitivities for $\beta^-\beta^-$ - decays

The dominant $2\nu\beta\beta$-decays are coming from $^{116}Cd$ and $^{130}Te$. With an assumed half-life of $3 \cdot 10^{19}$ a this produces a count rate of 94 events/day. Therefore a high statistics measurement of this decay is possible. For $^{130}Te$ with an assumed half-life range of $0.7 - 2.7 \cdot 10^{21}$ a 6 - 23 events/day are expected. This corresponds to a 6.4 % - 24.5 % contribution to the $^{116}Cd$ spectrum. Clearly a decision among the lower and higher half-lives for $^{130}Te$ can be made. A detection and proof of the geochemical half-life obtained for $^{128}Te$ will be very difficult, because it would roughly result in only about 1 event/a. The rather poor limit of $T_{1/2}^{2\nu} > 9.2 \cdot 10^{16}$ a for $^{114}Cd$ can certainly be improved, in case of using CZT for the first time a limit on the $2\nu\beta\beta$-decay of $^{70}Zn$ can be obtained.

With regard to neutrino mass limits again the main focus lies on $^{116}Cd$ and $^{130}Te$. Achievable half-life limits after 5 years of measurement are shown in Fig.3. In case of building a background free detector, the corresponding half-lives scale linear with measuring time, resulting in an even better sensitivity. Using the parameters given in Tab.1, a limit on $\langle m_{ee} \rangle$ in the region below 1 eV can be achieved. For an extensive discussion of the status of the necessary nuclear matrix element calculations see [27,28]. If no signal is observed, the observed limit on $\langle m_{ee} \rangle$ would strengthen the believe in the result already obtained with Ge, because of the uncertainties coming from nuclear matrix element calculations. Clearly a further improvement can be achieved by adding more detectors, which is possible because of the modular design of the experiment.

Also transitions to excited states can be investigated because of the good sensitivities of CdTe detectors for $\gamma$-rays. Current bounds for such transitions are in the order of $10^{21}$ a [29,30]. The modular layout of this experiment would allow to perform a high sensitivity search. The coincident detection of the de-excitation photon in one CdTe crystal and the corresponding electron signal in a neighbouring detector forms a clear signal. This will significantly reduce the background in searches for these channels.

4 Experimental sensitivities for $\beta^+\beta^+$ -decays

A wide range of results can be obtained for the various decay modes of $\beta^+\beta^+$ -decays given in Tab. 2. As already stated, the lowest expected half-life belongs to the $EC/EC$ - decay mode. The filling up of the two K-shell holes in $^{106,108}Pd$ coming from the decay of Cd-isotopes will result in a peak at 48.6 keV. A recent calculation for $^{106}Cd$ $EC/EC$ results in a theoretical predicted half-life of $4 \cdot 10^{20}$ a [31]. The expected count rate then is about 550 events/a, which should result in a clear observation. A corresponding peak for the $EC/EC$ of
$^{120}\text{Te}$ to $^{120}\text{Sn}$ would be at 58.4 keV. There is only a limit on the $\beta^+/EC$ of $4.2 \cdot 10^{12}$ a [32], which can be improved by many orders of magnitude, because the expected number for COBRA is $1.2 \cdot 10^7$ events/day. Transitions to excited states for $^{106}\text{Cd}$ and $^{120}\text{Te}$ can be explored in a similar fashion. While limits of the order of $10^{18}$ a exist for $^{106}\text{Cd}$ [35], nothing is known so far for $^{120}\text{Te}$.

5 Additional physics - dark matter searches and $^{113}\text{Cd}$, $^{123}\text{Te}$ -decay

As most low-level double beta detectors also CdTe could be used for dark matter searches. Detectors with thresholds of about 1 keV at a temperature of $-20$ degrees are available. From the theoretical point of view, $^{125}\text{Te}$ together with $^{129}\text{Xe}$ is among the theoretically most preferred isotopes to study spin-dependent interactions [37,38]. With 10 kg of CdTe it will be possible to probe the DAMA evidence [39] within reasonable time scales. Unfortunately no theoretical calculation for the usage of Cd-isotopes for dark matter searches exists.

A long standing discussion is connected with the $\beta$-decay of $^{123}\text{Te}$. This second forbidden unique electron capture occurs with a transition energy of $51.3 \pm 0.2$ keV to the ground state of $^{123}\text{Sb}$. Measurements concentrating on the detection of the 26.1 keV photons of K X-rays from $^{123}\text{Sb}$ resulted in a half-life of the order $10^{13}$ years [33]. However, a new measurement claims a value of $2.4 \pm 0.9 \cdot 10^{19}$ a [36], six orders of magnitude higher. The discrepancy might be associated with confusing the above X-ray line with the Te K X-ray line at 27.3 keV. Having a decay within the CdTe detector itself, in contrast to the above measurements, this problem can be solved because the full transition energy can be measured with high efficiency and good energy resolution. Even the long half-life would correspond to 19 decays per day.

Last but not least there is the $\beta$-decay of $^{113}\text{Cd}$. This 4-fold forbidden decay has an uncertain half-life of about $8 \cdot 10^{15}$ a and a Q-value of about 320 keV. Two measurements exist [34,35], but are within their errors in slight disagreement. In the COBRA-setup discussed here a very high statistics measurement can be done, having about 10 decays per second with good energy resolution.

6 Summary and conclusion

In this paper the physics potential of CdTe or CdZnTe detectors for double beta decay searches and other rare processes is discussed. CdTe detectors profit from the fact that source material and detector are identical. An experimental advantage of the described setup is the good energy resolution (in contrast to scintillators) also in combination with possible tracking and the possibility to
perform the experiment at room temperature or only slightly below (in contrast to cryogenic detectors). The unique chance of investigating in total $5(4)\ \beta^-\beta^-\text{ and } 4(3)\ \beta^+\beta^+$ - emitters at the same time in case of using CZT (CdTe) can be realised. For neutrinoless double beta decay an improvement on the existing half-life limits for the most promising isotopes $^{116}Cd$ and $^{130}Te$ by more than one order of magnitude with respect to current limits could be obtained. Thus for both isotopes a neutrino mass limit of $m_{ee} \lesssim 1$ eV would result. A high statistics measurement of the $2\nu\beta\beta$-decays of both isotopes is possible. Furthermore, a detailed investigation of $\beta^+\beta^+$ -decays can be done and for the first time an attempt to measure $EC/EC$ -decays in the theoretically predicted range can be performed. Sensitive searches for a large number of excited state transitions are feasible as well. As further topics a high statistics measurement of the 4-fold forbidden $\beta$-decay of $^{113}Cd$ can be conducted, the six orders of magnitude discrepancy for the electron capture of $^{123}Te$ can be solved and a sensitive search for dark matter can be done. The given numbers scale with the used mass and because of the modular design of the experiment a corresponding upgrade for improvements is possible as discussed for a 100 kg solution.

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Table 1
$\beta^- \beta^-$-isotopes of relevance for double beta decay in CdTe and CZT detectors. Given are the Q-values of the transition, the natural abundance, phase space factors and theoretical expectations for the half-lives. The $2\nu\beta\beta$-decay half-life is averaged over an acceptable range of the adjustable parameter $g_{pp}$. The theoretical predictions are taken from [4].

| Isotope | Q(keV) | nat. ab. (%) | $G_{2\nu}^{-1}$ (a) | $G_{0\nu}^{-1}$ (a) | $T_{2\nu}(a)$ | $T_{1/2} \cdot m_\nu (a \cdot eV^2)$ |
|---------|--------|--------------|---------------------|---------------------|---------------|-----------------------------------|
| $^{70}$Zn | 1001 | 0.62 | 3.17E21 | 4.27E26 | 3.99E22 | 9.83E25 |
| $^{114}$Cd | 534 | 28.7 | 6.93E22 | 6.1E26 | 1.74E24 | 5.07E25 |
| $^{116}$Cd | 2805 | 7.5 | 1.25E17 | 5.3E24 | 6.31E19 | 4.87E23 |
| $^{128}$Te | 868 | 31.7 | 1.18E21 | 1.46E26 | 2.63E24 | 7.77E24 |
| $^{130}$Te | 2529 | 33.8 | 2.08E17 | 5.89E24 | 1.84E21 | 4.89E23 |

Table 2
$\beta^+ \beta^+$ - isotopes of relevance in CdTe and CZT detectors. Given are the Q-values of the transition and the natural abundance. Also given are the possible decay modes.

| Isotope | Q(keV) | nat. ab. (%) | Decay modes |
|---------|--------|--------------|-------------|
| $^{64}$Zn | 1096.3 | 48.6 | $EC/EC$, $\beta^+/EC$ |
| $^{106}$Cd | 2771 | 1.25 | $EC/EC$, $\beta^+/EC$, $\beta^+\beta^+$ |
| $^{108}$Cd | 231 | 0.9 | $EC/EC$ |
| $^{120}$Te | 1722 | 0.10 | $EC/EC$, $\beta^+/EC$ |
Fig. 1. Schematic layout of the proposed COBRA experiment. An array of CdTe detectors is installed within two NaI detectors, serving as active veto and part of coincidence measurements. This will be installed inside an OFHC copper shield, surrounded by low level lead. As a veto the complete setup will be surrounded by a muon veto consisting of high efficiency plastic scintillators.
Fig. 2. Energy spectrum of a 1 cm$^3$ CdTe detector in the interesting range of 2.2 - 3.2 MeV. The measuring time corresponds to 135.5 hours. The detector was installed in a shielding of 10 cm standard grade copper surrounded by an additional shield of 20 cm of spectroscopy lead. The whole apparatus was surrounded by a 4$\pi$ veto made of plastic scintillators. The total shielding depth was about 5 mwe. For more details see [26]. Expected 0$\nu$\beta\beta-decayline are at 2529 keV ($^{130}$Te) and 2805 keV ($^{116}$Cd).
Fig. 3. Expected half-life limits for $^{116}\text{Cd}$ (solid line) and $^{130}\text{Te}$ (dashed line) as a function of measuring time. Assumed are the experimentally obtained background levels of 0.2 counts/keV/kg/a ($^{130}\text{Te}$ [12]) and 0.03 counts/keV/kg/a ($^{116}\text{Cd}$ [7]) as well as an energy resolution of 1 %.