First Results on Double Beta Decay Modes of Cd, Te and Zn Isotopes with the COBRA Experiment

T. Bloxham, A. Boston, J. Dawson, D. Dobos, S.P. Fox, M. Freer, B.R. Fulton, C. Gößling, P.F. Harrison, M. Junker, H. Kiel, J. McGrath, B. Morgan, D. Müntermeun, P. Nolan, S. Oehl, Y. Ramachers, C. Reeve, D. Stewart, R. Wadsworth, J.R. Wilson, and K. Zuber

1 School of Physics and Astronomy, University of Birmingham, B15 2TT, UK
2 Lehrstuhl für Experimentelle Physik IV, Universität Dortmund, Otto–Hahn Str. 4,44227 Dortmund, Germany
3 Laboratori Nazionali del Gran Sasso, S.S. 17 BIS km. 18.910, 67010, Assergi, L’Aquila, Italy
4 Dept. of Physics, University of Liverpool, Liverpool L69 7ZE, UK
5 Dept. of Physics and Astronomy, University of Sussex, Brighton, BN1 9QH, UK
6 Dept. of Physics, University of Warwick, Coventry CV4 7AL, UK
7 Dept. of Physics, University of York, Heslington, York, YO10 5DD, UK

(Dated: February 5, 2008)

Four 1 cm$^3$ CdZnTe semiconductor detectors were operated in the Gran Sasso National Laboratory to explore the feasibility of such devices for double beta decay searches as proposed for the COBRA experiment. The research involved background studies accompanied by measurements of energy resolution performed at the surface. Energy resolutions sufficient to reduce the contribution of two-neutrino double beta decay events to a negligible level for a large scale experiment have already been achieved and further improvements are expected. Using activity measurements of contaminants in all construction materials a background model was developed with the help of Monte Carlo simulations and major background sources were identified. A total exposure of 4.34 kg-days of underground data has been accumulated allowing a search for neutrinoless double beta decay modes of seven isotopes found in CdZnTe. Half-life limits (90% C.L.) are presented for decays to ground and excited states.

Four improved lower limits have been obtained, including zero neutrino double electron capture transitions of $^{64}$Zn and $^{120}$Te to the ground state, which are $1.19 \times 10^{17}$ years and $2.68 \times 10^{15}$ years respectively.

PACS numbers:

I. INTRODUCTION

In recent years, a range of neutrino oscillation experiments have successfully proved that neutrinos are massive particles. Although such experiments are sensitive to a mass-difference rather than absolute neutrino mass, the data suggest a neutrino mass eigenstate of at least 50 meV. To further probe the neutrino’s properties, it is necessary to look to other processes such as neutrinoless double beta decay ($0\nu\beta\beta$), which violates lepton number by two units; observation of this process would confirm the Majorana nature of the neutrino and the rate of this rare decay is proportional to the absolute neutrino mass scale. For recent reviews of double beta decay see Refs. and .

The COBRA experiment uses CdZnTe (CZT) semiconductors to search for $0\nu\beta\beta$. CZT contains nine double beta emitters, five of which can decay via double beta decay, i.e. emitting two electrons, and four of them via either double electron capture, a combination of a positron emission with electron capture or double positron emission. The study of the positron and electron capture modes can be used for lepton number violating decay searches on an equivalent level to $0\nu\beta\beta$, however the phase space for the positron modes is strongly reduced, making them less sensitive. Nevertheless, it has been shown that the positron/electron capture mixed modes have an enhanced sensitivity to right-handed weak currents and thus can help to disentangle the underlying physics mechanism of $0\nu\beta\beta$ if observed . In addition, excited states transitions can be explored with high efficiency and low background using coincidence techniques among the detectors. These decays would allow an independent search for double beta decay searching for the de-excitation photons together with the electron signal.

The main focus of the work described in this paper is the study of background through measurements performed underground, and energy resolution studies carried out in a surface laboratory. Optimisation of these quantities is vital for a successful search for $0\nu\beta\beta$, because, in the background limited case, the observable half-life depends on them with a square root behaviour. In addition, half-life limits for seven double beta isotopes contained in natural CZT have been determined from data collected with a small prototype detector accumulating an exposure of 4.34 kg-days.

II. SENSITIVITY

Although COBRA is able to search for $0\nu\beta\beta$ in a number of isotopes, the sensitivity for the modes with lower Q-values will ultimately be limited by background contributions from two neutrino double beta ($2\nu\beta\beta$) decays of the isotopes with higher Q-values. The contribution of $2\nu\beta\beta$ decay events to the current data set is negligible,
A half life of about 2.8 keV for the nuclear decay to will focus on but for a very sensitive neutrino mass search, COBRA Ref. [8]. Sensitivity (years)

\[ T_{1/2} = 50 \text{ meV using matrix elements from} \]

FIG. 1: (Color online) The expected half-life sensitivity for $\nu_{\beta\beta}$ decay of $^{116}$Cd in an array of 64,000 1 cm$^3$ detectors, enriched to 90% in $^{116}$Cd for three scenarios of background and energy resolution ($\Delta E = \text{FWHM}$):

- $A = 10^{-3}$ counts/(keV kg year), $\Delta E = 2\%$ at 2.8 MeV.
- $B = 10^{-3}$ counts/(keV kg year), $\Delta E = 1\%$ at 2.8 MeV.
- $C = 5 \times 10^{-4}$ counts/(keV kg year), $\Delta E = 1\%$ at 2.8 MeV.

A half life of about $2 \times 10^{26}$ years corresponds to a neutrino mass sensitivity of about 50 meV using matrix elements from Ref. [8].

but for a very sensitive neutrino mass search, COBRA will focus on $^{116}$Cd, which has the highest Q-value of 2809 keV for the nuclear decay to $^{116}$Pd. A peak will occur at this energy in the sum energy spectrum for the case of $\nu_{\beta\beta}$.

Crucial experimental parameters, besides the mass of the detector/sample, are energy resolution and the number of contaminating background events in this range, as shown in Fig. 1. Possible background sources include cosmic rays, the natural radioactive decay chains, radioisotopes produced by cosmic ray interactions within the materials used and neutrons. To get a first glimpse of the background using CZT detectors, a prototype setup has been installed in the Gran Sasso Underground Laboratory (LNGS) in Italy, which provides an average shielding of $\sim$3500 mwe against cosmic ray sources.

### III. EXPERIMENTAL SETUP

The data presented here were obtained with four 1 cm x 1 cm x 1 cm CZT semiconductor detectors, each of mass $\sim$0.5 g, provided by eV-PRODUCTS. They utilise coplanar grid technology to ensure that only the electron signal is read out and hence symmetric energy peaks are obtained. All four crystals were operated at a voltage of $-1500$ V with a 20–40 V grid bias applied between the two anodes. The crystal surfaces, except for the gold-coated cathode side, are covered with a passivation paint which prevents oxidation and deterioration in detector performance over time.

The four detectors were mounted in a copper brick separated from all preamplifier electronics by $\sim$25 cm. The copper brick was part of a (20 cm)$^3$ cube of electro-polished copper which was embedded in a further 15 cm of lead. The whole setup was located in a Faraday cage made from copper plates. The cage was surrounded by a neutron shield, consisting of 7 cm thick boron-loaded polyethylene plates and an additional 20 cm of paraffin wax at the bottom. This neutron shield was upgraded to cover 3 sides of the cage, as well as the base, with paraffin wax before the third data taking period (period C). Data collection commenced with a CAMAC based data acquisition (DAQ) system in which the signals were fed into four peak sensing ADC modules (LeCroy 3511 and 3512) via custom-built preamplifiers and shaping main-amplifiers. Prior to period C, the system was upgraded to a VME-based DAQ with four custom-built, peak sensing, 14-bit ADC channels.

### IV. DATA ACQUISITION

The data analysed in this paper can be divided into three periods, separated by upgrades to the experimental configuration that could have affected the background contributions. In period A, the crystals were held in perlux mounting plates and connected directly to lemo cables. These mounting materials were replaced by cleaner (in the radiopurity sense) delrin holders, whilst the lemo connections were exchanged for copper traces mounted on kapton foils at the start of period B. Before period C the data acquisition hardware was upgraded to the VME system and the paraffin neutron shielding was completed. During the latter periods not all crystals were fully operational, so only data from crystal 1 were analysed. In each period, individual runs were limited to one hour and selection criteria were applied on a run-by-run basis to reject data affected by “bursts” of abnormally high event rates. Subsequent studies have shown two main causes for such bursts: vibrations of the apparatus that cause a piezo-electric effect in the crystals resulting in false event signals, and breakdown effects due to faulty contacts to the crystal electrodes. To reject the affected data, firstly the dead-time was calculated from the total number of events per hour and the length of the event readout cycle.

| Subset | Livetime (days) | Events/(keV kg day) |
|--------|-----------------|---------------------|
| >500 keV | >600 keV | in 2–3 MeV range |
| 1A | 32.86 | 150.99 | 0.57 ± 0.02 |
| 2A | 0 | 112.34 | 0.59 ± 0.03 |
| 3A | 52.84 | 52.84 | 0.38 ± 0.03 |
| 4A | 62.62 | 134.64 | 0.34 ± 0.02 |
| 1B | 16.03 | 16.03 | 0.54 ± 0.07 |
| 1C | 197.53 | 197.53 | 0.56 ± 0.02 |

TABLE I: Livetimes for data sets prepared above two different energy thresholds (500 keV and 600 keV), and an indication of the average background level in the 2–3 MeV region.
The low-threshold data set comprises 2.36 kg·days, and threshold are given in table I. The total livetime in the range 500–600 keV. The livetimes for each subset with all crystals show fluctuations due to intrinsic and surface contaminants (as indicated by the values in table I). For this reason, data collected with each crystal, and in each period, were considered as a different data sub-set. The summed data for each of the collecting periods are shown in Fig. 2.

Although detectors have been operated for extensive periods with thresholds below 100 keV, at times it was necessary to raise the threshold for data collection to exclude electronic phenomena. Therefore, to maximise the livetime for analysis, two data sets have been prepared: one with an energy threshold of 600 keV, and one with a 500 keV threshold that omits any runs with thresholds in the range 500–600 keV. The livetimes for each subset and threshold are given in table I. The total livetime for the high-threshold data set is 4.34 kg-days, whilst the low-threshold data set comprises 2.36 kg-days.

The energy resolution and stability of the detectors was determined for each data subset with all crystals showing a linear increase in FWHM with increasing energy. FWHM values in the range 5–8% at 2809 keV were achieved. Variations in the resolution achieved can be attributed to changes in the contacting methods and the voltages applied between the different data taking periods. It should be noted that the detectors used here do not have the best energy resolution possible, since for this first study with unknown background a very good energy resolution was not considered to be essential and, hence, cheaper detectors were used.

V. BACKGROUND STUDIES

To understand the observed spectrum and disentangle the individual contributions, a background model has been developed. All materials used were measured for contaminants in the LNGS Ge-detector facility, though some of them could only be measured after the start of data taking with the prototype. As a consequence of these measurements, the pertinax holders and lemo cables were replaced by delrin holders and kapton foils (between periods A and B). No contamination of the CdZnTe could be detected with the Ge facility. With the known activities of contaminants in the individual components, extensive Monte Carlo modelling based on GEANT4 was performed to describe the observed spectrum (Fig. 3).

By far the largest background in the 2–3 MeV region evolves from the passivation paint on the detector surface. The precise prediction of this contribution varies slightly due to the unknown paint mass and the inhomogeneous paint thickness, which affects the alpha-particle simulation in particular. However, there is a slight advantage associated with the contaminated paint as the detector effectively acts as a self-calibrating device. The installation of the VME system at the start of period C significantly increased the timing resolution achieved for event read-out (from ≈1 ms to ≤10 µs) permitting the observation of β–α coincidence events from 214Bi. This isotope originates from the Th-decay chain, present in the passivation paint, and beta-decays with an endpoint of 3.3 MeV; the daughter isotope, 214Po, alpha-decays with a half-life of 164.3 µs, releasing a 7.7 MeV α. The rate of event pairs observed in the period C data-set was consistent with the measured activity of a paint sample.

Furthermore, it shows that any possible dead layer at the detector surface is insignificant, otherwise the alpha-particles would not be detected. In the meantime, an alternative solution for surface passivation of the CZT detectors has been found and is currently being explored at LNGS. Initial measurements show a reduction of this background by at least a factor of 8, if not more, in the region of interest around 2.8 MeV.

The measurements of pertinax contaminants prompted the replacement of all pertinax components with delrin, leading to a reduction of events by about a factor of 5 in the range 500–2000 keV, though some of this reduction can be attributed to the exchange of the lemo cables.
FIG. 3: (Color online) Summed data spectrum for period A, compared to simulated activities of the individual components. This clearly shows that events from the passivation paint on the detector surfaces contribute a significant background to the range of interest (2–3 MeV). The excess of events below 3 MeV is thought to be due to backgrounds associated with the lemo cables and solder.

VI. ACHIEVABLE ENERGY RESOLUTION

The underground studies are not currently limited by energy resolution and, therefore, it was not considered necessary to use the highest quality of crystals in this set-up. However, as background levels are reduced the energy resolution will become important, since a sharp peak is especially important in reducing the contribution of the irreducible background of $2\nu\beta\beta$ events to the $0\nu\beta\beta$ peak region. The fraction of $2\nu\beta\beta$ events in the peak region, as a function of energy resolution (FWHM) can be approximated by [10]

$$F = \frac{8Q}{m_e} \left( \frac{\Delta E}{Q} \right)^6$$

(1)

With this in mind, additional studies were performed outside the underground experiment to determine the resolution achievable with CZT coplanar-grid detectors and to investigate possible improvements.

Fig. 4 shows a $^{228}\text{Th}$ spectrum measured with a typical ‘medium quality’ CZT detector, resulting in a resolution of 2.6% at 2614 keV but resolutions as good as 2.1% have been measured with COBRA crystals. With such a resolution, for the case of 90% $^{116}\text{Cd}$ isotopic enrichment, $2\nu\beta\beta$ decays will only contribute $2 \times 10^{-4}$ counts/(kg yr) to the 59 keV wide signal region (calculated using the observed half-life of $2.7 \times 10^{19}$ yrs [11]). This is already well below the required background levels shown in Fig. 4 but detectors with still better energy resolution are commercially available and are being considered for use in a future stage of the experiment.

A further experimental option to improve the energy resolution is cooling of the detector. This might be especially important for searches in the low energy range, for decays such as two neutrino double electron capture ($2\nu\text{ECEC}$) that produce a signal below 100 keV. First measurements of cooling from 24°C to 10°C revealed an improvement in energy resolution of a factor two below 100 keV and an improvement of 5% on the typical resolution at 2809 keV.

VII. DATA ANALYSIS

The data analysis consists of two independent parts: simulation of the possible double beta decays to determine detection efficiencies and a maximum likelihood peak search.

The predicted signals in the crystals were determined through a GEANT4 based Monte Carlo simulation utilising calculations from the Fortran Decay0 code [12]. $0\nu\beta\beta$ decays to ground state (g.s.) and excited states were simulated for each of the candidate isotopes contained in natural CdZnTe. For $\beta^+\beta^-$ transitions, calculations based on the light Majorana neutrino exchange mechanism were used for ($0^+ \rightarrow 0^+$) transitions, whilst right-handed currents were used in the calculation for ($0^+ \rightarrow 2^+$) transitions. As there is no general connection between ground state and excited state matrix elements, they must be explored separately for each isotope.

The energy, $E_{\text{peak}}$, and intensity of the dominant peak for each $\beta^+\beta^-$ decay were determined from these simulations and are given in table II. The efficiency for observation of the full peak energy, $\epsilon$, determined from the peak intensity generally decreases with increasing peak energy. For decays to excited states, gamma escape probabilities also play a part.

For the isotopes that decay through $\beta^+\beta^+$ transitions,

\footnote{Only excited states already included in the Decay0 code were used, therefore some transitions, namely those to the higher excited states of $^{120}\text{Te}$, have been omitted from this analysis.}
### Table II: Specifications of the fits performed for $\beta^+\beta^-$ peaks.

| Isotope Decay | $E_{\text{peak}}$ (MeV) | $\Delta E_{\text{peak}}$ (%) | $\epsilon$ (%) | Fit range (MeV) |
|---------------|--------------------------|------------------------------|----------------|----------------|
| $^{116}$Cd to g.s | 2.609 | 4.7–7.6 | 66.5 | 2.21–3.20 |
| $^{130}$Te to g.s | 2.529 | 4.8–7.8 | 70.9 | 2.21–3.20 |
| $^{130}$Te to 536 keV | 1.993 | 5.0–8.5 | 61.2 | 1.70–2.28 |
| $^{116}$Cd to 1294 keV | 1.511 | 5.4–9.4 | 74.4 | 1.20–1.78 |
| $^{116}$Cd to 1757 keV | 1.048 | 6.0–11.0 | 60.4 | 0.90–1.30 |
| $^{70}$Zn to g.s | 1.001 | 6.1–11.3 | 93.3 | 0.60–1.30 |
| $^{128}$Te to g.s | 0.868 | 6.5–12.2 | 94.8 | 0.60–1.30 |
| $^{116}$Cd to 2027 keV | 0.778 | 6.8–12.9 | 67.4 | 0.50–1.20 |
| $^{116}$Cd to 2112 keV | 0.693 | 7.1–13.8 | 77.3 | 0.50–1.00 |
| $^{116}$Cd to 2225 keV | 0.580 | 7.7–15.4 | 76.6 | 0.50–1.00 |

The FWHM ($\Delta E_{\text{peak}}$) at that peak energy (range for all 6 data subsets), the efficiency, $\epsilon$, for observing that peak determined from simulations and the energy range over which the fit was performed. Note that decays not separated by a horizontal line were fit together.

A maximum likelihood fit was performed to determine the most likely number of signal events, $\theta_s$, over the combined data-set. Parameters describing the background were allowed to vary between crystals and data collection periods, but the $0\nu\beta\beta$ signal rate was assumed to be constant throughout. $i.e.$ Different background parameters were applied to different data subsets to allow for the varying background rates (indicated in table I) but the normalised background distributions fitted to each data subset were found to agree within errors for each fit scenario.

For $\beta^-\beta^-$ modes, $\theta_s$ enters the fit through the amplitude of a gaussian peak with width determined by the calibrated resolution of the relevant data subset. The range of peak widths (FWHM) for each fitted peak are given in table I along with the energy range used for each fit. Simulations showed that a range of ($E_{\text{peak}} \pm 3\Delta E$) or greater was required for each peak-search in order to adequately characterise the background continuum. The close proximity of some predicted signal peaks required these ground-state transition signals to be determined simultaneously: $^{116}$Cd and $^{130}$Te were fit together and the $^{70}$Zn and $^{128}$Te peaks were also fit simultaneously. Transitions to excited states are expected to be significantly suppressed with respect to ground state transitions due to phase-space arguments, so any contribution of excited state decays to the fitted peaks for ground-state transitions is assumed to be negligible. The limit for each signal arising from a transition to an excited state was determined in a separate fit. The high-threshold (> 600 keV) data set was used for all $\beta^-\beta^-$-mode peak searches except the decays to the third and fourth excited states of $^{116}$Cd.
The majority of spectra predicted for $\beta^+\beta^+$-mode decays have multiple peaks, each significantly smaller in amplitude than those arising from $\beta^-\beta^-$ decays to the ground state, thus justifying separate treatment in the analysis. Due to the complexity of these spectra, to determine the most likely number of signal events, $\theta_s$, the most likely scaling factor for the entire simulated spectrum, was extracted from the likelihood fit. For each decay the simulated spectrum was normalised to unity and convolved with the relevant resolution function for each data subset. The range for each fit (as given in table IV) was determined by Monte Carlo for each fit in order to calculate the fit probability. The $\chi^2$-fit is included in the fit.

For each fit, a chi-squared goodness of fit test was performed. However, due to the low statistics, this parameter was not expected to follow a true chi-squared distribution. Therefore, the distribution of the $\chi^2$ statistic was determined by Monte Carlo for each fit in order to calculate the fit probability. The $\chi^2$, and its respective probability, determined for each $\beta^-\beta^-$-search in table III. For the $\beta^+\beta^+$-decays, its calculated for each fit, the goodness of fit was also all $>80\%$. As a cross-check, fits were repeated with $\theta_s$ fixed to zero for each signal, all of which resulted in either negligible change or a decrease in the goodness of fit.

A detailed study of possible systematic effects was performed and the dominant uncertainties were found to be those that affect the number of candidate nuclei. Uncertainties in energy resolution and livetime, and possible biases in the fit procedure, were all found to have a negligible effect on the analysis. However, the possible existence of a dead-layer at the surface of the crystals could reduce the active volume by up to 10%. Observations of $\alpha$-particles from the passivation paint indicate that the dead layer is probably smaller than this but the effect was taken into account in a conservative manner by using $N_{iso} \times 0.9$ in the limit calculation. Due to the production process, the zinc content is only known to be in the range 7–11% resulting in an uncertainty in both the number of zinc nuclei and the number of cadmium nuclei. To ensure conservative half-life limits, 7% zinc content was used when calculating the number of zinc nuclei, and 11% zinc content was used in calculations for cadmium isotopes.

\section*{VIII. Results}

Table \textbf{III} shows all the $\beta^-\beta^-$ decay half-life limits (90\% C.L.) calculated in this work and table \textbf{IV} shows the limits calculated for $\beta^+\beta^+$ decays. The limits obtained from the combined fit to the $^{116}$Cd and $^{130}$Te $0\nu\beta\beta$ decay events (top) and $^{120}$Te $0\nu$EC/EC to ground state events (bottom) with the total high-threshold data set shown for the range of each fit. Also shown separately is the contribution from the fitted background.

\section*{IX. Summary}

A new double beta decay experiment, COBRA, is planned using a large amount of CZT semiconductor detectors. A low rate of background events in the peak
TABLE IV: 90% confidence limits obtained for all $\beta^+\beta^+$ decay peaks. The $\chi^2$/DoF goodness of fit parameter, and respective probability determined through Monte Carlo are included. The 90% confidence limits have conservative systematic uncertainties applied and are compared to the world best limits. \textsuperscript{†}Quoted limit is 68% not 90%.

| Isotope and Decay | Range (MeV) | $T_{1/2}$ limit (years) | This work | World Best |
|-------------------|-------------|-------------------------|-----------|------------|
| $^{110}$Cd to g.s | $0.5-1.3$   | $2.78 \times 10^{17}$   | $2.4 \times 10^{18}$ | $17$ |
| $^{110}$Cd to g.s | $0.7-1.3$   | $1.19 \times 10^{17}$   | $7.0 \times 10^{16}$ | $17$ |
| $^{120}$Te to g.s | $0.5-2.0$   | $1.21 \times 10^{17}$   | $2.2 \times 10^{16}$ | $21$ |
| $^{120}$Te to g.s | $1.2-2.0$   | $2.68 \times 10^{15}$   | $-         | -         |
| $^{120}$Te to g.s | $0.5-2.0$   | $9.72 \times 10^{15}$   | $-         | -         |
| $^{106}$Cd to g.s | $0.5-2.0$   | $4.50 \times 10^{17}$   | $2.4 \times 10^{20}$ | $22$ |
| $^{106}$Cd to g.s | $1.4-3.0$   | $7.31 \times 10^{18}$   | $3.7 \times 10^{20}$ | $22$ |
| $^{106}$Cd to g.s | $1.4-3.0$   | $5.70 \times 10^{16}$   | $1.5 \times 10^{17}$ | $23$ |
| $^{106}$Cd to g.s | $0.5-2.0$   | $1.81 \times 10^{17}$   | $1.6 \times 10^{20}$ | $22$ |
| $^{106}$Cd to g.s | $0.8-2.0$   | $9.86 \times 10^{17}$   | $2.6 \times 10^{20}$ | $22$ |

TABLE III: Results from fits for $\beta^+\beta^+$ decay peaks. The $\chi^2$/DoF goodness of fit parameter, and respective probability determined through Monte Carlo are included. The 90% confidence limits have conservative systematic uncertainties applied and are compared to the world best limits. New world best values from this work are shown in bold. The energy range used for each fit is also included.

X. ACKNOWLEDGEMENTS

This research was supported by PPARC and the Deutsche Forschungsgemeinschaft (DFG). We thank G. Cowan for useful discussions, V. Tretyak for providing the Decay0 code and eV-PRODUCTS for their support. In addition, we thank the Forschungszentrum Karlsruhe, especially K. Eitel, for providing the material for the neutron shield. We thank the mechanical workshop of the University Dortmund for their support and the Laboratori Nazionali del Gran Sasso (LNGS) for offering the possibility to perform measurements underground. The work has been supported by the TA-DUSL activity of the ILIAS program (Contract No. RI3-CT-2004-506222) as part of the EU FP6 programme.

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