Experimental study of ^{113}Cd β decay using CdZnTe detectors

C. Goessling,[1] M. Junker,[2] H. Kiel,[1] D. Muenstermann,[1] S. Oehl,[1] and K. Zuber[3,4]
[1]*Lehrstuhl für Experimentelle Physik IV, Universität Dortmund, Otto-Hahn Str. 4, D-44227 Dortmund, Germany*
[2]*Laboratori Nazionali del Gran Sasso, Assergi, Italy*
[3]*Denys Wilkinson Laboratory, University of Oxford, Keble Road, Oxford OX1 3RH, United Kingdom*
[4]*Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom*
(Received 26 July 2005; published 30 December 2005)

A search for the fourfold forbidden β decay of ^{113}Cd has been performed with CdZnTe semiconductors. With 0.86 kg · d of statistics a half-life for the decay of $T_{1/2} = [8.2 \pm 0.2(\text{stat.})^{+0.2}_{-1.0}(\text{sys.})] \times 10^{15}$ yr has been obtained. This is in good agreement with published values. A comparison of the spectral shape with the one given on the Table of Isotopes Web page shows a severe deviation.

DOI: 10.1103/PhysRevC.72.064328 PACS number(s): 23.40.−s, 27.60.+j

I. INTRODUCTION

In past decades the investigation of β decay played a major role in understanding the structure of weak interactions. Nowadays, such studies seem to be a little bit out of fashion, but there are still a lot of interesting problems to be investigated. Among them is the measurement of higher order transitions such as fourfold forbidden nonunique decays ($\Delta I = 4$ and no change in parity). Their log ft values, a characteristic quantity for various β decay modes containing the Fermi function and half life, are larger than 20, and correspondingly half-lives around 10^{15} yr and longer have to be measured. Only three isotopes of this type are known, ^{50}V, ^{113}Cd, and ^{115}In. No β spectrum measurement is reported for ^{50}V and only two recent half-life determinations are available for ^{115}In [1,2].

The transition $^{113}\text{Cd} \rightarrow {}^{113}\text{In}$ is characterized as a $1/2^+ \rightarrow 9/2^+$ transition with a log ft value estimated to be 23.2 [3] (Fig. 1). A first attempt to measure this decay with a small CdTe device resulted in a rather large half-life range of $(4-12) \times 10^{15}$ yr as reported in Ref. [4]. Two more recent measurements using $CdWO_4$ exist. One measurement using the material as a scintillator resulted in a half-life of $(7.7 \pm 0.3) \times 10^{15}$ yr [5]. The second experiment used $CdWO_4$ as a cryogenic bolometer and obtained a half-life of $[9.0 \pm 0.5(\text{stat.}) \pm 1(\text{sys.})] \times 10^{15}$ yr [6]. Here, we report on a completely independent new experimental approach by using room temperature CdZnTe semiconductor detectors. The measurement has been performed within the program of test measurements for the new COBRA double β decay experiment [7].

II. EXPERIMENTAL SETUP

The data presented are obtained with four 1 cm^3 CdZnTe detectors provided by eV-PRODUCTS based on coplanar grid technology (i.e., reading out only the electron signal). Measurements have been performed in the Gran Sasso Underground Laboratory (LNGS) in Italy, providing a shielding of about 3500 mwe. The four bare detectors are mounted in a copper brick with all preamplifier electronics moved to about 25 cm distance. This copper brick itself is part of a (20 cm)^3 cube made out of electropolished copper and a further passive shielding of 15 cm of lead. The whole setup is located in a Faraday cage made from copper plates. The cage is surrounded by a neutron shield, consisting of 7-cm-thick boron-loaded polyethylene plates with an additional 20 cm of paraffin wax at the bottom. The full paraffin shielding was finished at a later stage.

The energy resolution and stability of the detectors is calibrated regularly with the help of ^{137}Cs, ^{60}Co, and ^{228}Th sources. For the four detectors a CAMAC-based data acquisition system is used. The signals are fed into four 13-bit peak-sensing ADCs (types LeCroy 3511 and 3512).

III. DATA EXTRACTION

The total measuring period consists of 4781 h. Each individual run is limited to 1h. However, some data cleaning has been necessary for this low-energy range. Because of noise problems several run periods had to be performed with rather high discriminator thresholds. As a consequence, one detector cannot be used for the low-energy analysis presented here. Thus 25% of the total data had to be rejected. In addition, some data sets had to be rejected because of short-term distortions of the detectors. If the event rate per hour is histogramed, the distorted runs can easily be identified by having exceptional high event rates (Fig. 2). This has been done for every detector independently. In this way a further 57 runs were discarded. An instability in the threshold leads to a loss of 12 days for one of the ADCs.

For calibration purpose rather high energetic gamma sources were used; thus the data sets have been checked independently for background lines in the region of the ^{113}Cd decay. It has been found that the 351.9-keV γ line, which is located just next to the endpoint of the β spectrum, gives a suitable handle on the quality of the calibration in the low-energy region. This line originates from ^{214}Pb decay and is part of the natural decay chain of ^{238}U. The final set of good data has been selected by checking the position of this γ line for each measurement period and taking its position into account for the final calibration. The final sample comprises statistics of 0.86 kg·d.

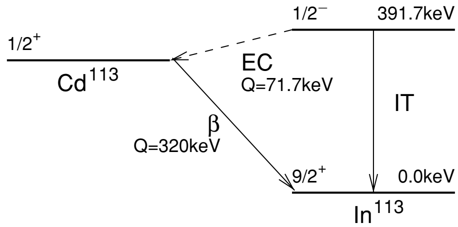

FIG. 1. Level scheme of the ^{113}Cd decay.

IV. RESULTS

A. Half-life of ^{113}Cd decay

The spectral shape of the energy spectrum of electrons emitted in a fourfold forbidden nonunique β decay cannot be predicted by theory; hence we follow the procedure described in Ref. [5]. A model spectrum is built using the form

$$N(E) = F(Z, E)p(E + mc^2)(Q - E)^2 S(E), \qquad (1)$$

with $F(Z, E)$ as the Fermi function, Q the endpoint energy of the β spectrum, p the electron momentum, and E the kinetic energy of the electron. The correction function $S(E)$ is assumed to be a polynomial of the form

$$S(E) \sim p^6 + C_1 p^4 q^2 + C_2 p^2 q^4 + C_3 q^6, \qquad (2)$$

with q as the neutrino momentum. Such a high-order polynomial provides a reasonable fit and is motivated by theoretical arguments on fourfold forbidden unique β decay. However, the decay of ^{113}Cd is known to be nonunique and it is not obvious that this spectral shape is correct. The correction functions used in this analysis are based on the measurement of the coefficients given by Ref. [5].

The corresponding model spectrum is folded with the detection efficiency, calculated with a Monte Carlo simulation based on GEANT4. Owing to the short range of low-energy electrons in CdZnTe the effect on the spectrum is marginal

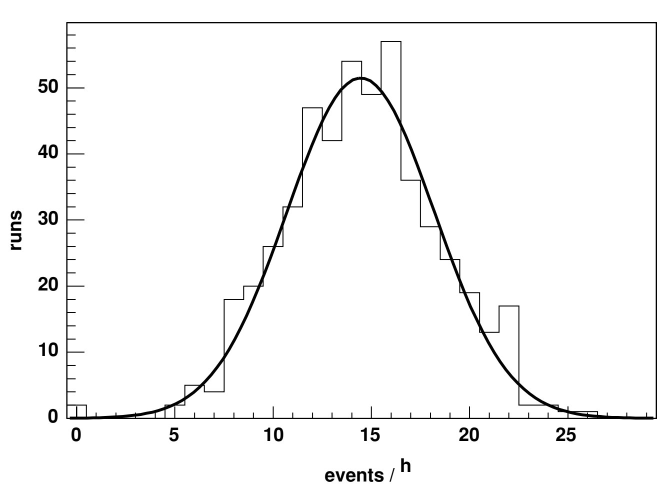

FIG. 2. Event rate distribution of individual runs for a selected period of time, shown for the energy range of 100–320 keV. As can be seen the runs are well described by a Gaussian distribution. Runs with electronic disturbances would show up with rates well beyond 30 events per hour and can be easily rejected.

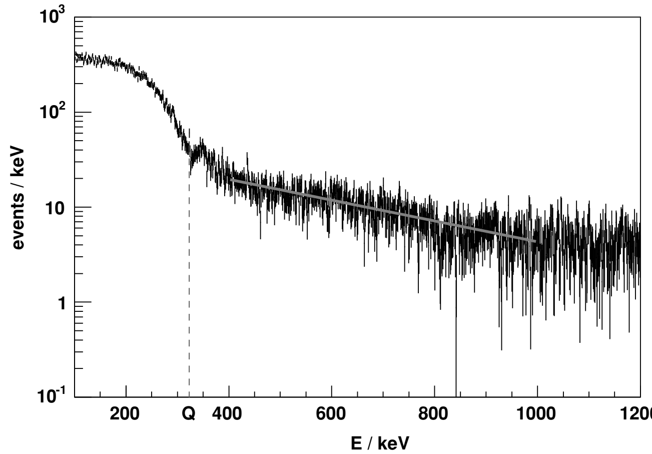

FIG. 3. The summed low-energy spectrum of three CZT detectors. The white curve corresponds to a exponential fit in the region 400–1000 keV. Also shown is the Q value of the ^{113}Cd decay at 320 keV.

and corresponds to only a modest shift of the maximum of 0.2%.

To get a more sophisticated energy resolution for the low-energy regime, intensive post calibrations have been done using γ-ray sources in the form of ^{152}Eu, ^{133}Ba, ^{57}Co, ^{241}Am, ^{60}Co, and ^{137}Cs sources. The measurements can be described well by a linear dependence of the energy resolution as a function of energy in the range of 100 keV to 1.4 MeV. For the collected data the energy resolution is extrapolated from the high-energy calibrations done during the measurements, resulting in an energy resolution (FWHM) averaged over the detectors of

$$\Delta E(\text{keV}) = 4.7\% \cdot E(\text{keV}) + 28\,\text{keV}. \qquad (3)$$

Before fitting the experimental data with the polynomial form, a background component is subtracted from the single spectra. Therefore, an exponential background of the form

$$B(E) = B_1 \exp(-E/B_2) \qquad (4)$$

is fitted first, well motivated by the observed data (Fig. 3). To avoid any contribution of the ^{113}Cd β spectrum itself the background fit is done using the energy range from 400 to 1000 keV. The noise threshold is not included in the fit because it is well below the chosen boundaries for the spectral fit described in the following. Before performing the fit, the 351.9-keV γ line with its Compton spectrum is removed for each detector independently. Again, this is based on a GEANT4 simulation of energy deposition of external 351.9-keV γs in a CdZnTe detector, smeared with the measured energy resolution.

An absolute calibration of the detectors has been performed after the measurements. Here, a ^{137}Cs source has been used to determine the relative efficiency of the detectors. When normalized to the most efficient detector, the remaining two had efficiencies of 67% and 80%, respectively [8]. The major additional uncertainty is the active volume. However, various information about the detectors provided by the supplier and the observation of α particles created at the surface lead to

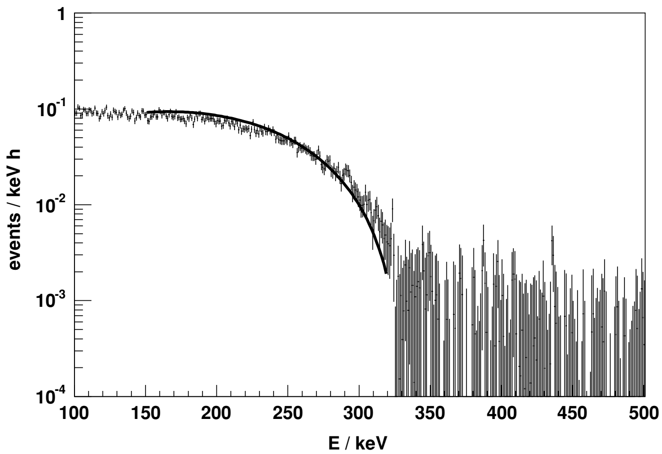

FIG. 4. The summed low-energy spectrum of three CZT detectors after background subtraction. The shoulder of ^{113}Cd is the most prominent feature in that energy range. Also shown is the best spectrum of the type given in [5] describing the data. Note, that only the normalization was varied; the solid curve is not a fit to the spectral shape.

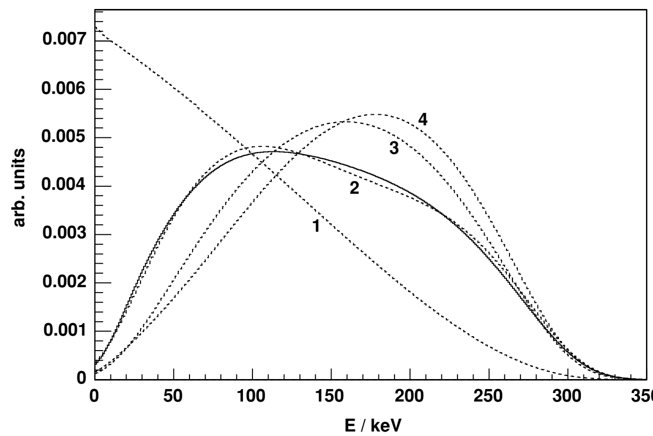

FIG. 5. Various possible spectra discussed for ^{113}Cd decay including the energy smearing caused by the energy resolution of the detectors. Shown as dashed lines are the spectra of [5] (4) and [6] (3), a rescaled ^{115}In spectrum [10] (2), and the Table of Isotopes Web page spectrum [11] (1) before applying a cut on the noise threshold. The solid curve corresponds to the best fit of the measured spectrum described in this paper.

a conservative upper limit of regions with reduced signals of 10%.

Finally, the three individual spectra are summed by taking the efficiency of the three detectors into account. The fit interval ranges from 120 to 310 keV, and the endpoint of the expected spectrum using the latest number on atomic masses is $Q = 320 \pm 3$ keV [9]. The fit range contains a total of about 37,000 events; 12.6% can be ascribed to background.

Systematic effects have been checked by varying the ranges of the fits for the signal and the background regions, as well as the energy resolution, which has been folded with the theoretical spectrum. All these variations cause an effect on the calculated half-life of less than 1%. The slight difference in spectral shape between the two best-fit spectra of [5] and [6] is negligible, being washed out by the energy resolution. As the typical Zn admixture is 7%–11%, the uncertainty in the amount of ^{113}Cd in the detector material is 1.8%.

The combined energy spectrum is shown in Fig. 4. Using the spectral shape of Ref. [5] including their best fit values results in a decay rate of $(15.98 \pm 0.41)\,\mathrm{h}^{-1}$ and thus a half-life of

$$T_{1/2} = [8.2 \pm 0.2(\text{stat.})^{+0.2}_{-1.0}(\text{sys.})] \times 10^{15}\ \text{yr}. \tag{5}$$

This half-life is in good agreement with the values quoted in Refs. [5,6]. Note that only the normalization of the fixed spectral shape has been changed; the half-life has not been determined by a fit to the spectral shape. The individual numbers including only statistical uncertainties are $T_{1/2} = (8.1 \pm 0.2) \times 10^{15}$ yr, $\chi^2/\text{ndf} = 117.2/169$ (Detector 1), $T_{1/2} = (7.5 \pm 0.3) \times 10^{15}$ yr, $\chi^2/\text{ndf} = 160.4/169$ (Detector 3), and $T_{1/2} = (9.3 \pm 0.4) \times 10^{15}$ yr, $\chi^2/\text{ndf} = 318.1/169$ (Detector 4).

B. Spectral shape of the ^{113}Cd β spectrum

Trying a real fit to the data to determine a half-life suffers from a number of problems: Several options exist to describe a fourfold forbidden nonunique β decay spectrum. They are compiled in Fig. 5 and are already smeared with the energy resolution. The spectra of Refs. [5] and [6] agree reasonably well. Another option is to compare the spectral shape with the one obtained for the fourfold forbidden nonunique βdecay of ^{115}In and to rescale it to the Q value of ^{113}Cd. In Ref. [1] a polynomial is introduced to describe the ^{115}In spectrum. During the development of a low-energy solar neutrino detector based on an In-loaded scintillator (LENS) the β spectrum of ^{115}In has been remeasured and their best-fit values [10] were used to obtain the spectrum shown in Fig. 5. Last, but not least, the spectrum from the Table of Isotopes Web page can be used [11].

The measured sum spectrum obtained with the CdZnTe detectors agrees reasonably well with the one expected from ^{115}In. However, it would have a significant effect on the event number and thus the half-life, if extrapolated below 120 keV, because the maximum is below 100 keV. Additionally, in this energy region the noise threshold for the measurement has to be considered. Approximating the threshold by an exponential function and subtracting it from the total spectrum results in a residual that looks more like the spectrum from Refs. [5] and [6]. Thus, it was decided to use their spectral shape, because they have already performed measurements of the ^{113}Cd spectrum below 100 keV. To solve this issue of different spectral shapes completely, the spectrum has to be measured down to at least 50 keV, which will be possible with the next step of COBRA, consisting of 64 detectors.

In addition to the polynomial approach, the electron energy spectrum of the Table of Isotopes Web page has been applied [11]. The efficiency correction and energy folding is done analogously to the procedure described before. This spectrum approaches zero only in the lowest energy bin. As can be seen in Fig. 6 the spectral shape is not reproduced in the data. The spectra are normalized to the total number of events in the range of 100–320 keV.

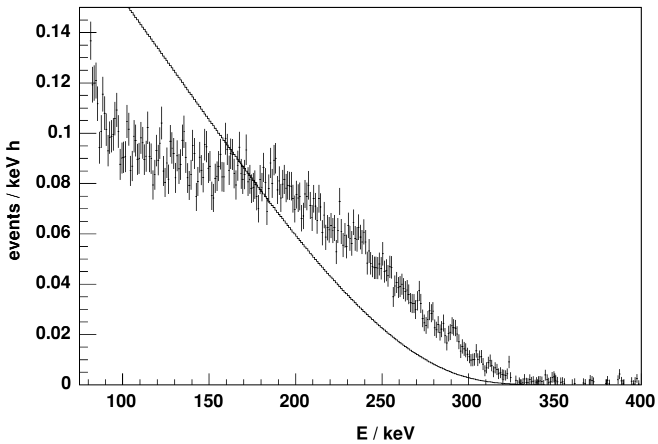

FIG. 6. Comparison of the observed energy spectrum with the spectral shape taken from the Table of Isotopes Web page [11], assuming a Q value of 320 keV.

V. SUMMARY

A new double β decay experiment COBRA is planned using CdZnTe semiconductor detectors. As a side product of the test measurements for this project, the fourfold forbidden nonunique β decay of ^{113}Cd has been measured. A first observation using four crystals clearly shows the signal, but only three of them could be used for a reliable half-life determination. The half-life measurements obtained from each of the detectors are in good agreement with each other and with published values. In the near future 64 CdZnTe detectors will be running, allowing a precision measurement and systematic studies of this decay by extracting single independent values for each detector. This will also include lower noise thresholds, allowing removal of the uncertainty that arises from the lack of knowledge of the spectral shape.

ACKNOWLEDGMENTS

We thank R. Firestone and J. Suhonen for useful discussions and comments. We are grateful to the LENS collaboration, especially S. Schoenert and L. Pandola, for providing their new ^{115}In spectrum parameters. 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 enabling us to perform measurements underground. K. Zuber is supported by a Heisenberg-Fellowship of the Deutsche Forschungsgemeinschaft.

[1] L. Pfeiffer , A. P. Mills, E. A. Chandross, and T. Kovacs, Phys. Rev. C **19**, 1035 (1979).
[2] I. Barabanov *et al.*, Nucl. Phys. B (Proc. Suppl.) **143**, 559 (2005).
[3] B. Singh *et al.*, Nucl. Data Sheets **84**, 487 (1998).
[4] L. Mitchell and P. Fischer, Phys. Rev. C **38**, 895 (1988).
[5] F. Danevich *et al.*, Phys. At. Nucl. **59**, 5 (1996).
[6] A. Alessandrello *et al.*, Nucl. Phys. B Proc. Suppl. **35**, 394 (1994).
[7] K. Zuber, Phys. Lett. **B519**, 1 (2001).
[8] H. Kiel, http://hdl.handle.net/2003/21509, Ph.D. thesis, University of Dortmund, 2005.
[9] G. Audi *et al.*, Nucl. Phys. **A729**, 337 (2003).
[10] S. Schoenert and L. Pandola (private communication).
[11] http://ie.lbl.gov (2004).