Pulse-shape discrimination techniques for the COBRA double beta-decay experiment at LNGS

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Abstract. In modern elementary particle physics several questions arise from the fact that neutrino oscillation experiments have found neutrinos to be massive. Among them is the so far unknown nature of neutrinos: either they act as so-called Majorana particles, where one cannot distinguish between particle and antiparticle, or they are Dirac particles like all the other fermions in the Standard Model. The study of neutrinoless double beta-decay (0νββ-decay), where the lepton number conservation is violated by two units, could answer the question regarding the underlying nature of neutrinos and might also shed light on the mechanism responsible for the mass generation. So far there is no experimental evidence for the existence of 0νββ-decay, hence, existing experiments have to be improved and novel techniques should be explored. One of the next-generation experiments dedicated to the search for this ultra-rare decay is the COBRA experiment. This article gives an overview of techniques to identify and reject background based on pulse-shape discrimination.

1. The COBRA experiment at LNGS
The aim of the Cadmium-Zinc-Telluride 0-ν Double Beta Research Apparatus (COBRA) is to search for the rare neutrinoless double beta-decay (0νββ-decay) with solid state detectors. The detectors are made of CdZnTe – an intrinsic, commercially available semiconductor at room temperature. Several candidate isotopes for a double beta-decay are naturally present in this material ensuring a high intrinsic detection efficiency. The most promising is $^{116}$Cd with a Q-value of 2.8 MeV, which is well above the highest prominent γ-lines occurring from natural radioactivity. Currently, a demonstrator setup [1] at the underground facility LNGS in Italy built of 4×4×4 monolithic, calorimetric detectors in a coplanar-grid (CPG) configuration is used to investigate the requirements to operate CdZnTe detectors stably under ultra low-background conditions [2, 3]. Each detector has a size of 1 cm$^3$ and is read out via pulse-shape sampling using a FADC (100 MHz, 12-bit). This allows for a complex offline analysis and event classification.

2. Background reduction via pulse-shape discrimination
Due to the large difference in the charge mobility of electrons and holes in CdZnTe, a special electrode readout design has to be used to compensate for this effect. The CPG anode consists of two interlocking comb-shaped grids with a small grid bias (GB) between them, referred to as collecting anode (CA) and non-collecting anode (NCA). A bias voltage (BV) between the cathode and anode plane causes the charge cloud created in a particle interaction to drift through the bulk of the detector. The deposited energy and depth of an interaction can be reconstructed based on the Shockley-Ramo theorem [4] and the known weighting potential (see Figure 1). This potential only depends on the detector geometry and can be used to predict the signal shape of the reconstructed charge pulse for different interaction points in a single detector.
2.1. Identification of lateral surface events

Interactions near the lateral detector walls are known to be affected by distortions of the weighting potential (see Figure 1). This causes characteristic features in the charge pulse, which can be used to distinguish between central and so-called lateral surface events (LSEs) [5]. Figure 2 illustrates pulse-shapes that are typically for LSEs and central events. Depending on the anode configuration, the charge pulse shows an early rise time or a prominent dip before rising to the full height. Both effects can be described quantitatively by defining selection criteria for each pulse. In combination with a cut on the interaction depth, α-emitting surface contaminations can be reduced by about one order of magnitude in the region of interest of $^{116}$Cd.

Figure 2. Typical pulse-shapes for near CA-side (left), central (middle) and near NCA-side interactions (right). The outer traces feature an early rise time or a characteristic dip of the charge signal (green) which can be quantified and compared to central events with smaller values.

2.2. Discrimination of single-site and multi-site events

The signal of a $0\nu\beta\beta$-decay is expected to be a single crystal event with a point-like energy deposition, hence, all multi-detector events and multiple interactions within the same crystal can be vetoed as background. The discrimination of signal-like single-site events (SSEs) and multi-site events (MSEs) is one of the key instruments to further reduce background. MSEs are typically caused by multiply-scattered highly energetic photons. The corresponding pulse shapes feature a plateau region in the charge equivalent difference pulse of CA and NCA. Hence, the number of peaks above an empirical threshold in the derivative of the charge pulse can be used to distinguish between those event typologies as illustrated in Figure 3.

3. Summary and further activities

The COBRA collaboration developed a set of techniques to distinguish between the expected signal of the ultra-rare $0\nu\beta\beta$-decay and background-like events by means of pulse-shape discrimination. Using those, a peak search for five $\beta^-\beta^-\text{g.s. to g.s.}$ transitions was performed with 216 kg d of data from the demonstrator at LNGS. No signal has been found and 90% credibility limits in the range of $10^{21}$ years based on a Bayesian analysis could be set for all investigated transitions. For one isotope, $^{114}$Cd, the world leading half-life limit was set [3]. To
increase the intrinsic detector efficiency and to reduce the impact of surface contaminations, a new detector generation is under investigation. The collaboration received funding from the German Research Foundation (DFG) to develop and build a prototype detector module consisting of nine CdZnTe crystals with a size of $2\times2\times1.5$ cm$^3$. Of special interest is a new type of CPG detector with a segmented anode plane, which is referred to as quad-CPG detector. Each of the four sectors acts as an individual CPG detector providing improved veto capabilities.

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References
[1] Ebert J et al, 2016, The COBRA demonstrator at the underground laboratory LNGS, Nucl. Instrum. Meth. A 807, 114-120
[2] Ebert J et al, 2016, Long-term stability of underground operated CZT detectors based on the analysis of intrinsic $^{113}$Cd $\beta^-$-decay, Nucl. Instrum. Meth. A 821, 109-115
[3] Ebert J et al, 2016, Results of a search for neutrinoless double-beta decay using the COBRA demonstrator, Phys. Rev. C 94
[4] Fritts M et al, 2013, Analytical model for event reconstruction in coplanar grid CdZnTe detectors, Nucl. Instrum. Meth. A 708, 1-6
[5] Fritts M et al, 2014, Pulse-shape discrimination of surface events in CdZnTe detectors for the COBRA experiment, Nucl. Instrum. Meth. A 749, 27-34
[6] Ebert J et al, 2016, Characterization of a large CdZnTe coplanar quad-grid semiconductor detector, Nucl. Instrum. Meth. A 806, 159-168