The neutrinoless double beta decay CROSS experiment: demonstrator with surface sensitive bolometers

A. Zolotarova[1], I.C. Bandac[2], A.S. Barabash[3], V. Berest, L. Bergé[5], Ch. Bourgeois[5], J.M. Calvo-Mozota[2], P. Carniti[6], M. Chapellier[5], M. de Combarieu[1], I. Dafinei[7], F.A. Danevich[8], L. Dumoulin[5], F. Ferri[1], A. Giuliani[5], C. Gotti[6], Ph. Gras[1], E. Guerard[5], A. Ianni[9], H. Khalife[1], S.I. Konovalov[3], P. Loaiza[5], M. Madhukuttan[5], P. de Marcillac[5], R. Mariam[5], S. Marnieros[5], C.A. Marrache-Kikuchi[5], M. Martinez[10], C. Nones[1], E. Olivieri[5], G. Pessina[6], D.V. Poda[5], Th. Redon[5], J.-A. Scarpaci[5], V.I. Tretyak[8], V.I. Umatov[3], M.M. Zarytskyy[3]

[1] IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
[2] Laboratorio Subterráneo de Canfranc, 22880 Canfranc-Estación, Spain
[3] National Research Centre Kurchatov Institute, Institute of Theoretical and Experimental Physics, 117218 Moscow, Russia
[4] Taras Shevchenko National University of Kyiv, Kyiv, Ukraine
[5] Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
[6] INFN, Sezione di Milano Bicocca, I-20126 Milano, Italy
[7] INFN, Sezione di Roma, I-00185, Rome, Italy
[8] Institute for Nuclear Research of NASU, 03028 Kyiv, Ukraine
[9] INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi(AQ), Italy
[10] Fundación ARAID & Centro de Astropartículas y Física de Altas Energías, Universidad de Zaragoza, Zaragoza 50009, Spain

E-mail: anastasiia.zolotarova@cea.fr

Abstract. The CROSS experiment is proposing to use a new technology of surface sensitive bolometers for low-background neutrinoless double beta decay searches. Efficient rejection of surface α and β events will allow to reach background in the region of interest below than 10^{-4} cnts/keV/kg/yr. The isotopes of interest, which are ^{130}Te and ^{100}Mo, are investigated with TeO_2 and Li_2MoO_4 bolometers. The surface sensitivity is achieved thanks to the evaporation of thin metallic film on the crystal surface that modifies the pulse shape of near-surface events. An investigation of various pulse shape parameters was performed. The analysis shows that one of the best parameters for discrimination is the integrated area of the raw signal both for TeO_2 and Li_2MoO_4 with Pd-Al (10 nm - 100 nm) bi-layer.

1. Introduction

Nowadays, double beta decay searches are an important point of interest in neutrino physics: the observation of neutrinoless double beta ($0\nu2\beta$) decay will give essential information on neutrino masses and nature as well as on lepton number violation [1]. The technological challenge for

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highly sensitive $0\nu 2\beta$ experiments includes the minimization of the background index in the region of interest. A ton-scale next generation bolometric experiment CUPID is aiming to reach the background index $\sim 10^{-4}$ cnts/keV/kg/yr and to cover fully the inverted ordering of neutrino masses [2]. If further improvements on sensitivities is required, new methods of background need to be developed and tested with a mid-scale demonstrator. The key feature of CROSS (Cryogenic Rare-event Observatory with Surface Sensitivity) is the active surface background rejection using bolometric detectors coated with thin metallic films. Such a film on the detector surface affects the conversion of the energy deposited by the particle interaction. The phonon reabsorption in the film leads to a modification of the pulse shape for close-to-film events. With the single-channel separation of surface α and β particles, the CROSS technology can be used for next-generation bolometric experiments, reaching a background index in the region of interest lower than 10^4 counts/keV/kg/yr.

2. Pulse-shape discrimination with CROSS technology

A key point of the CROSS project is the pulse-shape discrimination analysis - a careful investigation of all the differences in the shapes of the signals is required. The R&D phase of the experiment included cryogenic tests with several types of metallic films, described in [3],[4]. Both TeO_2 and Li_2MoO_4 bolometers were measured. In tests with aluminum coating an efficient α rejection was obtained, but no β discrimination by the pulse shape. Using palladium coating, we have demonstrated that usage of normal metal improves discrimination capability on β particles due to better thermalization of athermal phonons. But even with very thin (10 nm) Pd coating we face the problem of extra heat capacity, added by this film. To solve this issue, we used Al-Pd bi-layer (100 nm and 10 nm thick respectively, with Al on the top), which is becoming superconducting because of the proximity effect below T_C(Al-Pd) = 0.65 K.

To evaluate the efficiency of the pulse shape estimators, we use the discrimination power (DP) parameter. The DP is quantified as follows:

$$DP(\sigma) = \frac{\mu_{bulk} - \mu_{surface}}{\sqrt{\sigma^2_{bulk} + \sigma^2_{surface}}} \tag{1}$$

Where μ and σ are the parameters of the Gaussian fit of the pulse shape parameter at the energy of interest. We consider the discrimination acceptable when DP>3.2, which corresponds roughly to 99.9% rejection of background events.

Several pulse shape parameters were tested to select the best discrimination efficiency in the past [3]. So far the biggest DP was obtained with a parameter, that was comparing the average pulse, which is typically dominated by bulk events, and individual signal through a linear fit of their amplitudes at i-th moment of time. However, lower efficiency of this parameter was observed for measurements with TeO_2 with an Al-Pd bi-layer. A new study on pulse shape evaluation has demonstrated that the full area of the raw signal can be used as a pulse shape estimator with high efficiency. The area also characterizes energy release and can be sometimes used as an energy estimator instead of amplitude.

The following sections describe results, achieved on two compounds of interest with pulse shape discrimination, using the area as a pulse shape parameter. The coating is performed under vacuum — the residual pressure is typically 5 $\times 10^{-7}$ mbar. Before deposition of metallic film, an Ar bombardment is applied to remove a surface layer of about 1 nm. For the evaporation of coating material an electron gun is used, both Pd and Al evaporation are performed in the same vacuum chamber, with thickness controlled by piezoelectric quartz.

The cryogenic tests were performed in an aboveground pulse-tube cryostat in IJCLab, Orsay, France. The coated side of each crystal was facing a used uranium radioactive sources to test the detector surface sensitivity. They sources were created by drying up a drop of uranium acid solution on a copper foil. These sources provide two main α lines at $\sim$ 4.2 and $\sim$ 4.7 MeV from ^{238}U and ^{234}U respectively. Further disintegration ^{238}U to ^{234}Th and ^{234m}Pa provides a β spectrum with an end-point of 2.27 MeV.

2.1. PSD in TeO_2 with Pd-Al bi-layer
The cryogenic measurement of TeO_2 (20×20×10 mm^3) equipped with an NTD sensor and one surface covered with a Pd-Al (10-100 nm) bi-layer show that the discrimination capability between surface and bulk events is successfully achieved when using NTD (neutron transmutation doped) Ge thermistor for signal read-out. The data taking was performed at 15 mK. Using the area parameter, we can clearly distinguish the surface α and β events below the γ/muon band, see Fig. 1. After energy calibration (performed on the ^{214}Bi 609 keV line) we remark that α energy is strongly quenched with respect to the γ calibration. Also, we observe the variation of the discrimination power between the γ and α bands depending on the energy - discrimination improves with the decrease of the α energy, the DP value between α and muon bands ranges between 3.1-3.3.

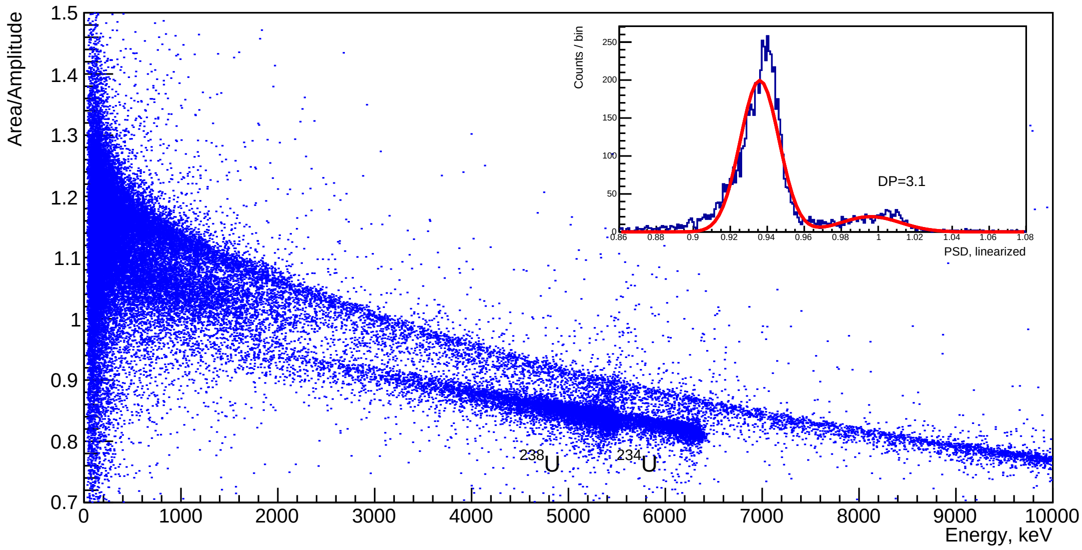

Figure 1. The area, used as PSD parameter is plotted as a function of the energy for a TeO_2 bolometer with Pd-Al film. In the inset, Gaussian fits of the surface and bulk event distributions allow us to extract the DP. The energy range used is 4.5-5.5 MeV. The two populations of separated events are clearly visible - α peaks (energy shifted due to quenching) and β events from the U source.

2.2. PSD in Li_2MoO_4 with Pd-Al grids
After successful tests with Pd-Al bi-layer, it was decided to further decrease the amount of material, used for surface coating and use grids instead of a simple film. The width of the grid lines was 70 μm and the spacing between each line was 700 μm. The measurement of Li_2MoO_4 (20×20×10 mm^3) equipped with an NTD sensor and one surface covered with a Pd-Al (10-100 nm) bi-grid using NTD was also performed at 15 mK. The detector was calibrated with intense ^{133}Ba source and calibrated with 356 keV γ line. Big shift of α lines energy was observed: the 4.2 MeV line appears at 7.4 MeV after γ calibration. This shift is connected to phonons

reabsorption in the film. The application of new pulse shape discrimination with the use of area showed significant improvement with respect to previously used parameters: the DP between α and muon bands has increased from $\sim$4.5 to $\sim$6-8, depending on the energy.

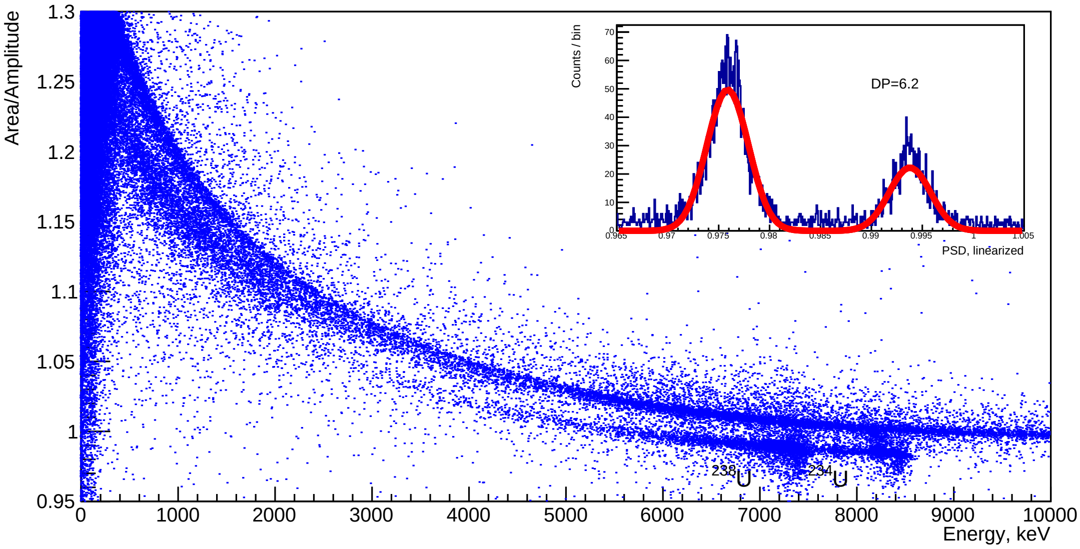

Figure 2. The area, used as PSD parameter is plotted as a function of the energy for a Li_2MoO_4 bolometer with Pd-Al grids. In the inset, Gaussian fits of the surface and bulk event distributions allow us to extract the DP. The energy range used is 7.0-8.0 MeV. The two populations of separated events are clearly visible - α peaks (energy shifted due to quenching) and β events from the U source.

3. Summary and perspectives

Small prototypes for the CROSS project demonstrate good particle discrimination with Pd-Al bi-layers both for TeO_2 and Li_2MoO_4 detectors. A new pulse shape evaluation parameter based on the area of the individual signals, was developed with promising results obtained. Definition of analysis procedure for pulse shape discrimination and selection of the events for future demonstrator are ongoing. The CROSS technology have to be confirmed in future on larger scale with cubic (45×45×45 mm) $\sim$280 g $Li_2^{100}MoO_4$ and $\sim$550 g $^{130}TeO_2$ bolometers. CROSS demonstrator will consist of at least 42 $Li_2^{100}MoO_4$ and 6 ^{130}Te cubic crystals with the goal to confirm robustness of technology for next-next generation experiments and to set a new limit on ^{100}Mo $0\nu2\beta$ half-life.

4. Acknowledgements

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