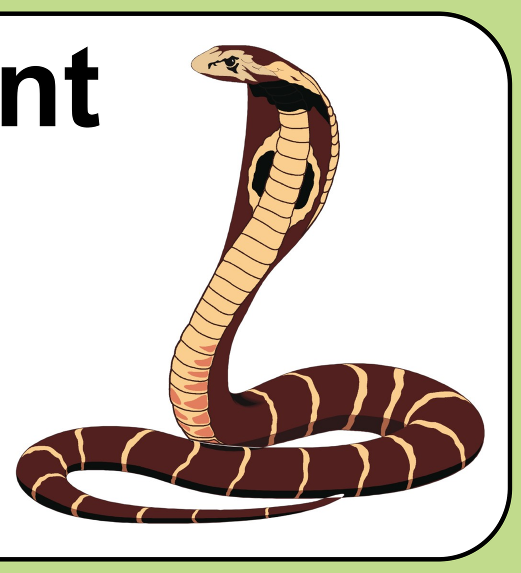
Status and Perspectives of the COBRA-Experiment



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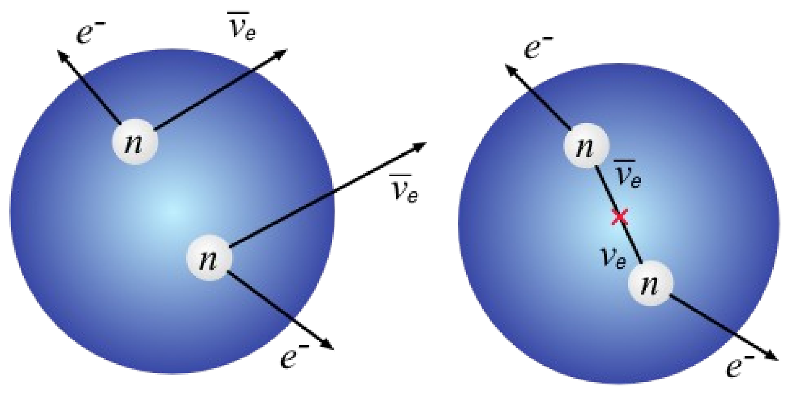
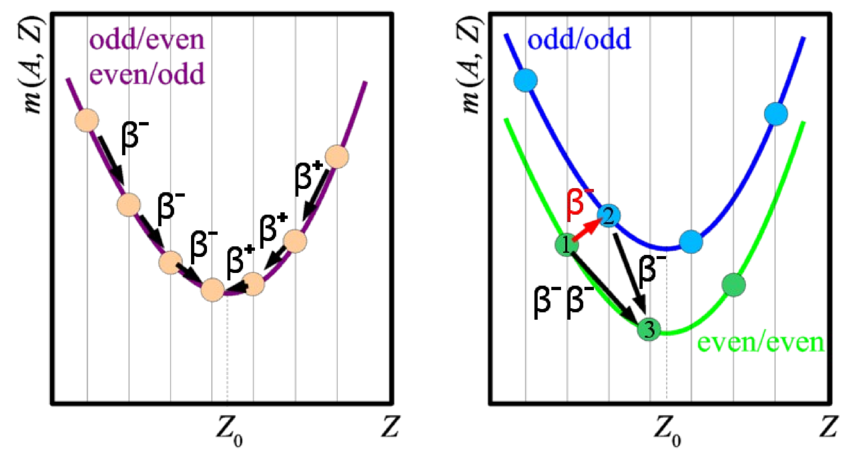
Double Beta Decay

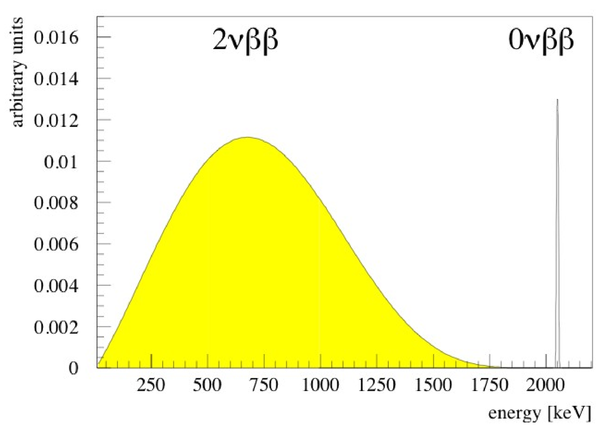
Some (even-even) nuclei cannot undergo beta decay for energetic reasons. However, they can decay to the next even-even nucleus by two consecutive decays, a second-order process and hence heavily suppressed: Half-lives are of the order of 10^{20} years.

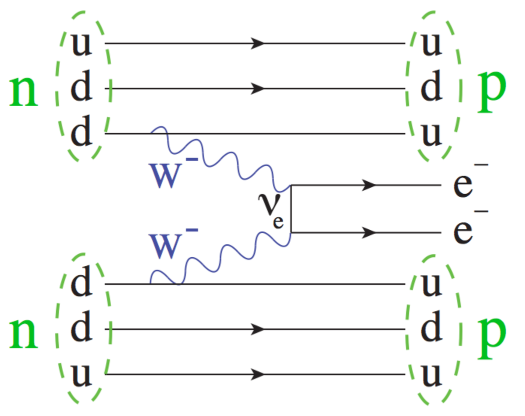




In addition to this standard model compliant process which is associated with the emission of two neutrinos (2νββ), one can also envisage a combination of beta decay and inverse beta decay, *if* the neutrino is its own anti-particle: Neutrinoless Double Beta Decay (0νββ).

Double beta decay can occur in the flavours $\beta^-\beta^-$, $\beta^+\beta^+$, β^+/EC and EC/EC which have different experimental signatures. All neutrino-emitting decays (but EC/EC) will exhibit a continuous spectrum, but in case of neutrinoless decays, the electrons/positrons will carry the complete decay energy, hence the sum energy spectrum will be a line at the Q-value of the decay.



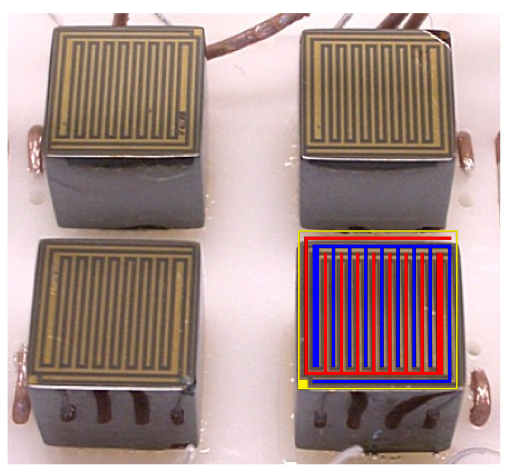


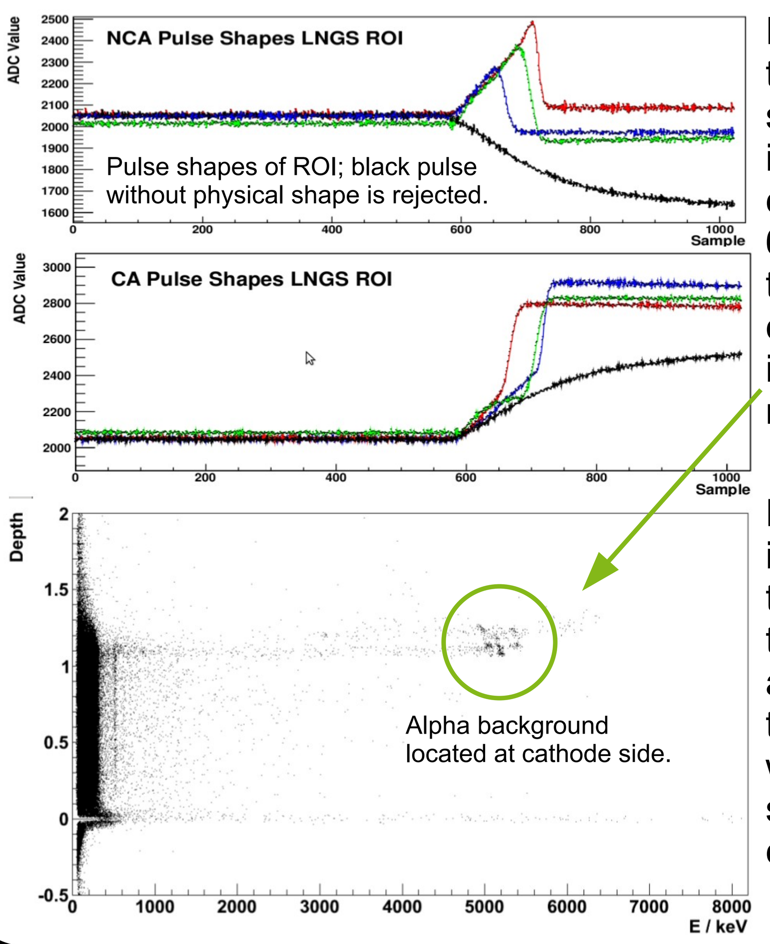
A line signature is of course very well visible experimentally, however, the expected half-lives of neutrinoless double beta decays are of the order of 10^{26} years so good background suppression is mandatory. While the half-lives scale with the effective Majorana neutrino mass, a measurement of angular distributions and/or of certain positron-emitting decays might help to disentangle the underlying mechanisms, e.g. right-handed weak currents.

Co-Planar Grid Detectors

One method to reach a single charge carrier sensitive device is the application of a Frisch-Grid-like approach proposed by Luke: The (anode) readout is done by two electrodes biased to slightly different potentials and the signal is obtained by subtraction. This readout scheme allows for quite large/thick detectors with sufficiently homogenious response. From the pulse shapes, also the interaction depth can be deduced allowing for fiducial cuts.

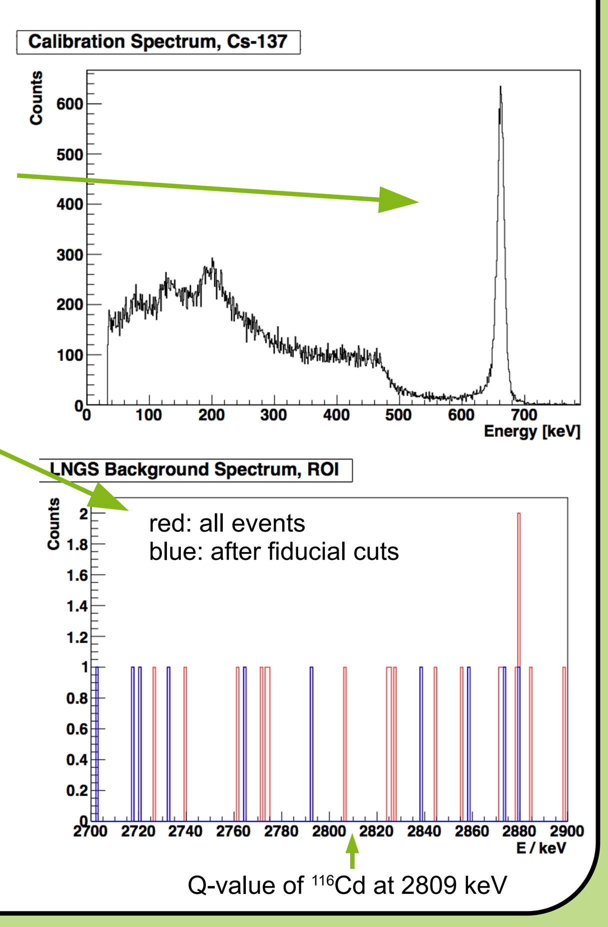
While earlier results were relying on analogue signal subtraction, new readout electronics based on Flash-ADCs have been developed and installed allowing to study the pulse shapes.





First results show that the energy resolution could be improved significantly up to 2% at 662 keV and that the back-ground could be further identified and reduced.

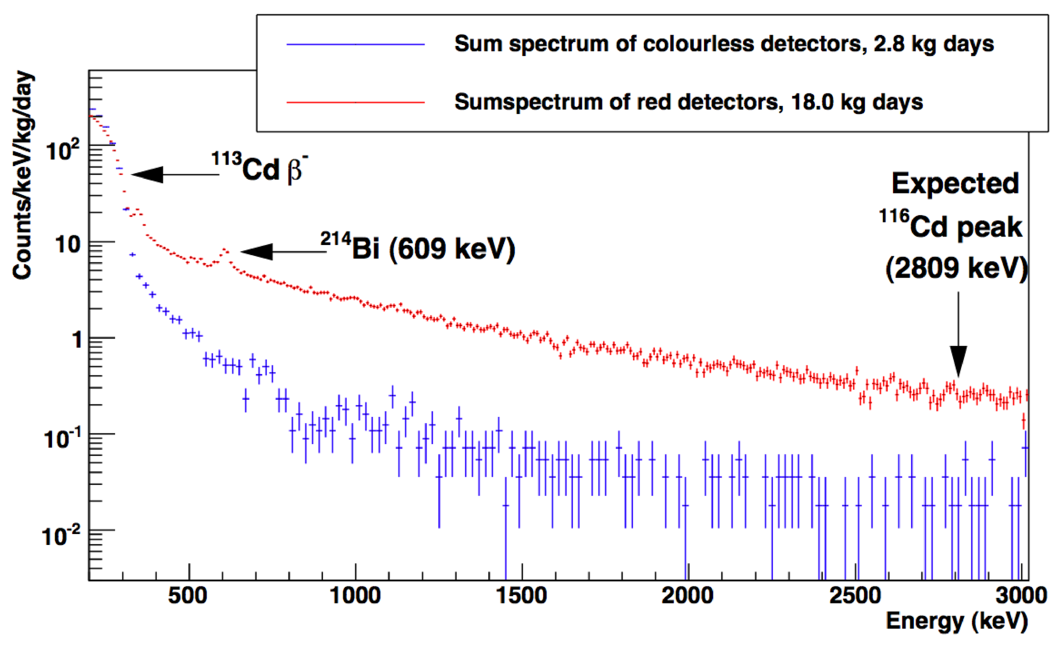
Evaluation of the instrumentation of the boundary electrode (yellow) to achieve discrimination power also with respect to the side surfaces is currently underway.



Results

Even though the experiment is still in its R&D phase, half-life limits for several isotopes and decay modes have been extracted from low-background data taken at the LNGS underground laboratory. Among these are 6 limits above 10^{20} years, and 6 limits within a factor 3 of the world-best.

The data used for this analysis still contained radioactive contaminations which have since been removed (red vs. blue spectrum) and was not yet taken with pulse shape analysis.



Isotope and decay	Fit range (MeV)	$T_{1/2}$ limts (years)	
		This work	Measured
^{116}Cd to gs	2.2–3.2	9.4×10^{19}	1.7×10^{23} [15]
^{130}Te to gs	2.2–3.2	5.0×10^{20}	3.0×10^{24} [26]
^{130}Te to 536 keV	1.7–2.3	3.5×10^{20}	9.7×10^{22} [27]
^{116}Cd to 1294 keV	1.2–1.8	5.0×10^{19}	2.9×10^{22} [15]
^{116}Cd to 1757 keV	0.9–1.3	4.2×10^{19}	1.4×10^{22} [15]
^{128}Te to gs	0.6–1.3	1.7×10^{20}	1.1×10^{23} [28]
^{116}Cd to 2027 keV	0.5–1.2	2.8×10^{19}	2.1×10^{21} [29]
^{116}Cd to 2112 keV	0.5–1.0	4.7×10^{19}	6.0×10^{21} [15]
^{116}Cd to 2225 keV	0.5–1.0	2.1×10^{19}	$1.0 \times 10^{20\dagger}$ [30]
^{130}Te to 1794 keV	0.5–1.2	1.9×10^{20}	2.3×10^{21} [31]
^{130}Te to 1122 keV	1.1–1.7	1.2×10^{20}	2.7×10^{21} [31]
^{114}Cd to gs	0.4–1.0	2.0×10^{20}	1.1×10^{21} [17]

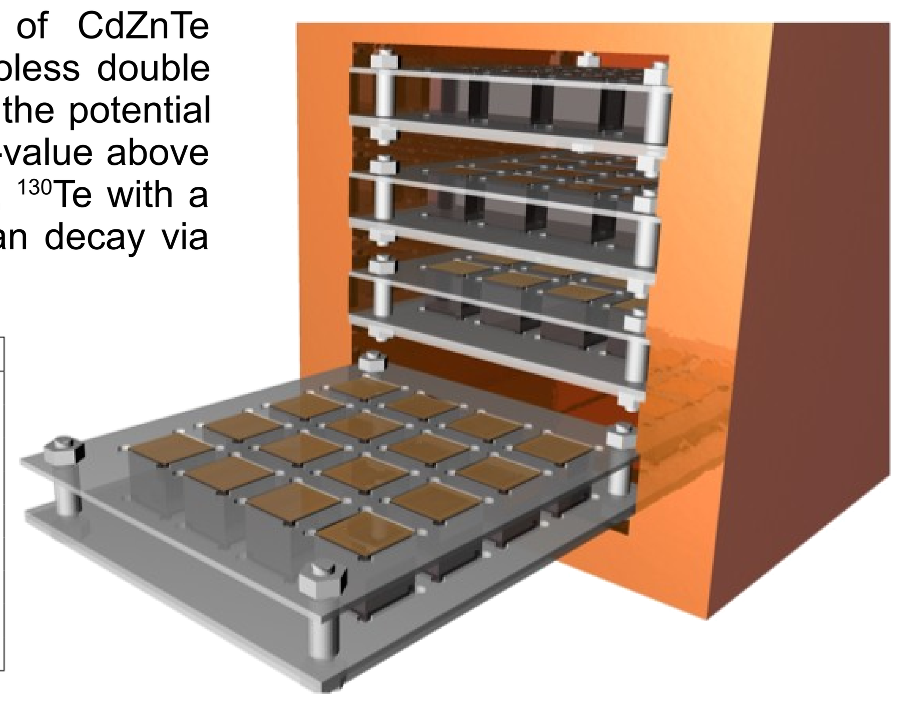
Isotope and decay	Fit range (MeV)	$T_{1/2}$ limts (years)	
		This work	Measured
^{64}Zn β^+EC to gs	0.5–1.1	1.1×10^{18}	4.3×10^{20} [16]
^{64}Zn 2EC to gs	0.5–1.3	3.3×10^{17}	1.1×10^{20} [16]
^{120}Te β^+EC to gs	1.0–2.0	4.1×10^{17}	1.9×10^{17} [18]
^{120}Te 2EC	0.8–2.0	2.4×10^{16}	6.0×10^{17} [18]
^{120}Te 2EC to 1171 keV	0.6–2.0	1.8×10^{16}	6.0×10^{17} [18]
^{106}Cd $\beta^+\beta^+$ to gs.	0.5–2.0	2.7×10^{18}	2.4×10^{20} [32]
^{106}Cd β^+EC to gs	1.5–3.0	4.7×10^{18}	3.7×10^{20} [32]
^{106}Cd 2 EC to gs	2.0–3.0	1.6×10^{17}	3.5×10^{18} [33]
^{106}Cd $\beta^+\beta^+$ to 512 keV	0.6–1.5	9.4×10^{17}	1.6×10^{20} [32]
^{106}Cd β^+EC to 512 keV	0.8–2.0	4.6×10^{18}	2.6×10^{20} [32]

see J. Dawson et al., Phys. Rev. C 80, 025502 (2009)

COBRA – Idea and Advantages

Low-background spectroscopy based on semiconductor detectors generally takes advantage of the good intrinsic radiopurity of the base material yielding a rather low background. In addition, particle tracking and vertexing might be feasible in form of a solid-state TPC using pixel detectors which would allow for much improved background reduction and the measurement of angular distributions.

The idea of COBRA is to use an array of CdZnTe semiconductor detectors to search for neutrinoless double beta decays. CdZnTe contains 9 isotopes with the potential to decay via DBD, among them ^{116}Cd with a Q-value above the highest naturally occuring background line, ^{130}Te with a natural abundance of 34% and ^{106}Cd which can decay via all β^+-modes.



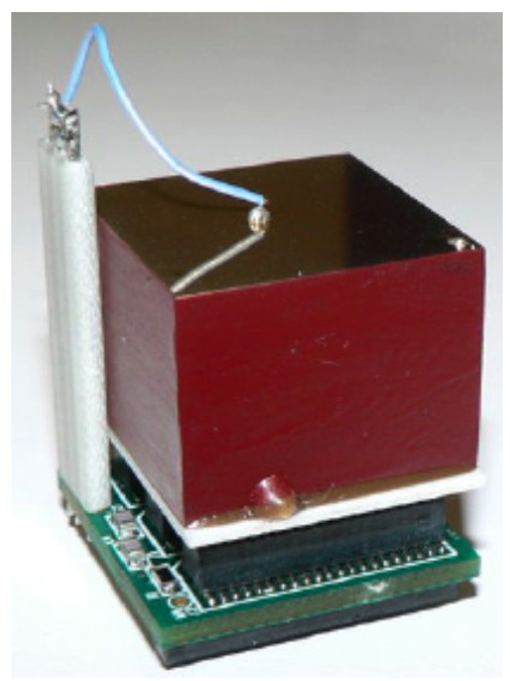
Isotope	decay mode	Q-value[keV]	nat. abundance [%]
^{64}Zn	β^+/EC, EC/EC	1096	48.6
^{70}Zn	$\beta^-\beta^-$	1001	0.6
^{106}Cd	$\beta^+\beta^+$, β^+/EC, EC/EC	2771	1.25
^{108}Cd	EC/EC	231	0.89
^{114}Cd	$\beta^-\beta^-$	534	28.72
^{116}Cd	$\beta^-\beta^-$	2809	7.47
^{120}Te	β^+/EC, EC/EC	1722	0.096
^{128}Te	$\beta^-\beta^-$	868	31.69
^{130}Te	$\beta^-\beta^-$	2529	33.80

Due to crystal growth limitations, the sizes of spectroscopy grade CdZnTe is currently limited to few cm³. To reach source masses of several 100 kg, the operation of a large, 3-dimensional array with $o(10^4)$ detectors is necessary.

In CdZnTe, the mobility-lifetime product for holes is quite poor; therefore, readout schemes relying solely on electrons are utitlised. COBRA investigates two of these, CPG-type and pixel readout.

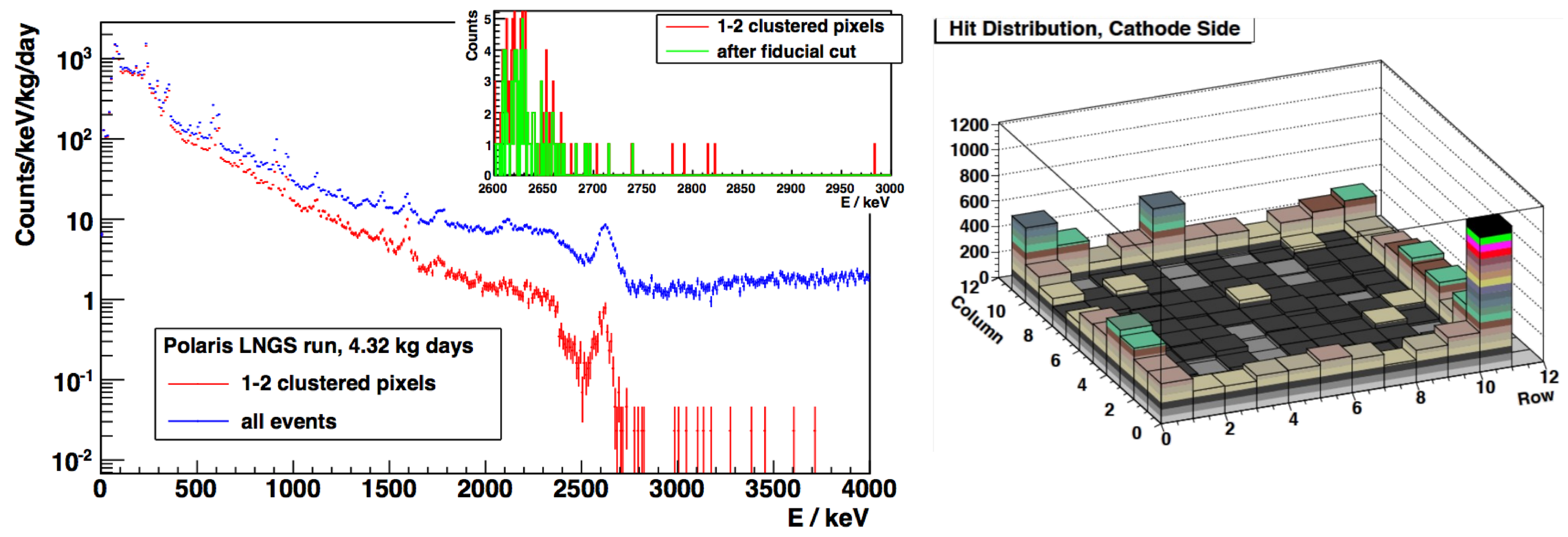
Pixel Detectors

Pixel detectors offer superior options for background reduction: Fiducial cuts to the side surfaces are possible simply based on excluding the outermost pixels. By instrumenting the cathode, also depth-sensing is feasible enabling 3-dimensional position sensing.

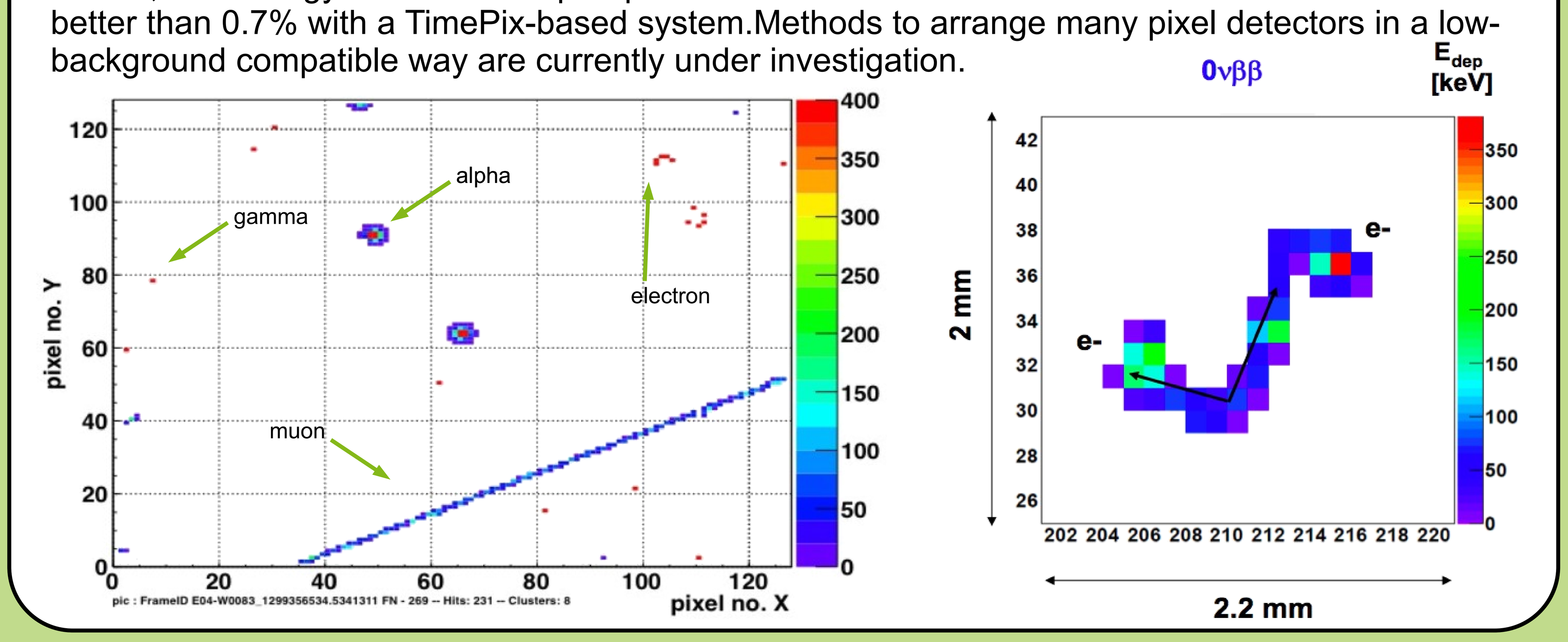


This was first demonstrated in the COBRA low-background setup at the LNGS underground laboratory with a Polaris system (Z. He, U. of Michigan) which comprises a very large CdZnTe crystal (2 by 2 by 1.5 cm) with 11 by 11 pixels. The pixels are small enough to enable electron-only readout, but large enough to collect all deposited charge in one (or two) pixels leading to superb energy resolution.

Although the system was not specifically prepared for low-background operation, the ROI of ^{116}Cd could be cleared of any event by applying a ficucial cut which leads to a background level of 0.9 counts/keV/kg/y. A preliminary analysis leads to a half-life limit for ^{116}Cd of better than 10^{20} years with only 4.3 kg d of data, clearly demonstrating the advantages of background suppression.



The second approach followed is that of a solid-state TPC: If the pixels are small enough (few hundred µm), the tracks of the decay electrons are visible and clearly distinguishable from alpha and gamma background. By means of neural networks, a significant S/B improvement is also achievable for single-electron background. In spite of the ΔE/E deterioration due to many-pixel events, the energy resolution of pair-production events at 1.59 MeV was measured to be still better than 0.7% with a TimePix-based system.Methods to arrange many pixel detectors in a low-background compatible way are currently under investigation.



Outlook

To achieve sensitivities for neutrino masses of the order of 50 meV, it is necessary to probe half-lives of about $2 \cdot 10^{26}$ years. With assumptions for the background of 10^{-2} to 10^{-3} counts/kev/kg/d, this requires source masses of ~400 kg CdZnTe enriched in the isotope of interest (^{116}Cd for the time being) to 90%. Such a setup would comprise e.g. 40 by 40 by 40 (i.e. 64000) CPG-type detectors of 1 cm³ size each or of an appropriate number of pixel detectors which would probably have larger surface (2 cm²), but less thickness (3 to 5 mm). Detailed studies for scalable setups are ongoing.