EXO-200
Event Reconstruction

Ryan MacLellan on behalf of EXO-200

Introduction

EXO-200 utilizes dual liquid xenon time projection chambers to observe the double beta decay (ββ) of ^{136}Xe. Each TPC yields 37 scintillation channel waveforms and 38 each of ionization and charge induction channel waveforms; all of which are 2 ms in length and sampled at 1 MHz. Event reconstruction is a process by which raw waveform traces are analyzed to determine the time, position, and uncalibrated energy of individual localized energy deposits.

The reconstruction of an event proceeds in three stages:
1. Signal **finding**
2. Parameterization of signal characteristics (**fitting**)
3. Bundling of coincident, characterized signals (**clustering**)

Signal Models

Signal shape templates are used extensively in reconstruction in both the signal finding and parameter extraction stages and are produced for all channels.

The models begin with unshaped signals: U- and V-wire response from the 2D weight potentials (eg. fig. 1); APD response is a step function.

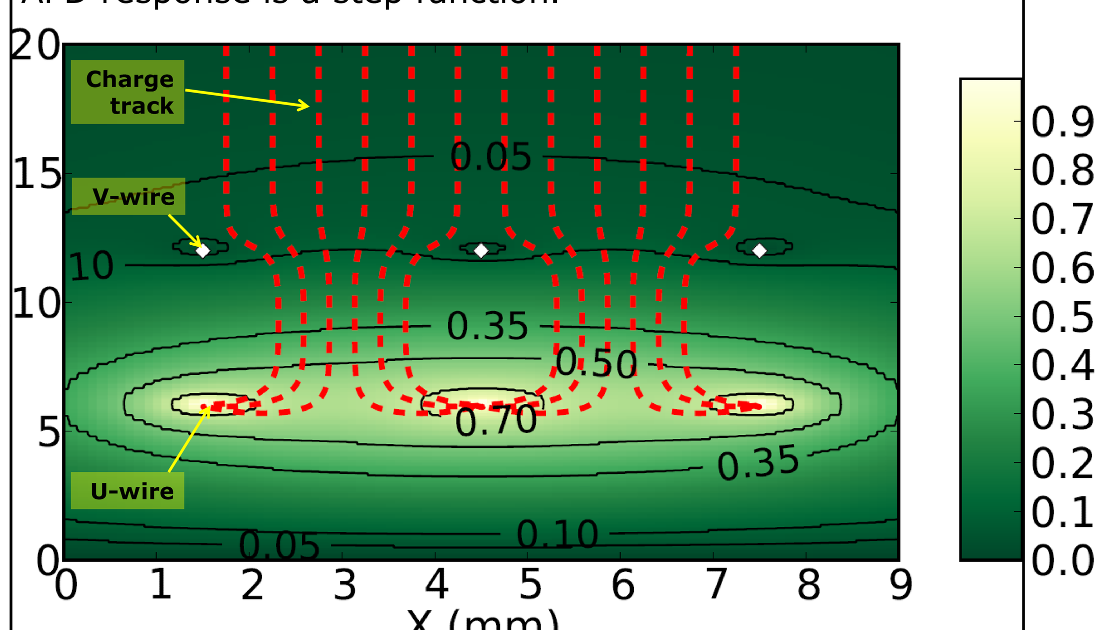


FIG. 1: The magnitude of the calculated weighting potential for a single U-wire readout channel.

The unshaped waveforms are then filtered using an appropriate transfer function, determined by the front-end electronics configuration: 3 differentiation (1 in preamp) and 2 integration. The transfer function parameters are:

Channel Type	Stage type: Integration		Differentiation		
APDs	3	3	10	10	300
U-wires	1.5	1.5	40	40	51 – 85 (nominal 60)
V-wires	3	3	10	10	60

μs shaping times. Third differentiation stage of the U-wire signals measured for every channel by fitting to pulse-shapes of injected calibrated charge.

Signal Finding

It is necessary to search for signals on waveform traces because they are not always guaranteed to arrive at a given time (e.g. specified by a trigger). Two methods are used to find signals on waveform traces: applying a matched filter, and waveform unshaping. The second method is used to identify pulses closely following one another within a signal found by the matched filter.

Matched filter

$$y(t) = \mathcal{F}^{-1}\{X(f)H^*(f)\}$$

Where $y(t)$ is the filtered signal, $\mathcal{F}$ is the discrete Fourier transform (FT), $X(f)$ is the FT of the original waveform, $x(t)$, and $H^*(f)$ is the CC of the FT of the transfer function, $h(t)$. All waveforms are filtered by applying the appropriate template model (APDs are summed for each TPC first).

Peaks are sought above a threshold (fig. 2) derived from frame specific noise. The noise algorithm starts from the mean absolute deviation (MAD) from the baseline and removes parts of the waveform exceeding $3\sqrt{\pi/2}\times$MAD; then recalculating the MAD. The threshold is defined as 5 (4) times the resultant MAD for wire (APD) signals.

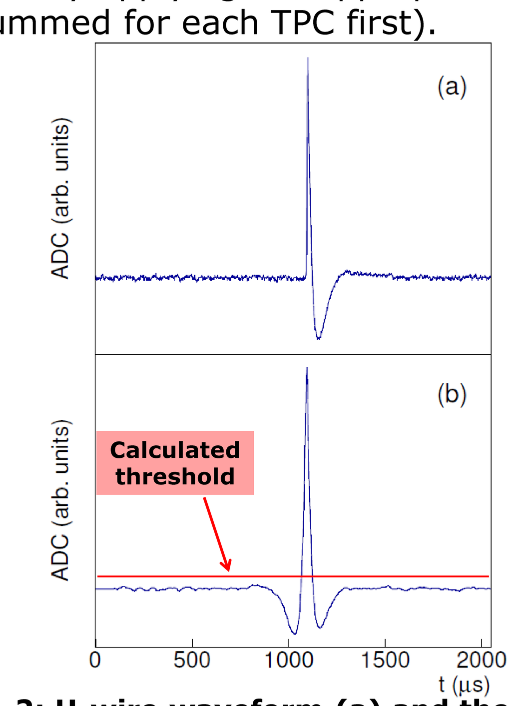


FIG. 2: U-wire waveform (a) and the result of the matched filter (b).

Waveform unshaping

The matched filter is ill-suited to disentangle multiple signals on a single trace when these signals arrive close in time. An algorithm dedicated to identifying these signals is additionally applied to the original waveforms. This algorithm unshapes the signal to obtaining the deposited charge $q(t)$:

$$q(t) = \mathcal{F}^{-1}\{H^{-1}(f)X(f)\}$$

Where $H^{-1}(f)$ is the inverse transfer function. $q(t)$ is subsequently reshaped with a 2 μs triangular, or moving average, filter. The reshaped waveform is then analyzed with a peak-search algorithm to determine the presence of any additional signals.

Signal Fitting

Amplitude and timing extraction

The amplitudes of all U- and V-wire, and both APD sum signals are measured by fitting the waveforms to their respective signal models by minimizing:

$$\chi^2 = \sum_{i=0}^{L}\left(\frac{x_i - b - \sum_{i=0}^{N} A_i f_{\rm SM}(x_i, t_i)}{\sigma_{\rm noise}}\right)^2$$

where x_i is the data sample at time i, b is the measured baseline, i is the index of the N signals on the waveform, A_i and t_i are the amplitude and time of the i^{th} signal, and $f_{\rm SM}$ is the signal model. A_i and t_i are the only floating parameters. The size of the fit window, L, typically extends ±40 (+140 for U-wire signals) μs around the signal. An example of fits to U- and V-waveforms is shown in fig. 3.

The amplitudes of the individual APD gang signals are also determined with the signal times fixed to those derived from the fit to the summed signals.

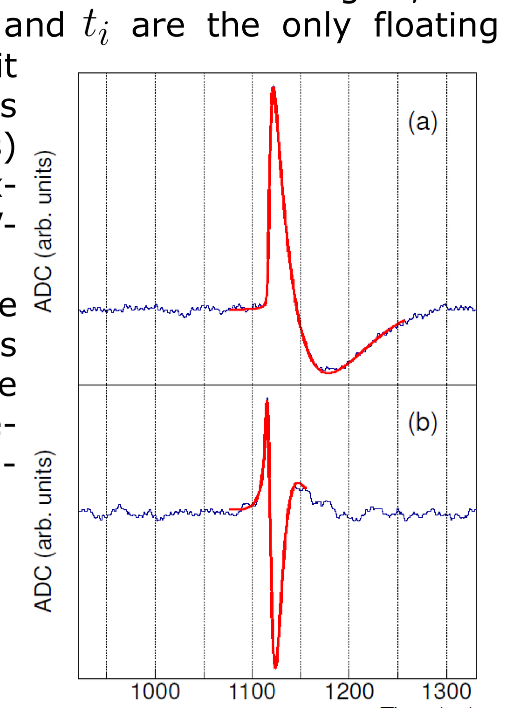
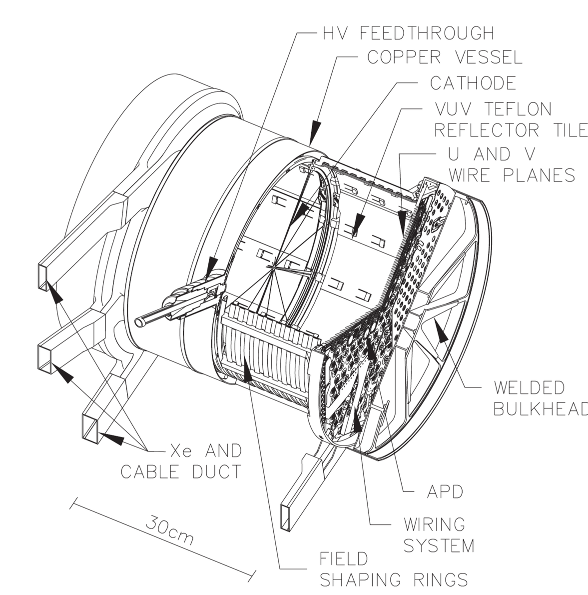
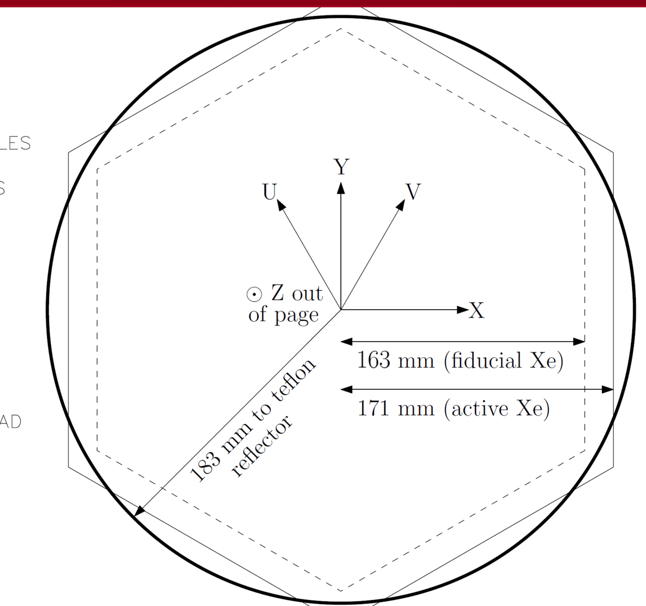


FIG. 3: Examples of fits to a U-wire (a) and V-wire (b).





Waveform characterization

Four additional metrics are derived from the U-wire signals in order to discriminate between true charge collection signals and induced charge only signals.

1. **Rise time** of pulse and time from the **pulse maximum** to the following pulse minimum.
2. **Pulse integral**: integral (unshaped) from 10 us before to 40 us after pulse maximum.
3. Goodness of fit: ratio of χ^2 for fits to signal with either signal models (-20 to +30 us window).
4. **Nearest neighbor amplitude**: total energy deposited within 50 us on neighboring U-wire channels.

Fig. 4 shows the distribution of these discriminants for simulated ^{228}Th decays. Signals are only tagged as induction if passing all 4 requirements (right of vertical dashed lines) leading to 99.9% acceptance of true charge collection signals with 77% induction signal rejection.

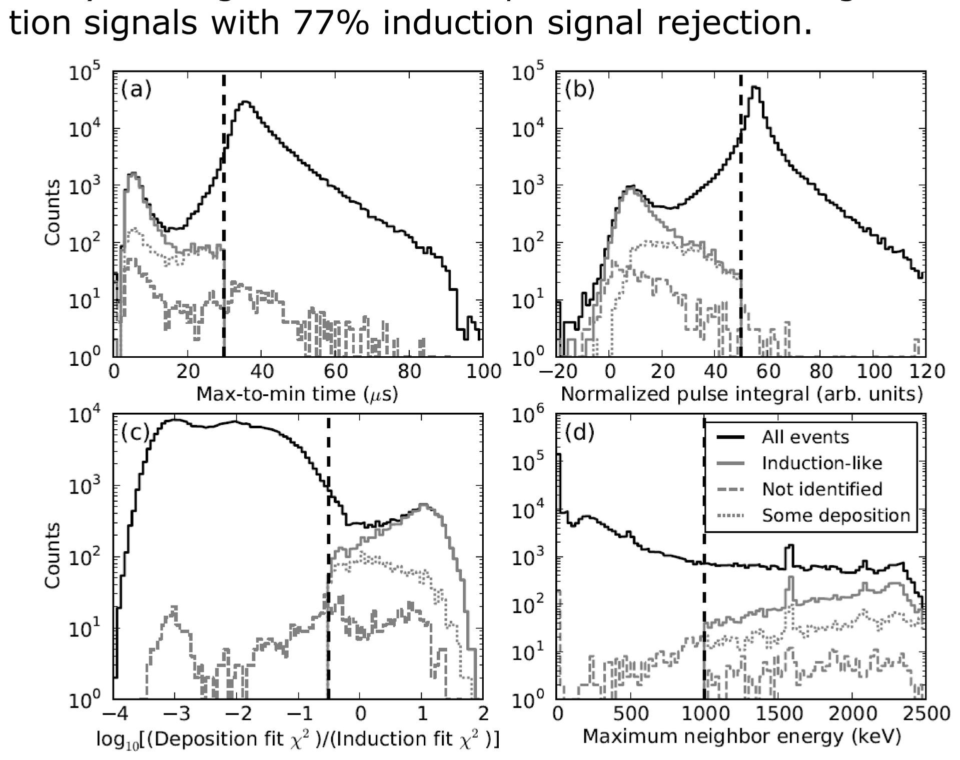


FIG. 4: 4 discriminants required to tag induction signals on U-wires (^{228}Th simulation). 77% induction signal rejection with >99.9% charge collection acceptance.

Signal Clustering

Once the time and amplitude of signals on U-, V-, and APD channels have been found (and gain corrected), these signals are grouped together to form 3-D clusters.

1. Signals on like channels are bundled.
2. U-wire signals identified as due to induction are ignored when constructing bundles.
3. Z-positions of bundles are then determined by associating them with APD bundles.
4. Wire bundles are grouped together to form fully 3-D reconstructed clusters.

Signal bundling

U-wire signals on adjacent channels arriving within 3.5 μs are bundled together. The bundle time is the amplitude-weighted average of associated signals. V-wire signals are bundled according:

$$|t_i - t_o - (2.97\mu s/\text{channel})\Delta\text{V-channels}| \leq 4.5\mu s$$

where t_o is the time of the largest amplitude V-channel signal, t_i is the time of the signal of interest, and ΔV-channels is the absolute channel number difference of the two signals.

APD signals are bundled if they arrive within 6 μs (sum of integration times) of one another. The time of the scintillation bundle is the energy weighted average over the component signals.

Positioning in 2 dimensions

2-D event position is reconstructed by grouping together U- and V-wire bundles in the most likely configurations to generate charge clusters. The negative log of the product of three PDFs (shown below):

$$L = -\sum_{i=1,2,3} \ln P_i$$

where the sum is over the three PDFs.

A matching algorithm rigorously tests all combinations of V- and U-bundles, including whether multiple bundles of one type may actually correspond to a single bundle of the other type. The best matching configuration is the one that minimizes the sum of all likelihoods divided by the number of connections (the smaller of the number of U- or V-bundles). A charge cluster is then created for each of the connections within this configuration and each charge cluster is linked with its associated scintillation bundle.

The PDFs used to cluster U- and V-wire bundles together depend on the Z-position of the U-bundle. The scintillation bundle with the smallest absolute time difference from the U-wire bundle is chosen. If no scintillation bundle lies within the maximum drift time of the U-bundle, the Z-position is indeterminant and the particular U-/V-bundle will not be further clustered.

The efficiency of signal finding is 100% above 700keV. If clustering fails to associate any bundle a cluster is not fully 3-D reconstructed. This efficiency amounts to 90.9±7.8%. It is also possible for clustering to fail on too many signals The total number of skipped events is < 0.18% of the final 2νββ counts above 700keV.

Amplitude correlation PDF

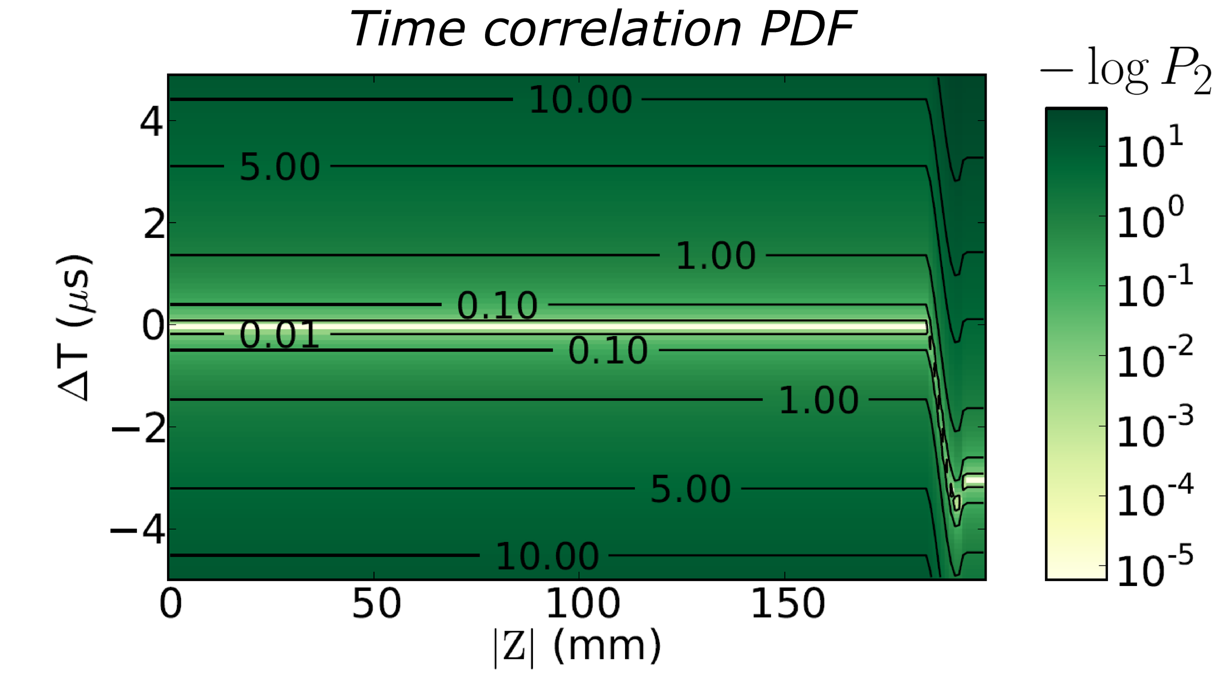
$$P_1(E_{\rm U}, E_{\rm V}, Z) = \begin{cases} A & |Z| > 160\,{\rm mm} \\ A\exp\left[-\left(\frac{\rho_E(E_{\rm U}) - E_{\rm V}}{\sqrt{2}\sigma_E(E_{\rm U})}\right)^2\right] & |Z| \leq 160\,{\rm mm}\end{cases}$$

where ρ_E is a linear parameterization and

$$\sigma_E(E_{\rm U}) = \begin{cases} a_E & E_{\rm U} < 350\,{\rm ADC_U} \\ c_E E_{\rm U} + d_E\sqrt{E_{\rm U}} & E_{\rm U} \geq 350\,{\rm ADC_U}\end{cases}$$

All free parameters are determined from calibration data.

Time correlation PDF



Physical plausibility PDF