Energy Calibration of the EXO-200 Detector

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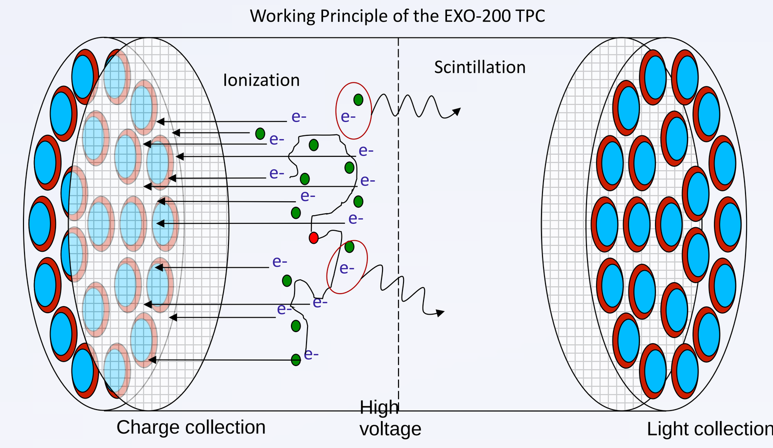
Introduction

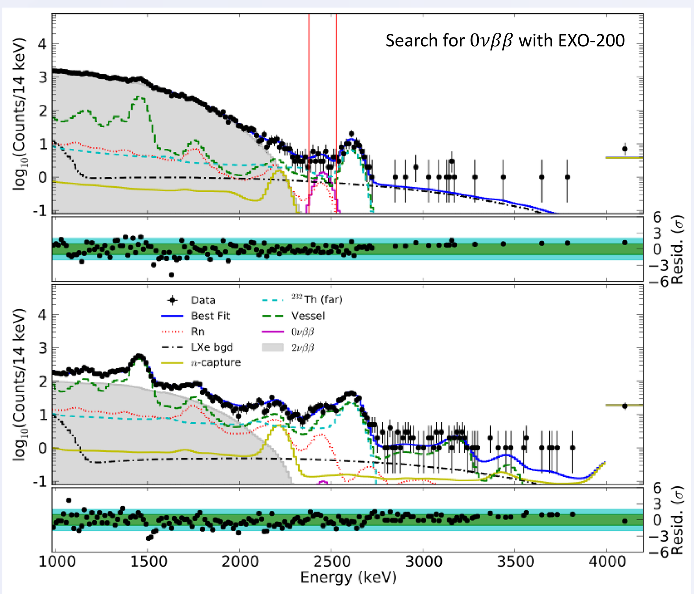
Working Principle of the EXO-200 TPC



The first stage of the Enriched Xenon Observatory (EXO), EXO-200, consists of an extremely low background time projection chamber (TPC) containing ~150 kg of enriched ^{136}Xe in liquid phase (LXe).

The cathode is placed in the middle of the TPC between two equidistant anodes. Near both anodes are located two identical detector packages hosting:

- a wire-grid composed of a shielding (V-wires) and a collection (U-wires) grid;
- and an array of large area avalanche photodiodes (APDs).



Interactions in the LXe produce free ionization charge and scintillation light. A uniform electric field drifts the ionization charge to the wire-grid, while the scintillation light is detected by the APDs. The wire-grid provides two spatial components for each observed interaction, while the time between scintillation and ionization signals provide the third one [1].

The search for neutrino-less double beta decay ($0\nu\beta\beta$) in LXe, performed by the EXO-200 Collaboration, strongly relies on features presented in the energy spectrum of the measured events [2].

Calibration System

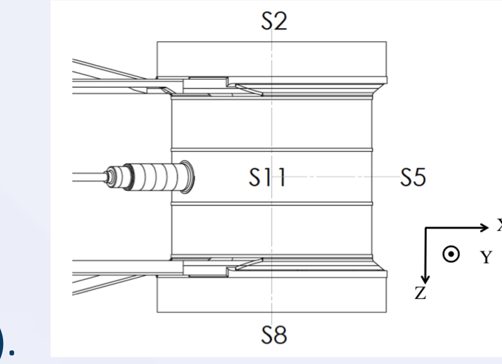
Four radioactive sources are utilized to calibrate the TPC response to gamma radiation:

^{137}Cs, ^{60}Co, ^{228}Th and ^{226}Ra

The calibration radioactive sources can be deployed at several positions around the TPC vessel.

^{228}Th data presents the characteristic ^{208}Tl peak at 2615 keV, near the $0\nu\beta\beta$ Q-value (2458 keV). Data with this source positioned at near the cathode (S5) is acquired three times per week to monitor time variations in the detector response (weekly calibration data).

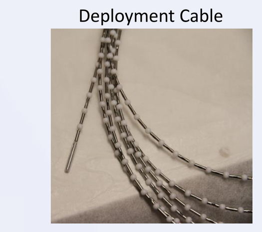
Every three months, ^{137}Cs and ^{60}Co are also deployed near the detector for a comprehensive calibration of the detector (calibration campaigns). More recently, a ^{226}Ra source was purchased and included in calibration campaigns.



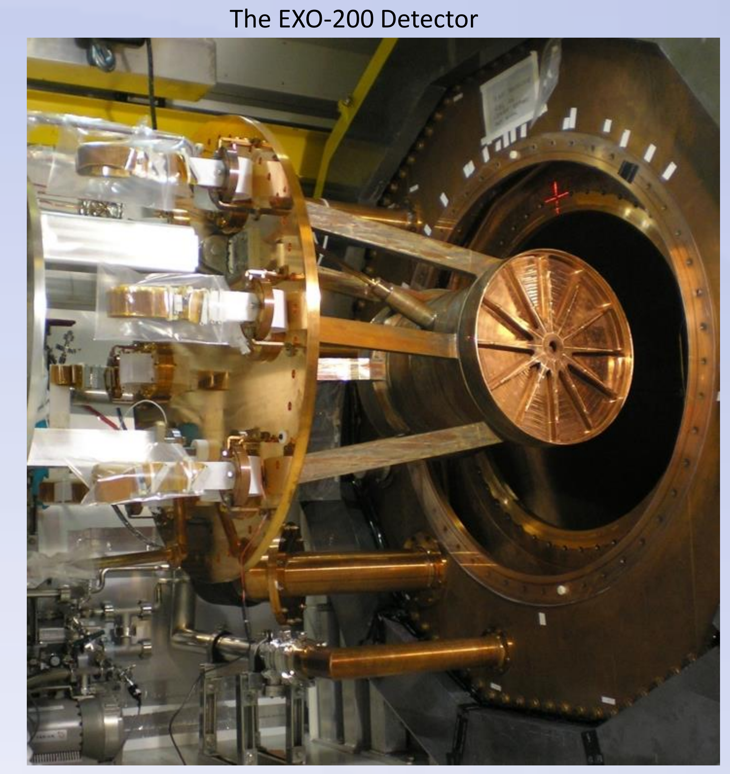
Calibration Source Locations

Radioactive Sources

Deployment Cable



The EXO-200 Detector



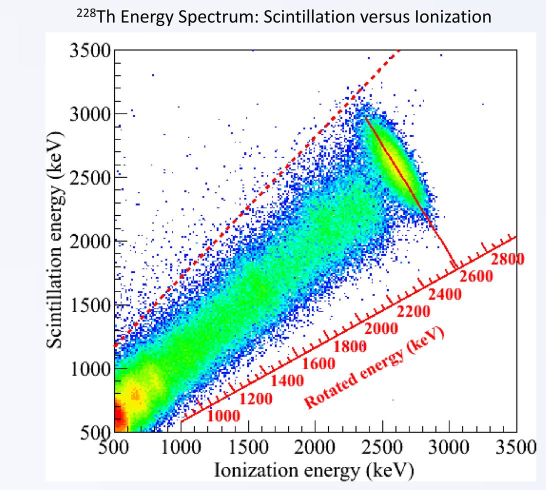
Anti-correlation Between Ionization and Scintillation

The energies obtained from the ionization and scintillation channels can be linearly combined into a *rotated energy*:

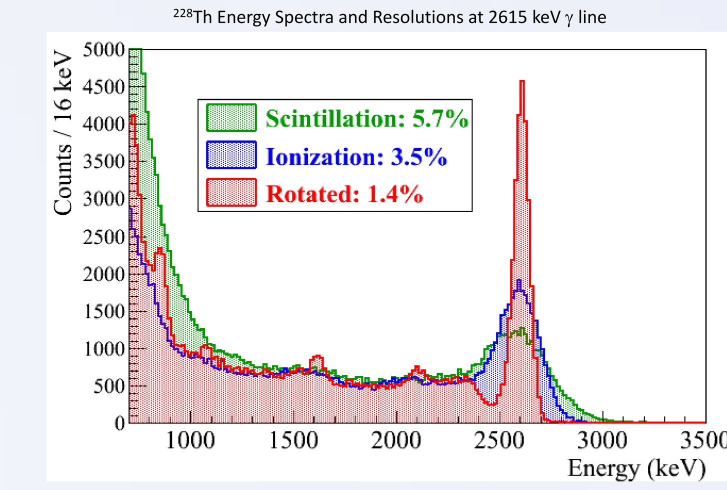
$$E = I\cos\theta + S\sin\theta$$

The resolution of the rotated energy is better than that of either individual channel because of the microscopic anti-correlation between charge and light production in xenon.

^{228}Th Energy Spectrum: Scintillation versus Ionization



^{228}Th Energy Spectra and Resolutions at 2615 keV γ line



The weekly ^{228}Th calibration data is fitted by the empirical function

$$g(E) = A\left(\mathrm{Gaus}(\bar{E},\sigma) + B\ \mathrm{Erfc}(\bar{E},\sigma)\right)$$

to obtain the energy peak position, $\bar{E}$, and its relative resolution, $\sigma/\bar{E}$, for various angles. A parabola is fitted near the minimum to calculate the angle that optimizes the relative resolution for each week.

Ionization Channel

The EXO-200 electronics responds to the charge cloud drifted to the anodes through two different physical effects:

1. Charge collected by the U-wires;
2. and induced signal on the V-wires.

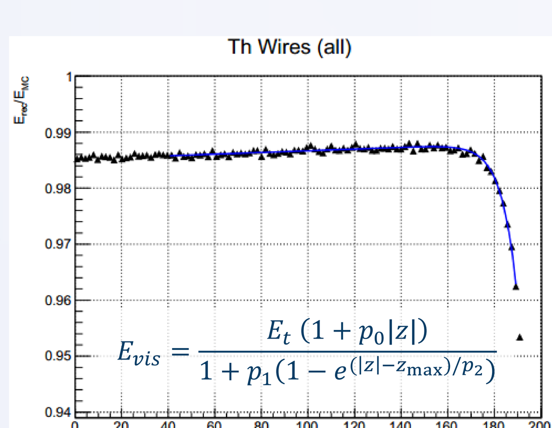
The induced signals are only used for position reconstruction. The amplitudes measured by the U-wire channels are corrected for the effects described below.

- **U-wire Channel Gains**

The absolute U-wire gains were measured prior to the second data acquisition period of the EXO-200 detector. The stability of the gain values is monitored daily using a charge injection circuit which is integrated into the front-end card. The relative gain values are also determined with calibration data using the pair-production peak of 2615 keV gammas. The mean gain is ~380 e-/analog-to-digital (ADC) unit, with 30% variation over all channels. The observed drift of the U-wire gains is < 1%, with < 0.1% relative channel-to-channel drift.

- **Grid Shielding Efficiency**

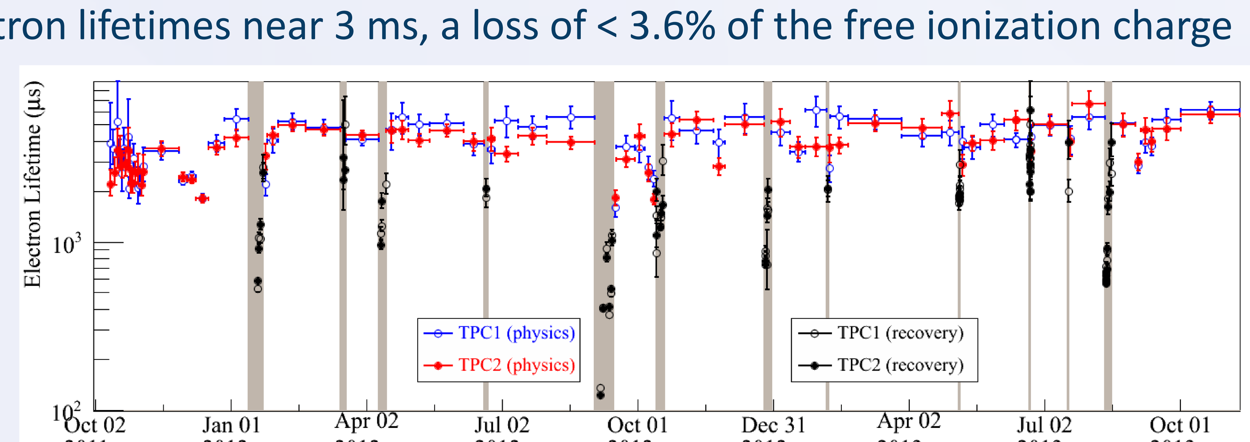
The V-wires provide a shielding effect on the U-wires, so that a charge drifting in the TPC region between the cathode and the V-wires will only have a small effect on the U-wires. This efficiency is estimated using Monte Carlo (MC) simulation (Maxwell 2D [3] for the electric field and GEANT4 [4] for energy deposits).



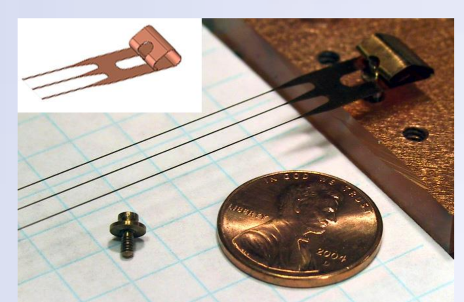
Estimation of the Grid Shielding Efficiency

- **Xenon Purity and Electron Lifetime**

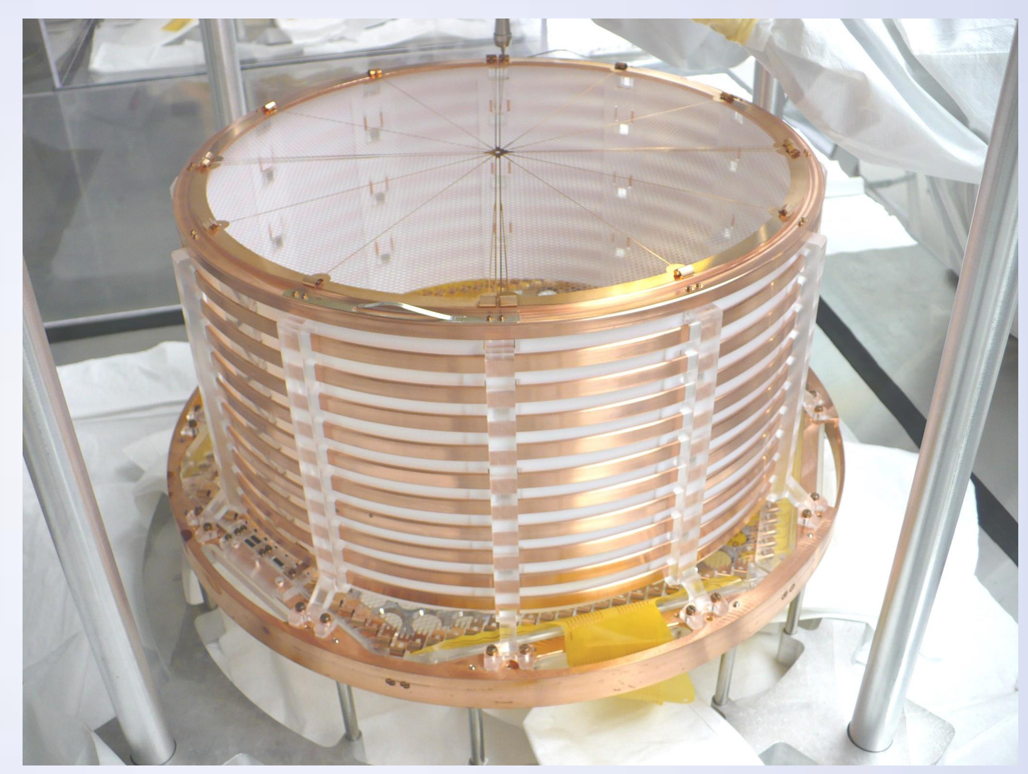
Electrons drifting in LXe can be captured on electronegative impurities leading to an exponential decrease with drift time: $N_e(t) = N_0\,e^{-t/\tau_e}$, where τ_e is the electron lifetime. The electron lifetime is measured for every ^{228}Th calibration run, and is observed to be largely correlated with the speed of the pump that forces the circulation of the xenon through a purification system. The increased statistics of combined calibration runs, those where the pump speed is stable, yields electron lifetimes near 3 ms, a loss of < 3.6% of the free ionization charge produced.



Measurement of the Xenon Purity

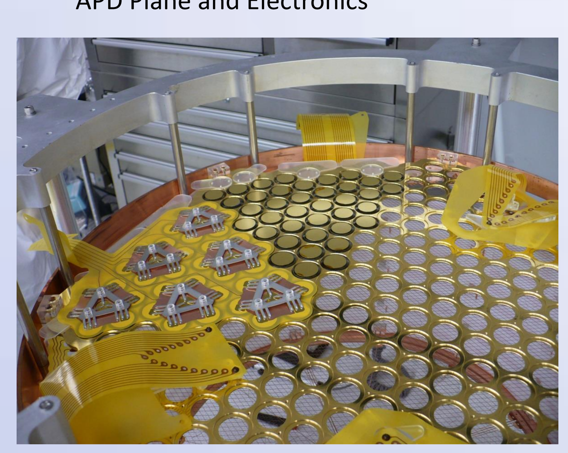


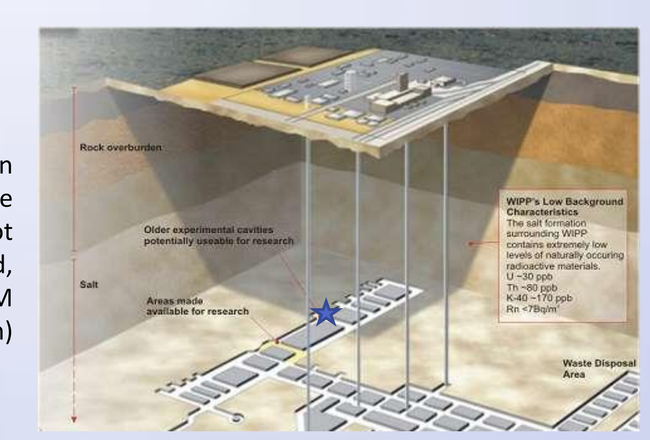
Wire "Triplet" Detail and Terminus



Half of the EXO-200 TPC: Cathode, Teflon Reflectors, Field Shaping Rings, and APD and Wire Planes

APD Plane and Electronics





EXO-200 Location at Waste Isolation Pilot Plant, Carlsbad, NM (Depth of 655 m)

Scintillation Channel

The amplitudes measured by the APD channels are input into a *denoising algorithm*. This algorithm combines these amplitudes with their channel responses and electronic noise correlations to provide the light measurement that optimizes the resolution in the scintillation channel.

Each APD channel response is described by a time- and position-dependent lightmap, which also accounts for the individual channel gains. This lightmap is assumed to be separable

$$L_i(t,\vec{x}) = G_i(t) \times R_i(\vec{x})$$

for each APD channel i, where $G_i(t)$ represents the channel gain over time, and $R_i(\vec{x})$ describes the channel response to photons produced at a given location. The time-dependent lightmaps are measured with source calibration data. The separability assumption allows the use of the full set of calibration data to determine both time and spatial dependences of the channel responses.

The coherent noise across the APD channels is obtained from solicited triggers in runs dedicated to physics analyses. The denoising algorithm fits linear weights to the contribution from each APD channel to the measurement of the scintillation light in each event [5].

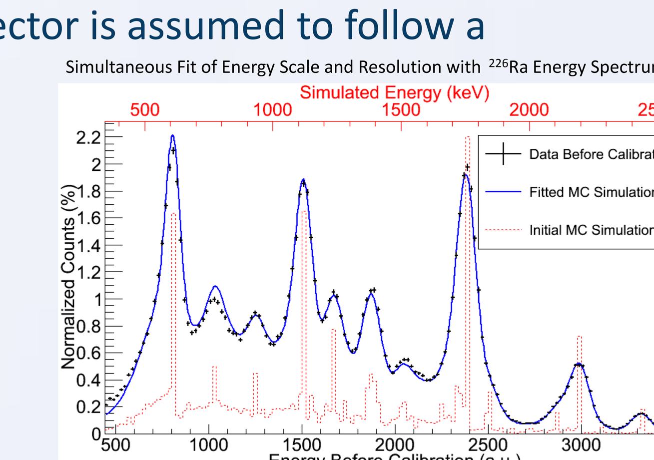
Energy Scale and Resolution

After rotation, the energy scale and resolution are simultaneously calculated by fitting the unsmeared MC energy spectrum to the corresponding source calibration data. The resolution of the detector is assumed to follow a conditional Gaussian distribution

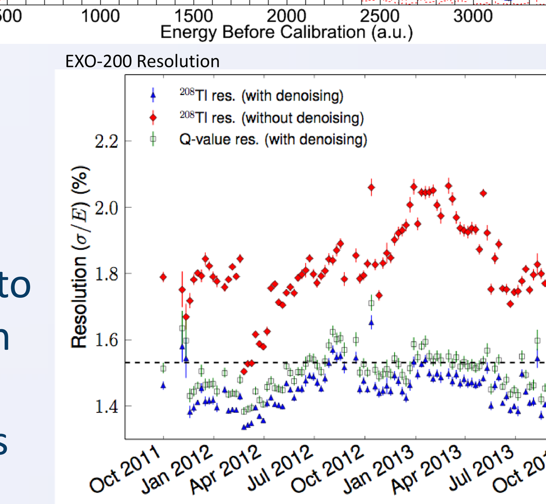
$$\sigma^2(E_t) = a^2 + b^2E_t + c^2{E_t}^2,$$

where a, b and c are motivated by contributions from electronic noise, statistical fluctuations and gain drift broadening, respectively, and E_t is the calibrated energy. The energy calibration is given by $E_t = \alpha + \beta E + \gamma E^2$.

Simultaneous Fit of Energy Scale and Resolution with ^{226}Ra Energy Spectrum



EXO-200 Resolution



Weekly parameters are fitted considering $c = 0$ and $\gamma = 0$, while the data from the calibration campaigns is used to fit the time-average resolution parameters and quadratic corrections to the weekly calibration parameters. The correction is at sub-percent level. A likelihood function weighted by the weekly livetime of physics runs is optimized in this fit.

References

[1] EXO-200 Event Reconstruction, poster by R. MacLellan, Neutrino 2014
[2] Results from EXO-200, talk by M. Marino, Neutrino 2014
[3] ANSYS, Maxwell 2D, http://www.ansys.com
[4] J. Allison *et al.*, IEEE Trans. Nucl. Sci., 53, 270 (2006), ISSN 0018-9499
[5] EXO-200 APD Denoising, poster by C. Davis, Neutrino 2014

Neutrino 2014, Boston University, Boston, MA, USA