Deep Neural Networks for Energy and Position Reconstruction in EXO-200

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Neutrinoless Double Beta Decay

- $0
\beta \beta$ decay is a hypothetical decay forbidden in the Standard Model where a nucleus undergoes a double beta decay w/o emitting neutrinos
- Only possible in few nuclei, e.g. $^{76}$Ge, $^{116}$Cd, $^{130}$Te, $^{136}$Xe
- Theoretical implications:
  - Neutrinos are Majorana particles ($\nu = \bar{\nu}$)
  - Violation of Lepton number conservation
  
  
  \[ 136 \text{Xe} \rightarrow 136 \text{Ba}^{++} + 2e^- + 2.457 \text{MeV} \]

Deep Learning

- Machine learning technique based on representation learning via multiple successive layers of units with an increasing level of abstraction and complexity
- Many architectures exist each with certain advantages
- Convolutional Neural Networks suited for image recognition by applying a convolution operation to the previous layer and a receptive field (feature map)
- Training by adjusting the unit weights
- Done by minimizing the discrepancy of network output and target value via backpropagation

EXO-200 Experiment $[1]$

- Located in the Waste Isolation Pilot Plant (WIPP), Carlsbad, NM, US
- Detector is a double-sided single phase ultra-low-background time projection chamber
- 175 kg of liquid Xe enriched in $^{136}$Xe (~80%)
  - Simultaneous detection of scintillation light (by APDs) and ionization charge (by crossed induction and collection wire grids)
  - Complementary energy and full 3D position reconstruction
  - Multi-parameter analysis

Data driven position reconstruction $[3]$

- Position reconstruction using raw light waveforms from recombination and excitation
- Approach solely based on data without reliance on a MC simulation
- Valuable for events with insufficient charge collection (i.e. near PTFE reflectors)
- Training on real data waveforms with single charge deposits in the detector against the position extracted from the ionization signal (X-Y) and timing difference of light and charge ($t_x$)
- Events from source calibration runs ($^{228}$Th, $^{226}$Ra, $^{60}$Co) at different source positions
- Event image is fed to deep convolutional neural network

- Produce uniform position and energy distribution of training events (70,000)
- Performance limit is charge position resolution ($\sigma_{\text{mc}} = 3mm$)

- Position resolution of light channel only (after 200 epochs): $\sigma_{\text{mc}} = 24.5nm$

Charge-only energy reconstruction $[3]$

- Energy reconstruction using raw charge waveforms of all charge collection (U) wires
- Training on MC events (~750,000) with real noise including single and multiple scatters in the LXe against the total deposited energy that is distributed uniformly in energy
- Event image is fed to deep convolutional neural network

- Energy reconstruction (after 100 epochs) w/o energy dependent features
- MC: Energy resolution ($\sigma$) at the $^{208}$Tl full absorption peak (2615keV)
  - DNN: 1.22% (Single Site: 0.94%)
  - EXO-200 Recon: 1.29% (SS: 1.15%)
- No significant dependence on the event position
- Data (not MC): Energy resolution ($\sigma$) at the $^{208}$Tl full absorption peak after combining with denoised light channel
  - from EXO-200 reconstruction
  - DNN: 1.65% (SS: 1.50%)
  - EXO-200 Recon: 1.70% (SS: 1.61%)

References

[1] EXO-200 Collaboration, JINST 7 (2012), P05010

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