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Enhancing Pulse Shape Discrimination with Gradient Boosted Decision Trees and Twin Neural Networks

High-purity germanium (HPGe) detectors play a critical role in nuclear physics experiments, including searches for neutrinoless double-beta decay. Traditional pulse shape discrimination (PSD) methods help distinguish signal from background events in such detectors. However, the performance of these traditional PSD methods declines at lower energies (500 ⊠ keV). This low-energy regime is promising for exploring beyond-standard-model physics, such as bosonic dark matter, electron decays, and sterile neutrinos. To improve sensitivity, we developed a novel machine learning pipeline for PSD in HPGe detectors. Our pipeline combines a twin neural network (TWINNN) that encodes waveforms into a 64-dimensional latent space with a gradient-boosted decision tree (GBDT) that interprets the encoded data with the help of additional human-curated input features. The algorithm was trained on the "Majorana Demonstrator Publicly Released dataset for AI/ML". Our approach leverages both the TWINNN's ability to model complex, non-linear behavior and capture temporal context, as well as the GBDTs interpretability and ability to make use of additional human-curated input features. When applied to waveforms from a Majorana Demonstrator calibration run, our approach improved classification accuracy from 87.5% to 92% and increased near-surface event identification by 13%. Two energy spectrum peaks, corresponding to single-site and multi-site events, were excluded during training, yet the model correctly retained or removed these events during full-spectrum evaluation, demonstrating generalization into unseen energy regions. Future work will involve Monte Carlo validation of the low-energy calibration spectrum, further study of latent-space topology with a variational inference model, and improved PSD generalization across a broader energy range. This work underscores the transformative potential of machine learning in nuclear physics instrumentation and data analysis while offering a new method for event characterization in rare-event searches and fundamental physics experiments.

AI keywords

Twin Neural Network; Pulse Shape Discrimination; Latent Space; Interpretability; Gradient Boosted Decision Tree

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Track Classification: Inference & Uncertainty