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Two-Stage Gamma-Neutron Source Classification in Water Cherenkov Detectors: Energy Threshold Screening and Machine Learning Pulse Analysis

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Water Cherenkov detectors (WCDs) provide a durable and cost-effective solution for real-time radiation monitoring by exploiting Cherenkov light emitted when charged particles exceed the speed of light in water. This work introduces a two-stage classification framework for gamma-neutron source discrimination: a physics-driven energy threshold filters out unambiguous low-energy gamma sources, while a machine learning (ML) ensemble resolves ambiguities at higher energies, balancing interpretability and accuracy.

The detector response was characterized using controlled sources: ^{60}Co (1.17/1.33 MeV), ^{137}Cs (0.66 MeV), and a shielded ^{241}AmBe source (neutrons/gammas). Lead, paraffin, and cadmium isolated neutron and gamma interactions, generating enriched datasets. Charge spectra (analog-to-digital units, ADUs) were calibrated against known gamma energies, yielding a linear ADU-to-MeV conversion (R^2 = 0.966). A 3σ significance cutoff defined a neutron threshold at 2.62 ± 0.77 MeV, corresponding to the 2.22 MeV neutron-capture gamma in water. Stage one classifies sources as pure gamma (below threshold) or neutron-emitting (at threshold). To resolve the ambiguous region above the threshold, we assembled a machine learning pipeline centered on pulse-shape analysis. A soft-voting ensemble (combining Bagging, CatBoost, and a Multilayer Perceptron) achieved 81.6% accuracy and an area under the receiver-operating-characteristic curve (AUC) of 0.921.

This hybrid "traffic light" scheme (red/green/yellow classification) filters low-energy gamma sources via physics-based cuts, reserving ML for ambiguous cases. Future work will integrate deep-learning architectures for waveform analysis and advanced statistical models for low-energy spectra. The framework's interpretability and scalability make it ideal for nuclear security, nonproliferation monitoring, and fundamental radiation research.

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