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Neutron Studies in a Highly Segmented Detector of the T2K Experiment

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The T2K long-baseline neutrino experiment studies neutrino oscillations using a beam produced at J-PARC, the near-detector complex ND280, and the Super-Kamiokande far detector. The upgraded ND280 includes the Super Fine-Grained Detector (SuperFGD), a highly segmented plastic-scintillator target with three-dimensional readout and precise timing capabilities. These features make SuperFGD particularly suitable for neutron studies, since neutrons do not leave a direct ionization track before interacting.

This work presents a Monte Carlo study of neutron transport and energy reconstruction in SuperFGD. First, monoenergetic neutron samples were used to study flux attenuation as a function of detector depth and neutron kinetic energy. An energy-dependent neutron interaction cross section was extracted using the positions of first interactions and compared with the published SuperFGD prototype measurement on hydrocarbon.

The analysis was then extended to charged-current muon antineutrino interactions inside SuperFGD. Events were classified by interaction mechanism and final-state topology, with particular attention to neutron-containing final states. For each primary neutron, its kinetic energy was reconstructed using the flight distance and time interval between its production point and first hadronic interaction. For neutrons whose first hadronic interaction occurs inside the active detector volume, the TOF-reconstructed kinetic energy shows a strong correlation with the true value. A major limitation at the truth level is the finite detector volume, since some neutrons leave SuperFGD before interacting.

The TOF-reconstructed neutron energies were then used in a simplified truth-level calorimetric reconstruction of the incident muon antineutrino energy. The result was compared with an otherwise identical estimator using the true neutron kinetic energies. The comparison shows that TOF reconstruction introduces only a small additional energy bias. This demonstrates the potential of neutron time-of-flight information for accounting for the energy carried by neutrons in charged-current antineutrino events. The remaining energy imbalance requires further study, including the role of nuclear effects and the treatment of the final state. Future work will also include detector response, finite timing resolution, detection thresholds, and hit-level reconstruction.

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