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Neutron beam test with 3D-projection scintillator tracker prototypes for long-baseline neutrino oscillation experiments

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The long-baseline neutrino oscillation experiments rely on detailed models of neutrino interactions on nuclei. These models constitute an important source of systematic uncertainty, driven in part because detectors to date have been blind to final state neutrons. We are proposing a three-dimensional projection scintillator tracker as a near detector component in the next generation long-baseline neutrino experiments such as T2K upgrade and DUNE. Such a detector consists of a large number of scintillator cubes with three orthogonal optical fibers crossing through each cube. Due to the good timing resolution and fine granularity, this technology is capable of measuring neutrons in neutrino interactions on an event-by-event basis and will provide valuable data for refining neutrino interaction models and ways to reconstruct neutrino energy. Two prototypes have been exposed to the neutron beamline in Los Alamos National Lab (LANL) in both 2019 and 2020 with neutron energy ranging from 0 to 800 MeV. These beam tests, aimed at characterizing our detector's response to neutrons, is a critical step in demonstrating the potential of this technology. In this paper, the LANL beam test setup will be described and a neutron total cross section measurement methodology will be shown.

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[*] Speaker

1. Introduction

The future long-baseline neutrino oscillation experiments accomplish a measurement of the CP violating phase with an unprecedented precision by aiming beams of neutrinos and anti-neutrinos at a detector located several hundred kilometers or more away and measuring the oscillation of the (anti-)neutrinos between flavor eigenstates. In order to discern the oscillation phenomena, the experiments reconstruct the energy of the neutrino or anti-neutrino that undergo charged current interactions in the detector based on the resultant visible particles. While it is relatively straightforward to reconstruct charged particles, neutrons present a special challenge. Accounting for the energy in the form of neutrons typically results in large systematic uncertainties. Given common challenges, the DUNE and T2K experimentshave embarked on a joint R&D program to develop a high-quality plastic scintillator-based near detector. The fine-grained tracking detector design is composed of optically isolated plastic scintillator cubes with a size of 1 cm x 1 cm x 1 cm. Three wavelength shifting fibers cross each cube in three dimensions and a readout MPPC is attached on one end of the fiber [1]. Such a scintillator tracker, also called 3DST, provides three 2D views and a combination of those views can form a 3D reconstructed image. There are three key features of this tracker : fine-grained spatial resolution (<3 mm space point resolution in 2D space), fast timing (1 ns resolution for a single channel with light from a minimum ionizing particle [2]) and excellent neutron sensitivity (high efficiency 10 MeV and above [3]).

2. Detector and experiment setup

Two 3DST prototypes have been assembled and delivered to Los Alamos National Lab Weapon Nuclear Research (WNR) facility. One has a dimension of 24 cm x 8 cm x 48 cm (superFGD prototype) while the other 8 cm x 8 cm x 32 cm (US-Japan prototype). Those two prototype detectors were proposed and built by a collaboration with scientists from 14 institutions in 6 countries and CERN. The superFGD prototype has been exposed to a charged particle beamline in CERN and the results can be found in [4]. The WNR facility provides a neutron beam with energy ranged from 0 to 800 MeV. Each beam bundle is separated by 1.8 μs. Two separate run time in December 2019 and 2020 was allocated. In 2019, the prototypes were deployed at 90 m and 20 m locations from the proton target and in 2020, the prototypes were deployed only at 90 m location. A gamma flash, which provides a t0 signal, comes before the neutron arrives, which allows a neutron energy measurement with the time-of-flight. Given the outstanding time resolution in the detector, time difference between the gamma flash and the neutron arrival time has been used to obtain a 2% level energy resolution across a broad energy range. Fig. 1 shows the principle of the time-of-flight technique and what we observed in the detector. In both 2019 and 2020 runs, the neutron beam was collimated to a narrow profile of either 7 mm or 1 mm diameter. On average, with the 7 mm collimator setup, a neutron interaction is observed in the detector every 10 micropulses at 90 m location. This allows us to detect individual neutron interaction with its kinetic energy information.

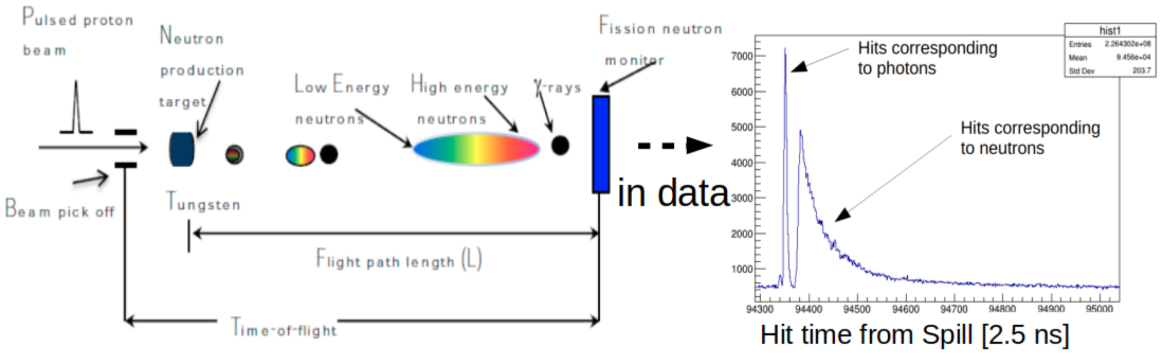

Figure 1: The principle of measuring neutron energy with time-of-flight and the time distribution measured in the detector.

3. Physics measurements and plans

The prototype detectors can measure each individual neutron interaction in the beamline and each individual interaction is analyzed based on the topology, time and energy deposit information. Fig. 2 shows two example neutron-induced event candidates. The neutron kinetic energy is obtained with the time-of-flight between the neutron production location and the detection location. The neutron-induced deposit energy is always smaller than the neutron kinetic energy. The beam is from the right to the left and the color corresponds to the detected charges. As a consequence, a number of neutron interaction deliverables will be extracted and input to the neutrino interaction modeling. The major measurements as functions of the neutron energy include

- Neutron-induced signal topology characterization,
- Neutron total and exclusive channel cross section,
- Neutron detection efficiency in the detector,
- Neutron secondary scattering rate and angle.

As a first step, given the simplicity, a total neutron cross section measurement as a function of incident neutron kinetic energy has being pursued using the so-called extinction method.

4. Neutron total cross section measurement

4.1 Method

With the extinction method, at each energy bin, an exponential curve is fit to the neutron interaction vertices along the beam direction. The exponential coefficient can provide a direct result of the neutron cross section. The left panel on Fig. 3 shows all the detected primary interaction vertices on the YZ plane. The beam is straight and narrow thus an exponential fit along z is desired. With this method, the only information we care is the relative neutron primary interaction rate at each depth (layer) along the beamline. Therefore the expression of the extinction measurement can

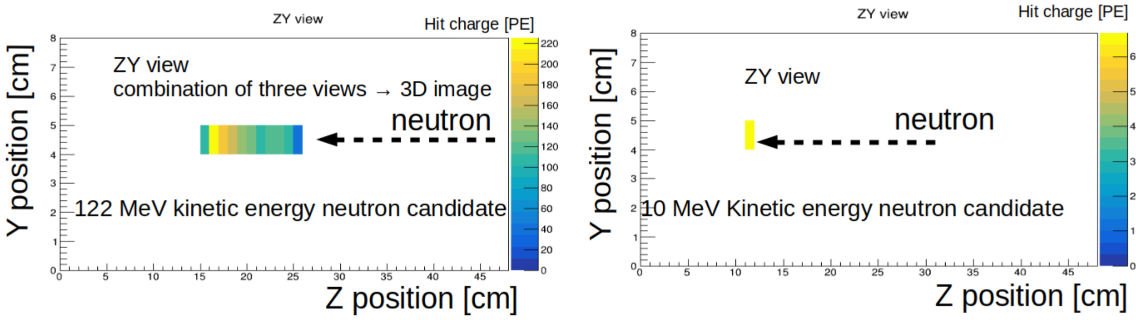

Figure 2: Two neutron-induced candidates on one of the three views in the superFGD prototype. The deposit energy can be calculated from the number of collected photoelectrons and it is less than the neutron kinetic energy.

be written as:

$$N_i^m/N_i^n = \frac{\sum\begin{pmatrix} N^m_{i,\text{primary single track}} \\ N^m_{i,\text{primary invisible}} \\ N^m_{i,\text{primary double track}} \\ \ldots \end{pmatrix}}{\sum\begin{pmatrix} N^n_{i,\text{primary single track}} \\ N^n_{i,\text{primary invisible}} \\ N^n_{i,\text{primary double track}} \\ \ldots \end{pmatrix}} = \frac{\sum\begin{pmatrix} N^m_{i,\text{primary single track}} \\ N^m_{i,\text{primary single track}} \times \epsilon_i \end{pmatrix}}{\sum\begin{pmatrix} N^n_{i,\text{primary single track}} \\ N^n_{i,\text{primary invisible}} \times \epsilon_i \end{pmatrix}} = \frac{N^m_{i,\text{primary single track}}}{N^n_{i,\text{primary single track}}}, \tag{1}$$

where N_{im} is the number of primary neutron interactions at ith energy bin and mth depth layer, ϵ_i is the cross section ratio between single track and non-single track at ith energy. Note that ϵ_i is depth independent. Hence Eq. 1 shows that a measurement of the single-track topology events depletion along the beam depth results in a measurement of the total cross section.

4.2 Reconstruction and event selection

The gain and light yield for each channel were calibrated for the neutron beam test. The gain was obtained for each channel with dedicated LED runs. The temperature variation is accounted for in the analysis. The light yield for each channel was obtained from a dedicated cosmic sample collected at LANL.

The reconstruction of the readout signals include three steps:

- 2D processing: on each 2D view, a photoelectron cut is applied in order to remove the noise and cross talk. The time clustering was performed. The time gap is detemined to be 17 ns based on empirical measurements of individual neutron-induced signal duration.
- 3D matching: three 2D views were combined to form 3D voxels. 3D spatial clustering: the 3D voxels was clustered with the DBSCAN algorithm. The sptial gap is determined to be 1.8 cm in order to identify the gap between clusters.

- Linearity analysis: a principle component analysis (PCA) was performed on each individual time and spatial cluster. A linearity value and a cluster width value can be obtained with the PCA returned eigenvalues on the 3D space.

The information included in each neutron interaction include the number of time clusters, number of spatial clusters and linearity information for each cluster.

A series of cuts were developed to select the neutron-induced single-track events. Firstly, a requirement of the single time cluster and single spatial cluster is applied. Then a high linearity condition with small cluster width is required for the cluster. The resulting cluster is single-track topology. An exponential function is fit to the event rate at each depth layer at each energy bin. The coefficient is the product of the nuclear density and the total cross section. The right panel in Fig. 3 shows an example exponential fit of the event rate along depth for incident neutron kinetic energy 200-250 MeV.

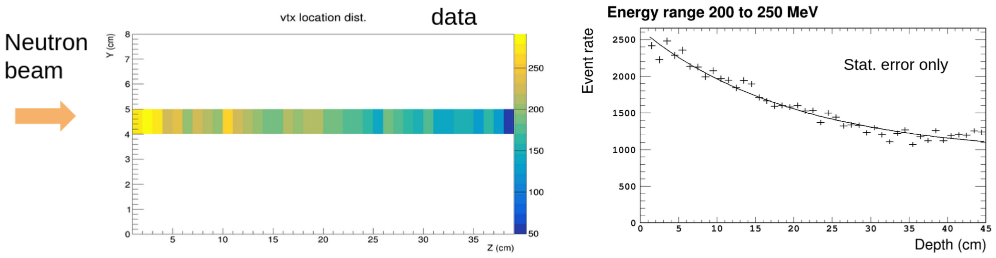

Figure 3: Left: vertex locations of all neutron interactions on the YZ plane. Right: Single-track event rate along the depth layer for incident 200-250 MeV KE neutrons with an exponential fit.

4.3 Systematic uncertainty

The statistics from the 2019 and 2020 neutron physics runs is very high so the result uncertainty is highly systematic dominant. The systematic uncertainty include four main contributors: invisible scattering, detection and reconstruction, energy resolution and light yield. The first two dominate our measurement precision. The invisible scattering uncertainty accounts for the fact that we may only detect the secondary neutron interaction and miss the primary interaction due to our detector threshold. A full interaction and detector simulation is developed and used prominently to understand this effect. The detection and reconstruction uncertainty mainly accounts for the non-uniformity of the detector response across the detector depth layers. All of the systematic uncertainties are being studied carefully and a final result is expected by the end of 2021.

References

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