Neutron Time-Of-Flight spectrometer based on HIRFL for studies of spallation reactions related to ADS project Postprint

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Abstract

A Neutron Time-Of-Flight (NTOF) spectrometer, based at the Heavy Ion Research Facility in Lanzhou (HIRFL) was developed for studies of neutron production of proton induced spallation reactions related to the ADS project. After the presentation of comparisons between calculated spallation neutron production double-differential cross sections and the available experimental data, a detailed description of the NTOF spectrometer is given. Test beam results show that the spectrometer works well and data analysis procedures are established. The comparisons of the test beam neutron spectra with those of GEANT4 simulations are presented.

Full Text

Preamble

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Neutron Time-of-Flight Spectrometer Based on HIRFL for Studies of Spallation Reactions Related to ADS Project

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Abstract: A Neutron Time-of-Flight (NTOF) spectrometer based at the Heavy Ion Research Facility in Lanzhou (HIRFL) was developed for studies of neutron production from proton-induced spallation reactions related to the ADS project. Following comparisons between calculated spallation neutron production double-differential cross sections and available experimental data, a detailed description of the NTOF spectrometer is provided. Test beam results demonstrate that the spectrometer functions well and that data analysis procedures have been established. Comparisons of the test beam neutron spectra with GEANT4 simulations are presented.

Keywords: Time-of-Flight spectrometer, Neutron production cross section, Spallation reaction, ADS project, GEANT4

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Introduction

Interest in spallation reactions [**?**, **?**] has grown with the development of Accelerator Driven Systems (ADS) and applications of Spallation Neutron Sources (SNS) in fields such as nuclear waste transmutation, nuclear energy generation, materials irradiation, and neutron scattering science. Spallation reactions are defined as interactions between a light projectile (e.g., a proton) with energies in the GeV range and a heavy target nucleus, resulting in the emission of numerous hadrons (mostly neutrons) or fragments. Various nuclear models, including the intra-nuclear cascade-evaporation (INC/E) [**?**] model and the quantum molecular dynamics (QMD) model [**?**], have been developed to study these reactions. These models are coded for thin-target simulations, but practical applications require calculations for complex geometries and multiple composite materials, necessitating embedding within sophisticated transport codes. Consequently, nuclear models combined with Monte Carlo transport codes such as MCNP [**?**], GEANT4 [**?**, **?**], FLUKA [**?**, **?**], and nucleon-meson transport codes (NMTC) [**?**] are widely utilized in designing engineering facilities based on spallation reactions.

However, the nuclear models embedded in these transport codes require validation through experimental measurements. Several laboratories worldwide \cite{11-14} have constructed dedicated experimental setups to measure the double-differential cross sections and spectra of neutrons produced in proton-induced spallation reactions. These experiments typically employ time-of-flight techniques with organic liquid scintillators (or plastic scintillators) and/or recoil proton measurements combined with magnetic spectrometers. Such measurements have significantly contributed to improving nuclear models. To further investigate reaction mechanisms and neutron production in proton-induced spallation reactions relevant to the ADS project, a Neutron Time-of-Flight (NTOF) spectrometer has been designed based at the Heavy Ion Research Facility in Lanzhou (HIRFL).

In this work, we examine the predictive capability of three nuclear models embedded in GEANT4 for double-differential cross sections of spallation neutron production by comparing calculated results with available experimental data [?]. The configuration and test beam results of the NTOF spectrometer are presented and discussed in detail.

II. Theoretical Calculations

GEANT4 is a Monte Carlo transport code developed at CERN for simulating particle passage through matter. It finds wide application in particle and nuclear physics, accelerator physics, medical science, astrophysics, and aerospace studies. GEANT4 offers users extensive choices of physics models to handle particle interactions with matter across a broad energy range.

Spallation reactions are typically described in two stages: the intra-nuclear cascade and de-excitation. In the first stage, the incident particle transfers kinetic energy to target nucleons through elastic collisions and a cascade of nucleon-nucleon collisions. Particles that acquire sufficient energy to escape the nucleus are emitted. The residual nucleus may also emit low-energy particles called pre-equilibrium particles before the de-excitation stage; these generally have higher energies than particles emitted later. In the de-excitation stage, excited nuclei lose energy through evaporation of neutrons, protons, or light charged particles. If nuclei lack sufficient energy for particle evaporation, they may emit gamma rays and decay to a stable state.

In this work, the BIC [?], INCL [?], and QMD [?] models embedded in GEANT4 were employed to calculate the first reaction stage, while a statistical model handled the second stage. The dynamical model interfaces with the de-excitation handler provided by GEANT4, enabling calculation of the double-differential cross section for neutron production at each stage.

Figure 1 [Figure 1: see original paper] compares experimentally measured neutron production double-differential cross sections from 800 MeV protons on a tungsten target at detection angles of 30° to 150° with simulated results from the BIC, INCL, and QMD models in GEANT4. Figure 2 [Figure 2: see original paper] presents similar comparisons for 800 MeV to 1600 MeV protons at a 30° detection angle. Both sets of spectra are multiplied by factors of 10^{-n} (n = 0, 2, 4, 6) from top to bottom. The INCL calculations show good agreement with experimental measurements across the entire angular and energy range examined, while BIC and QMD calculations slightly underestimate experimental results in some portions of the neutron spectrum, particularly in the high-energy tail. These discrepancies depend on both neutron detection angle and incident proton energy.

III. NTOF Spectrometer

The NTOF spectrometer is capable of measuring neutrons across wide energy and angular ranges. It consists of a beam pick-up detector and ten individual neutron detection modules. A schematic view appears in Figure 3 [Figure 3: see original paper].

The beam pick-up detector comprises a BC404 plastic scintillator (5 cm × 5 cm × 0.2 cm) with dual-PMT readout at both ends, positioned upstream from the target. It provides the time and position of the incident particle beam. Each neutron detection module consists of a thin plastic scintillator detector (veto detector) and an organic liquid scintillator detector. Two sizes of cylindrical BC501A organic liquid scintillator detectors are deployed at different angles. The larger detectors (12.7 cm diameter × 12.7 cm length) detect higher-energy neutrons with longer flight paths, while the smaller detectors (5.08 cm diameter × 5.08 cm length) measure low-energy neutrons. In front of each BC501A detector, a BC404 plastic scintillator (15 cm × 15 cm × 0.3 cm) coupled to a 9813KB PMT serves as a veto detector to distinguish charged particles from non-charged particles (neutrons and gamma rays). Gamma-ray separation from neutrons utilizes the pulse shape discrimination (PSD) property of the organic liquid scintillator detector. Neutron kinetic energy is calculated from the time-of-flight (TOF) spectrum between the organic liquid scintillator detector and the beam pick-up detector. The neutron flight path from target to detector is approximately 1.5 m, and a 400 ns TDC range is used to measure neutrons above 0.1 MeV.

A VME-based data acquisition system (DAQ) records experimental data on an event-by-event basis. The DAQ software, built on the CERN ROOT framework, runs on a Linux operating system and provides data acquisition, online monitoring, and offline data analysis with a graphical user interface (GUI) for convenient operation.

IV. Results and Discussion

A test experiment for the complete NTOF spectrometer system was performed by measuring the energy spectra, production yields, and angular distributions of neutrons, gamma rays, and charged particles from a tungsten target bombarded with a 400 MeV/u ^{16}O beam.

In the experiment, the combination of light output spectra from the veto detector and BC501A scintillator detector separated charged particle events from non-charged particle events (neutrons and gamma rays), as shown in Figure 4 [Figure 4: see original paper]. The anode signal from the BC501A scintillator detector was split into three pulses, with two fed into charge-to-digital converters (QDCs) having different gate widths (total and slow). QDCs with total and slow gates eliminated gamma-ray events through PSD using the two-gate integration method. A typical PSD result appears in Figure 5 [Figure 5: see original paper]. TOF spectra were measured between the beam pick-up detector and the BC501A detector. Figure 6 [Figure 6: see original paper] shows a typical TOF spectrum after excluding charged particle events, where the prompt gamma peak serves as the time reference. Energy calibration of the organic liquid scintillator detectors was accurately determined by comparing experimental light output from standard gamma sources with GEANT4 simulations [?].

Figure 7 [Figure 7: see original paper] compares experimental neutron production yields at detection angles from 10° to 60° (using larger BC501A detectors) with GEANT4 results. Neutron production yield was converted from TOF spectra normalized by unit solid angle and incident ion number. The simulations reproduce the experimental neutron spectral shapes well, with experimental data normalized to the simulation at 10°. These results demonstrate that the complete NTOF spectrometer system functions properly and that the data analysis procedure is established.

V. Conclusion

Sophisticated simulation tools based on nuclear reaction models are essential for nuclear engineering facilities. In this work, spallation neutron production cross sections from the BIC, INCL, and QMD reaction models embedded in GEANT4 were compared with available experimental data. The INCL model results show good agreement with experimental data across all energy and angular ranges studied, while BIC and QMD model predictions exhibit slight discrepancies with experimental results. Accurate nuclear data are required for ADS project design, motivating development of the NTOF spectrometer at the Institute of Modern Physics, Chinese Academy of Sciences. A test run of the complete spectrometer system using 400 MeV/u ^{16}O bombardment of a tungsten target demonstrates that the experimental apparatus functions well and the data analysis method is established. Future experiments will further improve and validate nuclear models embedded in Monte Carlo transport codes, which will serve as primary simulation tools for designing the spallation target of China’ s ADS project.

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Note: Figure translations are in progress. See original paper for figures.