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Fundamental neutron physics beamline at the spallation neutron source at ORNL

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ABSTRACT

We describe the Fundamental Neutron Physics Beamline (FnPB) facility located at the Spallation Neutron Source at Oak Ridge National Laboratory. The FnPB was designed for the conduct of experiments that investigate scientific issues in nuclear physics, particle physics, astrophysics and cosmology using a pulsed slow neutron beam. We present a detailed description of the design philosophy, beamline components, and measured fluxes of the polychromatic and monochromatic beams.

1. Introduction

Cold neutrons and ultracold neutrons (UCN) have been employed in a wide variety of experiments that shed light on important issues in nuclear, particle, and astrophysics. These include the determination of fundamental constants, the study of fundamental symmetry violation, searches for new interactions in nature and tests of the fundamental laws of quantum mechanics. Their special combination of properties make them a good choice to address the expanded list of fundamental scientific questions which now confront us in the wake of the discoveries of dark matter and dark energy, which shows that 95% of the energy content of the universe reside in unknown forms. In many cases, experiments with slow neutrons provide information not available from existing accelerator-based nuclear physics facilities or high-energy accelerators [1–3].

For this reason, most major neutron user facilities have included, as a component of their scientific program, the investigation of fundamental interactions. The great majority of these facilities have been located at continuous-wave (CW) spallation sources or intense research reactors to take advantage of the highest neutron intensities available. However, many precision experiments could benefit from the special characteristics of pulsed mode spallation neutron sources, which enables experiments to use the time and energy structure of the slow neutron beam to advantage. The peak and average cold neutron fluxes from pulsed reactors like the Frank Laboratory of Neutron Physics and spallation sources like the Los Alamos Neutron Science Center (LANSCE), the Spallation Neutron Source (SNS), the Japanese Spallation Neutron Source (JSNS), the ISIS spallation source at the Rutherford Appleton Lab, and the future European Spallation Source (ESS) are now high enough that a relatively broad class of fundamental neutron physics experiments can be best performed at such facilities.

In this paper we describe the construction and commissioning of a pulsed slow neutron beamline and facility at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory which is optimized to conduct certain experiments in this field. The design of the facility attempted to preserve the advantages of pulsed spallation sources in reducing systematic errors in a broad class of fundamental neutron physics experiments. One such feature is the well-known time structure of the beam. It can be used to identify and analyze the neutron energy dependence of background signals which are invisible at a CW source, to shape the beam phase space in special ways using time-dependent neutron optical components, or to help perform absolute neutron polarization measurements.

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Another feature of a spallation neutron source is the fact that the neutron source is off by the time the slow neutrons arrive at the apparatus, which generally reduces background signals in detectors. With improved neutron optics technology one can bend the slow neutron beam enough to eliminate line-of-sight to the production target and to guide it far from the spallation source so that the very high energy neutrons and gamma rays generated in spallation do not adversely affect the physics experiments.

Furthermore, since this beamline is operated as a user facility with all beam time allocated on the basis of independent peer reviews, it was essential to design the facility to accommodate a wide variety of different types of slow neutron experiments and especially to avoid precluding to the extent possible new unforeseen ideas for future experiments. An Instrument Development Team for the beamline facility reached a consensus based on experience at other facilities combined with feedback and discussions from potential future users in the form of the following design principles:

1. Total intensity was to be maximized. Essentially all of the experiments in this field are limited by statistics. The facility design must not include features that lead to a permanent reduction in the neutron fluence (total number per second).
2. Cold neutron intensity is of the highest priority. Almost all of the experiments of relevance for the areas of nuclear and particle physics prefer low energy neutrons. Slower neutron beams raise the signal/background ratio in neutron decay experiments. The opportunities for creative manipulation of the beam properties (phase space, polarization, etc.) are greater for cold neutrons.
3. The unique properties of a spallation neutron source should not be compromised in the beamline design. The advantages that a spallation source offers experiments in this area relative to a steady-state source are directly or indirectly rooted in the built-in use of neutron time-of-flight and a corresponding potential for increase in the signal/background ratio. Everything must be done to preserve this advantage while at the same time being consistent with (1) and (2).
4. Accommodate the different demands of different classes of experiments consistent with (1)–(3).
5. Leave as much floor space as possible. This allows for flexibility in the design of future experiments.

In the remainder of this paper we describe the details of the design of the facility which we have realized consistent with these principles and the physical constraints and properties specific to the Spallation Neutron Source at ORNL. We hope that this detailed description of the beamline design and properties will be useful both to potential scientific users and to the design of possible future facilities at pulsed spallation sources such as the ESS [4]. The specific design choices made for the SNS facility are by no means unique: we encourage the reader to contrast the SNS facility with the other fundamental neutron beamlines constructed at pulsed spallation neutron source, namely the pioneering beamline at LANSCE [5] and the fundamental neutron physics beamline at the JSNS, which supplies a collection of three slow neutron beamlines with different phase space profiles optimized for different sub-classes of experiments [6,7]. We also encourage a comparison with the intense CW slow neutron beam facilities for fundamental neutron physics already in operation or under development at PSI [8–11], ILL [12], and NIST [13,14].

2. The spallation neutron source

The Spallation Neutron Source (SNS) is the most intense pulsed neutron source in the world, designed to deliver a sub-microsecond proton pulse onto a mercury target at a repetition rate of 60 Hz with time-averaged proton power of 1.4 MW. The released spallation neutrons are moderated by supercritical hydrogen and water moderators. The resulting slow neutrons are used for a variety of experiments. The SNS can support 24 instruments which can conduct experiments simultaneously.

The SNS uses a cesium-enhanced, RF-driven multi-cusp ion source [15] to provide a 65 keV H^- beam at 60 Hz with a pulse length of up to 1 ms. The normal conducting linac consists of six drift tube linac (DTL) tanks, which bring the H^- beam energy up to 86.8 MeV, and four coupled cavity linac (CCL) structures, which supply additional acceleration to bring the energy to 185.6 MeV. This is followed by a superconducting linac consisting of 11 medium-beta ($\beta = 0.61$) cryomodules and 12 high-beta ($\beta = 0.81$) cryomodules. The medium-beta cryomodules each contain 3 cavities and provide 10.1 MV/m, bringing the H^- ions up to an energy of 379 MeV. The high-beta cryomodules (consisting of 4 cavities each) are designed to provide up to 15.9 MV/m resulting in a maximum proton energy of 1.3 GeV. In June of 2014, the SNS was operating at 940 MeV of proton energy.

The H^- pulses arrive at the ring injection point via a 150-m long beam line which is used for energy collimation (bending magnets) and transverse halo collimation (straight sections). The ring consists of four straight sections as well as four arcs, with a total flight path corresponding to 1 us of accumulated proton pulse length. The incoming H^- beam is stripped of its two electrons by passing through a thin carbon or diamond foil, and is merged in phase space with the circulating proton beam. Currently, the ring design allows operation at up to 1.0 GeV, but RF systems and injection kickers have been designed to support 1.3 GeV operation with minimal upgrades.

The protons are incident on a target of circulating mercury, producing spallation reactions as they deposit their energy. The mercury is contained inside the stainless steel target module, one of the components of the target system. The target module is made of two concentric vessels, where the inner vessel contains the target mercury during normal operation, and the outer vessel contains any mercury that may leak from the inner vessel. The main process loop contains $\approx 1.4\ m^3$ of mercury, circulating at ≈ 325 kg/s, at a pressure of ≈ 0.3 MPa. The inner vessel is cooled by flowing mercury, whereas the outer vessel is cooled by water. The two vessels are separated by a helium-filled interstitial region, where there are two instruments present. A heated resistance temperature detector (RTD) is able to detect leakage as well as distinguish between mercury and water; an electrical conductivity probe detects the presence of mercury between the contacts [16,17] (Fig. 1).

Spallation neutrons are moderated by undergoing repeated scattering primarily with hydrogen and beryllium atoms. The configuration at the SNS includes four moderators, two of which are viewed from both sides of the target. Three moderators are supercritical hydrogen at ≈ 20 K, and one is liquid water at ≈ 320 K. The moderators are surrounded by a water-cooled beryllium inner reflector, which is then surrounded by water-cooled stainless steel [16,18]. The configuration can be seen in Fig. 2. The viewed faces of all the moderators are 10 cm (horizontal) by 12 cm (vertical).

The FnPB views the bottom downstream moderator, where the hydrogen is delivered through the bottom of the vessel via a jet, which forces the hydrogen to circulate. This moderator is fully coupled unpoisoned hydrogen (nominally parahydrogen) at 20 K (viewed from one side only), with a curved viewing surface and maximum moderator thickness of 60 mm (average of 55 mm). The moderator is surrounded by ≈ 20 mm of light water acting as a premoderator.

3. Fundamental neutron physics beamline - overview

The Fundamental Neutron Physics Beamline (FnPB) is one of three experimental areas which view this coupled liquid hydrogen