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Demonstration of a single-crystal reflector-filter for enhancing slow neutron beams ☆

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ABSTRACT

The cold polycrystalline beryllium reflector-filter concept has been used to enhance the cold neutron emission of cryogenic hydrogen moderators, while suppressing the intermediate wavelength and fast neutron emission at the same time. While suppressing the fast neutron emission is often desired, the suppression of intermediate wavelength neutrons is often unwelcome. It has been hypothesized that replacing the polycrystalline reflector-filter concept with a single-crystal reflector-filter concept would overcome the suppression of intermediate wavelength neutrons and thereby extend the usability of the reflector-filter concept to shorter but still important wavelengths. In this paper we present the first experimental data on a single-crystal reflector-filter at a reflected neutron source and compare experimental results with hypothesized performance. We find that a single-crystal reflector-filter retains the long-wavelength benefit of the polycrystalline reflector-filter, without suffering the same loss of important intermediate wavelength neutrons. This finding extends the applicability of the reflector-filter concept to intermediate wavelengths, and furthermore indicates that the reflector-filter benefits arise from its interaction with fast (background) neutrons, not with intermediate wavelength neutrons of potential interest in many types of neutron scattering.

1. Introduction

In moderators for slow neutron sources, a reflector-filter can be used to enhance the emission of cold neutrons while suppressing the fast neutrons comprising a major source of instrumental background. Some of the neutrons emitted with wavelength less than approximately 4 Å are reflected back into the moderator (reducing the fast neutron emission) and get another chance to be scattered down to desirable energies before being emitted once again. The reflector-filter has only recently been implemented at the Lujan Center [1], where its observed performance was documented. It increased the source emission above 4 Å by more than a factor of two, while reducing the (for these instruments) undesirable neutron intensity below 1 Å by a factor of four. Unfortunately, the reflector-filter also suppresses beam intensity between 1 Å and 4 Å—these neutrons are not necessarily background, but potentially very important. For many scattering instruments this is an acceptable trade-off, but for some scattering instruments, the loss of 1–4 Å neutrons is unacceptable. It has been theorized that a single crystal can also be used as an effective reflector-filter [2–4]. A single crystal does not have the same sharp Bragg edge associated with a polycrystalline filter—the effective cross section is the same at long wavelengths, but remains low through the 1–4 Å range as well. We therefore anticipate that a single-crystal reflector-filter will augment the neutron emission at long wavelengths just as the polycrystalline reflector-filter does, but will also enhance (or at least not decrease) the neutron emission at energies 1–4 Å relative to a conventional cold moderator without any reflector-filter.

Reflector-filters, both polycrystalline and single-crystal, were tested on an unreflected pulsed neutron source at the I.V.

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Kurchatov Institute of Atomic Energy [3,4], indicating gains approaching a factor two at long wavelengths from 40 mm layers of beryllium and quartz, respectively, placed adjacent to the moderator, covering the viewed moderator area as well as significant additional solid angle. As such, the reflector-filters tested there did not distinguish between the gains arising from a (partial) reflector assembly, such as is now common [5], and a reflector-filter blocking only the outgoing beamline within the neutron reflector. Studies in Japan [6] and at the Lujan Center [7,8] on the beryllium (polycrystalline) reflector-filter reinforce this distinction. The optimum thickness for a polycrystalline beryllium reflector in the unreflected Kurchatov measurement is 20–40 mm, and gives a factor of two low-energy intensity gain [3]. An even thicker beryllium reflector filter (50 mm) was tested in Japan and found to provide no low-energy gain [6], which those authors attribute to the fact that their test assembly was already fully reflected. At the Lujan Center, the successful deployment of a beryllium reflector-filter in a fully reflected system, which did achieve that factor two gain at low energies, required a much thicker reflector-filter of 120 mm [7,8].

This study describes a set of experiments carried out at the Low Energy Neutron Source [9–11] (LENS) between 21 April 2014 and 11 May 2014. The aim of this campaign was to demonstrate the concept of a single-crystal reflector-filter on a reflected pulsed slow neutron source.

2. Single crystal reflector-filter concept

The concept of a cold beryllium reflector-filter on a reflected pulsed slow neutron source was first proposed in [12], and has later been implemented in the moderator system at the Lujan Center [1]. The concept of a reflector-filter is simple—by placing a thick block of material with high coherent scattering cross section but small incoherent and absorption cross sections on the front face of the moderator (nominally blocking the neutron beamlines), many fast (energy greater than 1 MeV, wavelength less than 3×10^{-4} Å), slowing-down (energy between 1 eV and 1 MeV, or wavelength between 3×10^{-4} Å and 0.3 Å), and slow (energy below 1 eV, wavelength above 0.3 Å) neutrons which would have leaked out through the neutron beam-ports will have some chance of scattering in the filter, returning to the moderator, and increasing the neutron density in the moderator. Beryllium, with its large but predominantly coherent scattering cross section, is an ideal reflector-filter material. A cold beryllium reflector-filter will scatter many neutrons with wavelengths less than that of the so-called Bragg edge at 4 Å (5 meV), but it is very nearly transparent above that wavelength. This property of beryllium is frequently exploited as a beam-line filter [13], taking advantage of the change in the scattering cross section from some 6 barns per atom below 4 Å to less than 0.005 barns per atom above that wavelength (cross sections from ENDF/B-VII.0). As the reflector-filter returns neutrons below 4 Å to the moderator and increases the total neutron density therein, the neutrons have a much higher chance of being emitted at wavelengths above the Bragg edge than would otherwise be the case.

While the cold neutron emission increase at wavelengths above the Bragg edge is significant (as much as a factor two in the right geometry, such as at the Lujan Center [1,7,8]) the major problem with a polycrystalline reflector-filter is the suppression of neutrons with wavelengths below the Bragg edge at 4 Å but still within the slow neutron range useful for neutron scattering. These 1–4 Å neutrons are essential to many instruments, even those primarily considered to be "cold neutron instruments."

The single-crystal reflector-filter [2] exploits the fact that, in a single crystal, only very narrow portions of wavelength-angle phase space meet the Bragg condition and will be scattered by the reflector-filter material. The transmission at long wavelengths (above the Bragg edge) will be just as high as in the polycrystalline case (if not higher, given the possibility of more small-angle scattering in the polycrystal), but the transmission between the Bragg edge and the wavelength at which inter-atomic effects become important (that is, around 1–4 Å) will also be high. This can be exploited in the same way as the conventional reflector-filter to scatter fast neutrons back into the moderator to increase the neutron density, while letting neutrons over the entire wavelength range of interest escape.

As a corollary, a comparison of the wavelength-dependent gain factors of the polycrystalline reflector-filter and the single-crystal reflector-filter (relative to a conventional moderator) should allow us to proportionally attribute the neutron emission gains from that polycrystalline reflector-filter to the wavelength ranges below 1 Å and from 1 Å to 4 Å:

- If the single-crystal reflector-filter provides a gain factor comparable to the polycrystalline reflector-filter at long wavelengths, and additionally provides a gain ($G(\lambda) > 1$) between 1 Å and 4 Å, then the reflector-filter benefit is coming primarily from the previously described process acting on fast and slowing-down neutrons ($\lambda < 0.5$ Å).
- If the single-crystal reflector-filter provides a reduced gain factor at long wavelengths, and imposes a loss ($G(\lambda) < 1$) from 1 Å to 4 Å as compared to a conventional moderator, then the reflector-filter benefit is coming primarily from the previously described process acting on slow neutrons below the Bragg edge ($1 < \lambda < 4$) Å.

In neutron scattering, it seems that there is no agreement as to whether one should use wavelength or energy for neutrons. In this work, we will use primarily wavelength, for its direct comparison to time-of-flight and easy identification of Bragg edges, even though discussing "fast neutrons," which have energy greater than 1 MeV, in terms of wavelength (less than 3×10^{-4} Å) is unusual.

3. Experimental setup

3.1. LENS Moderator test facility

The Low Energy Neutron Source (LENS) is a small scale neutron facility, producing neutrons from a 13 MeV proton beam impinging on a beryllium target, which we use for moderator research and development [14]. For this experiment LENS was set up to produce 13 µs pulses at 40 Hz, resulting in a time-averaged beam power of 142 W. The beryllium target is embedded in a cylindrical reflector of 300 K light water, with a cavity where the moderator system can be lowered from above. The water reflector is surrounded by lead shielding, embedded in alternating layers of lead-epoxy and borax-epoxy-polyethylene. The water tank and shielding have an opening enabling four beam-lines to view the moderator location; see Fig. 1. When operated as a moderator test facility, the moderator usually used in LENS is removed, and test moderator assemblies can be sequentially installed.

3.2. Instrumentation

In addition to a proton beam current measuring device (the Q-box) used for normalization, our experimental instrument suite consists of two detectors: a low-efficiency beam monitor within the SANS beam-line and an emission time analyzer we add to the SANS beam-line for moderator tests.

The SANS beam-line beam monitor is a thin low-density ^{3}He