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Neutron Moderator Development Research at the Low Energy Neutron Source

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Abstract

The Low Energy Neutron Source at Indiana University completed its construction phase roughly three years ago, and one of the more active research thrusts at the facility since that time has been our attempts to advance the state of the art in neutron moderation. This research program includes basic materials characterization, especially total neutron cross section measurements, as well as in-situ testing of the performance of various prototype moderators. This paper reviews a number of the more noteworthy results we have uncovered and describes the goals of the moderator development program at LENS.

Keywords: Neutron moderators; Very Cold Neutrons;Total Neutron Cross Section

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1. LENS Neutronic Design

LENS is a University-based neutron source that has been constructed at Indiana University to support materials research with neutron techniques, promote education in the neutrons sciences at all levels, and to develop advance neutron technologies [1]. A key element of the technology development program at the facility is our efforts to improve the performance (increased efficiency, decreased spectral temperature) of neutron moderators, but we also have active programs in detector development as well as improving instruments that rely on neutron spin manipulation.

The facility is well-suited to moderator research because the efforts devoted to design the Target/Moderator/Reflector (TMR) to facilitate the exchange of moderators in a short period of time with minimal need for remote handling of components [2]. This was accomplished through the extensive use of aluminum alloys near the target and the use of high-purity shielding and target materials (particularly Pb with minimal Sb impurity), and setting the proton energy to 13 MeV (to avoid production of ^{3}H and ^{7}Be in the target). We also sacrificed some neutronic efficiency in the design, in order to allow the system to accommodate moderators that were thicker than would be optimal for normal operation of LENS as a neutron scattering facility since in many cases such thicker moderators are of interest to spallation sources, and perhaps other facilities as well. As discussed later in this paper, we have since discovered that there may even be a role for quite thick moderators in low-energy sources such as LENS. Another very useful feature of LENS for all the work presented here is that its pulse parameters may be varied to the demands of a particular experiment. In our research to date we have extended the frame down to neutron energies of less than 0.05 meV by reducing the source frequency to 10 Hz, and conducted emission time measurements with pulse widths as small as 14 μsec. at frequencies up to 40 Hz. For standard operation, the facility normally runs at 20 Hz with a pulse width of something greater than 0.6 msec.

Two other aspects of the LENS design make it attractive for exploring the physics relevant to increasing the flux of very long-wavelength neutrons (say on the order of or greater than 2.0 nm) available from moderators. The moderator in the LENS TMR experiences a much smaller radiation dose than do similar moderators at spallation or reactor sources. This is due not only to the low operating power of LENS (operations for moderator research are typically conducted at power levels less than 1 kW), but also due to the much lower flux of high-energy neutrons and gamma rays from the target itself. The use of water and/or polyethylene as premoderators has reduced this radiological load even further, and it also significantly lowers the heat load on the moderator itself. In our most recent configuration, we have measured a beam-induced heat load of approximately 30 $\mu W/cm^3$ for 1 kW of proton beam power. For the standard LENS moderator (which has a volume of only 155 cm^3) this will correspond to a beam-induced heat load of on the order of 30 mW even for operations at highest power LENS has yet operated (6 kW), and consequently we are able to maintain a temperature of less than 6 K with a simple closed-cycle refrigerator design. At this moderator temperature, we routinely operate with a spectral temperature below 25 K with our standard moderator (1 cm thick methane, with premoderators of roughly 6 cm of room temperature water and 1 cm of polyethylene held at 30 K).

2. VCN regime

One of the goals of our moderator program is to lower the spectral temperature available at LENS to something significantly less than 10K (i.e. a push toward the regime that has become known as Very Cold

Neutrons [VCN's]). The scientific program at the facility is focused primarily on large-scale structures, and our instrument performance will be increased by this. There is, however, a general interest in the development of neutron sources with ever colder neutron spectra, since the statistical quality of the data collected is directly related to the phase space density of the beam in many cases [3,4]. Unfortunately, the development of VCN sources is hindered by the lack of reliable data in the standard cross-section libraries and kernels available for use in the extensive Monte Carlo modeling of neutron transport that is crucial to today's approach to the design of neutron sources. In a recent review of ENDF and ACE library data for water and ZrHx, significant deviations of the library models from available total cross-section data for even these comparatively well-studied materials at neutron energies below 1 meV [5]. In the case of H2O, available models overestimate the total cross section by a factor of almost 2 for energies near 0.1 meV, with even larger deviations seen at lower energies. Design of optimized sources is impossible if the available models are unable even to accurately describe the total cross section of the relevant materials in the energy range of interest. Of course, accurate modeling requires far more than the ability to reproduce the total cross-section, but we take this as a minimal criterion for a model to show promise in the VCN regime. Therefore, one of the experimental programs at LENS that supports moderator research is a series of measurements of total cross sections on materials of relevance to future VCN sources. To date this program has concentrated on demonstrating the facility's capabilities (in particular the range of energies that we can cover in a given experiment), but in the future we expect to investigate a number of deuterated materials that should be of direct interest in VCN moderators.

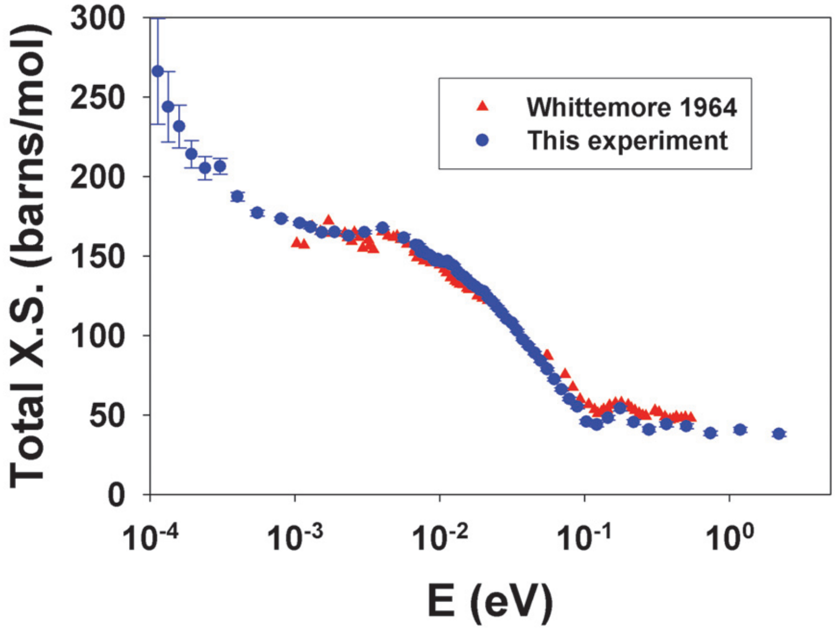

Fig. 1 Total cross section of ZrH_2 as measured on the SANS instrument at LENS demonstrating our ability to reach energies on the order of 0.1meV in such measurements. Data collected at LENS are compared with data published in [6].

Figure 1 shows data collected recently on a sample of ZrH_2. The measurements were performed on the SANS beamline at LENS, using a Li-glass (GS-20) scintillation detector, sample at a distance of 8.0 m from the source and a secondary flight path of roughly 30 cm. We discovered that, despite the limited gamma field from the target itself, the long-wavelength limit of this measurement was determined by an unexpectedly large background from gamma rays (we have estimated that the instrument saw roughly 4 decay gammas from activated ^{28}Al for every neutron with an energy below 1eV), and therefore we added a room-temperature lead filter in place to extend the measurement down to 0.1 meV. The lead filter had the added bonus of limiting the importance of dead-time corrections near the peak in our spectrum (where instantaneous count rates would reach 60 Kcps for a period of several msec, in the absence of the filter). The transmission was measured using a sample-in, sample-out technique, with an upstream ^3He beam monitor used to remove any residual variation in incident beam intensity from the measured intensity ratio. In this case, we have made no correction for small-angle or multiple scattering contributions to the measure transmitted spectrum, but we believe that the use of the SANS beam line for these measurements will allow for such corrections to be included in future analyses.

Our future experiments in this program will include surveys of deuterated materials that might be suitable for future VCN moderators. In addition, total cross-section measurements can be used to screen for materials with enhanced spectral weight at low energies in our on-going efforts to find materials that are even more effective than methane for cold neutron moderation. With simple changes to the present setup (such as using moderator ideas discussed below, employing a ^3He detector, and/or increasing source power), we believe that routine measurements of total cross-sections with a statistical precision of better than 10% down to energies of 0.05 meV will be possible at LENS within the next year.

3. Moderator Prototyping

The low temperature and efficiency of the LENS moderator facilitates measurements such as those discussed above, but it is the ability to characterize the performance of multiple moderators in a short period of time that is the more novel capability of the facility. To date, we have conducted 4 different experiments that have utilized this feature at LENS. These have included measurements to validate models for predicting the performance of Cd and Gd poison plates in a room temperature polyethylene moderator [7]. Only small differences near the major Cd and Gd absorption resonances were seen between the measured and modeled ratio of the spectra from the two moderators. Based on the success of these measurements the poison plate design of the SNS cryogenic moderators is being changed for the next replacement of the inner reflector plug to employ Cd rather than Gd poison plates. This is expected to increase the useful lifetime of this rather expensive component of that facility by roughly 50%. In this case, polyethylene was used as a convenient moderating medium for the experiment, and a testing ground for the modeled performance of the two poison plate materials. The cryogenic moderators actually used at the SNS, of course, employ liquid hydrogen.

In a similar manner, polyethylene was used as the moderating medium to test a novel idea for a heterogeneous moderator, although it is our expectation that this idea will prove far more useful when deployed in a solid methane or liquid ortho-hydrogen moderator. The basic idea here is to construct a moderator that consists of a laminated structure of moderating medium with single crystal vanes. The thickness of these moderating layers is chosen to be roughly a mean free path for thermal neutrons and the crystal vanes are made somewhat thinner. In the experiment described here, the moderating layers were 2mm-thick sheets of polyethylene, and the crystal vanes were Si wafers 0.5mm thick. Roughly 32 wafers and 33 polyethylene sheets were stacked to form a moderator with an 80x80 mm face and 80 cm thickness. The idea behind this configuration is that the Si wafers act as selectively transparent slices through the moderator, so that cold neutrons (with wavelengths on the order of the Bragg cutoff for silicon or longer) are able to escape from the moderator even from deep within its volume, rather than only from a relatively thin layer on the moderators viewed face. This is very much like the well-established concept of the grooved or castellated moderator, but unlike that idea, in this case the grooves are much thinner and they make at least some contribution to the moderating process by scattering neutrons with wavelengths much shorter than the Bragg cutoff back into the moderating layers for further reductions in their energy. Instruments viewing the edges of the Si in this moderator are therefore expected to see an increased neutron intensity and a reduced spectral temperature, compared to what they would see from a monolithic block of the moderating medium itself (of the same size).

For this experiment, we measured three different, but related, cryogenic moderators within a two-week period. In each case, the moderator was framed with a Cd mask that removed any direct path to the reflector behind the moderator from the detector's view. In addition to the design described in the above paragraph (we refer this configuration as the horizontal stack below), we measured two controls; one of these consisted of a stack of 40 polyethylene sheets with no Si wafers (polyethylene only), and the other was the same stack of polyethylene and silicon, but viewed from the face of the polyethylene rather than fron the edges of the layers (a vertically-oriented stack). Due to the rapid moderator exchange planned for this experiment, we used very little beam power for these measurements (proton power was reduced to 310 W and spectra collection times typically lasted from 5 to 20 minutes). The personnel dosimeters on the experimenters working on the activated moderator components recorded minimal exposure (i.e. less than 10 mrem), and subsequent experience has confirmed that considerably more beam can safely be employed in these sorts of experiments (opening up opportunities to measure emission tme distributions as well as spectra in future studies).

Each of the three moderators was cooled down to 60K (as measured by a Si diode thermometer mounted on the frame holding the stack together) and then the spectrum was measured using the same scintillation detector employed for the total-cross section measurements described above and positioned at the sample location on the SANS instrument. In this case no filter was included in the beam path, other than the Si wafers used as windows on the evacuated flight path, a few air gaps in the flight path (roughly 1.5 m altogether), and the walls of two thin monitor detectors place further up the beam path in case the moderator was not aligned horizontally with adequate precision to fall within the acceptance of the instrument's full primary flight path collimation. Our measurements suggest that we were able to achieve sufficient accuracy in our alignment (roughly +/-0.6 deg), and the spectra shown in figure 2 have not been corrected for the filtering effects of these various objects in the primary flight path of the instrument since our primary goal here is to compare the relative intensity of the different moderators. We note in passing, that we did confirm a significant shift in spectral intensity when the moderator angle was shifted by about 1 deg.

Figure 2 compares the intensity from the moderator with horizontal vanes to that from the monolithic polyethylene moderator. The two moderators exhibit identical spectra above 0.5 eV, but distinctly different spectra below this energy. In particular, it should be noted that near 3 meV, the moderator with horizontal vanes exhibits a flux that is roughly a factor of 2.5 greater than the polyethylene-only moderator.

Should future experiments confirm that this concept yields similar benefits for in the case of methane as the moderating medium, this result could prove to be a significant boost for the performance of facilities such as LENS. This concept would require a much thicker moderator than presently employed at LENS (several cm rather than 1 cm), but at 6kW it should still have a beam-induced heat load of less than 0.1 W, which would still allow operation well below 10K. The thicker moderator may also obviate the need for the Be filter presently utilized on the SANS instrument (to limit background induced by fast neutrons). If this could be realized with a tolerable impact on the instrument background, typical data collection times on the SANS instrument could be reduced by a factor of 3 or more.

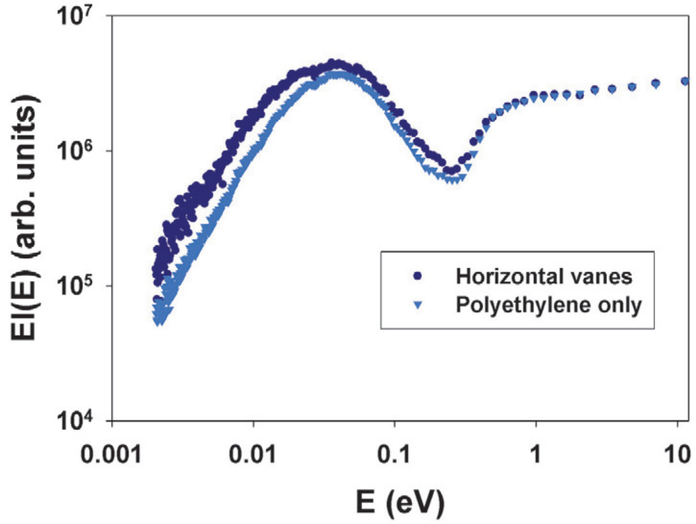

Fig. 2 Lethargy flux measured from two moderators inserted into the LENS TMR and held at a temperature of 60K. One is a laminated composite of polyethylene sheets and horizontally oriented single crystal vanes of Si, and the other is a simple stack of polyethylene sheets. We note that the intensity from the composite moderator is approximately a factor of 2.5 greater at energies on the order of a few meV.

4. Conclusions

Experiments conducted to date at LENS have demonstrated our ability to measure total cross sections of materials relevant to moderator research to energies at least as low as 0.1meV, and we expect to reduce this by at least a factor of two over the next few years. We have also demonstrated our ability to measure multiple moderator prototypes in a short period of time (up to three different moderators have been measured within two-week run cycles on multiple occasions) without any need for remote handing of components. In one such experiment, we have demonstrated a novel concept in moderator design that holds promise to boost the cold neutron flux by more than a factor of 2, and perhaps even greater gains in the performance of some instruments may be possible using this and related ideas.

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