THE LOW ENERGY NEUTRON SOURCE AT INDIANA UNIVERSITY
(an example of the power and versatility of small accelerator-based neutron sources)

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The Low Energy Neutron Source (LENS) at Indiana University was built to provide a novel facility for exploring new concepts in neutron scattering, unique opportunities for education in neutron related fields, and to serve as a regional facility for the application of neutron scattering to materials research. The source uses a 13 MeV proton beam to create neutrons in a flat water-cooled Be target. The neutrons are fed into a number of beamlines from a thin solid methane moderator. At the moment two beamlines are operating, one devoted to SANS and the other devoted to exploiting neutron spin manipulation to explore density correlations in materials up to length scales on the order of a micron. The facility has now been operating for several years and similar facilities are presently under consideration or construction in several countries throughout the world. We describe the source design and some of the science that we have investigated at the facility as well as some of the plans for similar facilities at other labs.

I. Introduction (the idea of small sources)

The last decade has seen an increasing global interest in the development of small-scale accelerator-driven neutron sources. Present and anticipated applications for such sources range from centers for education and research in the neutron sciences [1,2,3], radiography (including both engineering and homeland security) [4], and neutron capture therapy [5,6,7]. As such, the size of such facilities range from units that might be transported on a truck for use in the field, to small neutron scattering facilities. The Union of Compact Accelerator-driven Neutron Sources (UCANS) was formed in 2010 to provide a forum for exchange of technical information and coordination among various groups engaged in the construction and operation of such facilities [8]. Such facilities can be constructed using either electron or proton accelerators, with each type of source having advantages for particular applications. Electron linacs with an energy on the order of 25 to 50 MeV are suitable for sources based on photo-neutron production using heavy metal targets. Proton-based sources have been considered with both Li and Be targets, with the former being suitable in lower-energy (4MeV or less) applications and the latter generally being more convenient if higher proton energies are available.

Sources based on a Li target are primarily of interest due to the low threshold of the neutron-producing reaction and the relatively large production cross-section near this threshold. This allows one to construct a source with significant neuron flux with a particularly soft spectrum using a low proton energy. Therefore, this design has been particularly attractive in situations where minimizing the shielding around the target is a major concern (e.g. portable sources for radiography or for BNCT). The design of the target for this type of source is complicated by the low melting point and high vapor pressure of Li, as well as the production of ^{7}Be in the primary reaction (which is not often discussed, but would lead to a high level of activation in the source) [7].

Facilities based on electron accelerators typically produce the hardest neutron spectrum of the three types considered here. Such sources also have very significant gamma and x-ray fields near the target due to the high energy of the electrons and the high atomic number of the target material. On the other hand, these facilities have significant advantages due to the simplicity, reliability, low cost, and low maintenance of the electron accelerators they employ. Another significant advantage is the short duration of the electron pulse, which results in a very sharp leading edge on the resultant neutron pulse. Two groups have already demonstrated that this pulse structure can be used to obtain remarkably detailed information regarding the atomic structure of materials (including identification of material phases, particle sizes, and even polycrystalline texture) through simple neutron transmission measurements [9]. This is a striking new development that could greatly expand the utility of compact neutron sources for materials research.

For LENS we were primarily interested in a facility that would be versatile and have modest gamma and fast neutron backgrounds along with limited activity near the source after the beam was shut down. Neither of the above two reactions seemed suitable for this application.

II.A An Overview of LENS

The LENS facility at Indiana University was constructed with a three-fold mission of facilitating advances in neutron technology (particularly advanced

neutron moderator concepts and devices for neutron spin manipulation), introducing new users and students to the power and technical details of neutron scattering, and conducting materials research with neutrons (particularly in the realm of large-scale structures in materials). The desire to emphasize experimental research on neutron moderation and instrumentation, particularly in the context of a long-pulse source, as well as the availability existing infrastructure and expertise, were primary motivators for using the (p,n)^{9}Be reaction at this facility. By limiting the proton energy to 13 MeV, we avoid production of ^{7}Be and ^{3}H in the target, which is another significant consideration for the experimental program in neutron moderation. As shown below in figure 1, the facility actually encompasses two neutron target stations (one devoted to cold neutron production and neutron scattering, and the other devoted to epithermal and fast neutron production for radiography and studying neutron radiation effects in electronics).

Fig. 1 Schematic layout of the LENS facility showing the accelerator and RF power systems on the left, the radiography/irradiation target station on the lower right, and the cold neutron target station and its associated instruments in the upper right.

The primary operational issues we have encountered with this facility have been associated with the target (both radiolysis-induced water chemistry problems leading fouling of the target with a subsequent loss of cooling and blistering of the target with the embedded hydrogen), and the RF power systems. The water chemistry issues were initially handled with the insertion of a sacrificial anodic element to the cooling circuit along with the introduction of a small amount of sodium nitrite to the cooling water.

If we neglect the diffusivity of hydrogen then the vast majority of the protons incident on the target stop in roughly a 0.2 mm thick region near the Bragg peak (roughly 1.0 mm below the surface since the 13MeV beam is incident on the target at a 45^{o} angle in our original target design). As a result, hydrogen builds up in this region at a rate of roughly 30 ppm/kWh, and even at several hundred degrees Celsius, the solubility is only a few ppm [10]. Therefore, in relatively short order (integrated beam on target on the order of several dozen kW.days) the concentration of hydrogen exceeds the material's capacity and mechanical failure liberates some of the trapped hydrogen. Target failure was therefore indicated by a burst of hydrogen entering the beam line and forcing the closure of the fast-acting valve inserted upstream of the target to protect the accelerator.

For hydrogen diffusion to change this scenario qualitatively at an operating power of 4kW, the hydrogen would have to diffuse the 1mm to the surface on a time scale on the order of 1 week, and experience a negligible barrier at the surface. This would require a diffusion constant in excess 10^{-8}cm^{2}/s. There is considerable scatter in published data for H diffusion in Be (due to both the limited solubility and the presence of a surface oxide barrier), but some of the available data suggest that sufficient diffusivity could be reached near 400 K, while others suggest that it would not be reached until 650K [11] or even more. Our experience, which involved running with a target surface temperature of roughly 150-200^{o}C, suggests that the diffusivity in our targets in this temperature range is insufficient to allow enough hydrogen to reach the target surface (or that the oxide barrier prevents enough hydrogen from leaving the target).

This hydrogen build-up problem was addressed by changing to a 1mm-thick Be target oriented normal to the incident beam so that the majority of the protons range out in the cooling water rather than in the target itself. The level of radiolysis in the cooling water increased as a result of this change, and consequently additional measures were then required to avoid recurring water chemistry problems. These measures involved adding a large reservoir (roughly 50 gal), inserting 20 and 5 micron filters, and adding an ion exchange column (as a replacement for the sacrificial anodic element) to the target cooling water circuit to reduce the concentration of any dissolved solids in the water. With this system we have succeeded in maintaining a water resistivity in excess of 1MΩ-cm and a pH of about 10 and we have not experienced any further problems with fouling of the target.

To address the RF problems we have encountered, we are in the process of changing from obsolete switch tubes in the klystron control decks to a newer design that to date has exhibited trips more frequently than one would like. We are awaiting arrival of improved switch tubes with the expectation that this will fix the tripping issue and allow us to increase beam power above the 4kW at which we are presently running.

In the remainder of this paper, I will concentrate on the cold-neutron production station and its

instrumentation. This station presently feeds neutrons into two instruments. One instrument, is a conventional pin-hole time-of- flight SANS instrument with a Q range on the order of from 0.07 nm^{-1} to 0.3 nm^{-1} and a useful flux on the sample on the order of 10^4 $n/cm^2.s$. This instrument is presently being utilized to study adsorption of several fluids in a variety of porous media, but its research program is being expanded to include a broader spectrum of nano-structured materials. The same instrument is being used to measure neutron total cross sections on a variety of materials of potential use to Very Cold Neutron production. In this mode, we have demonstrated an ability to perform such measurements to energies below 0.1meV.

The second instrument employs a polarizing bender to produce a guided and polarized beam of neutrons. This will be used in the development of a variety of instrumentation for neutron spin manipulation, including the Spin-Echo Scattering Angle MEasurement (SESAME) technique [12]. This technique probes real-space correlations in materials out to length scales as long as several microns in both SANS and reflectometry geometries and serves as an example of the sort of instrumentation development that a source of this scale can support. The facility is presently also supporting activities devoted to improving components for neutron instrumentation (particularly involving neutron spin manipulation and long-pulse source applications).

II.B. Moderator Research Program

A key component of our neutron instrumentation development program is associated with the investigation of novel moderator concepts and materials. This program exploits features of the cold-source target station that are afforded by the low proton energy and the careful selection of construction materials near the target. This allows access to the moderator and associated systems after two to three days of cool-down time subsequent to extended periods of running the facility at several kW of beam power. Removal of the moderator vessel is accomplished without dedicated remote handling equipment using an overhead crane, but this does involve removing roof beams over the vault, and two caps (one of borated polyethylene and one of lead) over the moderator. Typical dose rates at the most active part of the moderator are several mSv/hr on contact upon extraction, with the activity being dominated by alloying elements in the 6061 aluminum vacuum and moderator vessels (primarily ^{56}Mn, ^{64}Cu, and ^{65}Zn). This activity is strongly localized near the moderator location, and with the use of the crane and prudent handling, workers involved in the extraction receive no recorded dose.

A second moderator assembly has been constructed for use in testing novel moderator ideas. This assembly is capable of cooling a test moderator down to below 6K and can accommodate moderators at least as large as 8cm thick and up to 15x15 cm^2 lateral dimension (subject to more constraining volume limits for some materials). In typical experiments, we have been able to use this assembly to test up to four different moderators within the course of a single experiment lasting two weeks. This has included tests of different poison plate materials in polyethylene moderators, tests of hydrogen moderators, and tests of inhomogeneous moderators. Measurement capabilities include characterization of neutron spectra and emission time distributions for different moderator materials, temperatures, orientations and time. In doing these measurements, we typically find that we can extract the moderator after cool-down periods of a day or less with even lower activity on the assembly than described above (due to the much lower beam power and integrated time on target typically needed for these measurements compared to normal operation for scattering experiments).

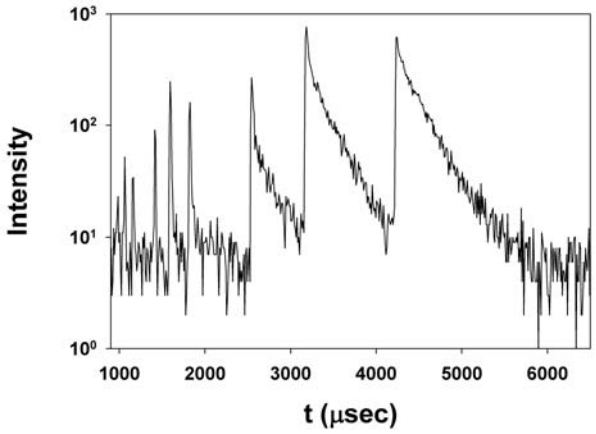

Fig. 2 A sample emission time spectrum from the standard LENS moderator collected with roughly 8 hours of beam time running at 40Hz with a 14 μsec proton pulse width using the <111> family of planes from a Ge crystal (held at 9K with a closed-cycle refrigerator). Peaks from 3rd through 13th order (6th and 10th are extinct for this family of Bragg planes) are clearly visible, although full pulse shapes are only available for 3rd through 5th order (25 to 69 meV). Measurements of the pulse width are possible up to 12th order (400 meV) with this length of data run (albeit with a sizeable error bar).

Emission time distribution measurements have been performed with a cooled Ge crystal using the <111> family of reflections in a time-focused geometry [13]. These measurements can be performed simultaneously with measurements of moderator spectra (typically with pulse widths on the order of 50 μsec and a pulse frequency of 10 to 15 Hz if high resolution is not required). Alternatively, one can take advantage of the source flexibility to run with more narrow pulses (we

have used pulses as short as 10 μsec) and frequencies of at least 40 Hz if greater time resolution or a higher energy range is required. To provide some indication of the facility's capabilities in this regard, we show above a set of data collected at 40 Hz with a 14 μsec proton pulse width from the standard LENS coupled methane moderator. The sharp change in the nature of the emission time distribution as you cross over from the thermalization region (represented by the 3rd through 5th order peaks) to the slowing-down regime is clearly visible in these data. Based on these data, we can expect to accumulate over 1000 counts in the 7th order peak (140meV) and useful data to be available (roughly 300 counts) in the 12th order peak (400 meV) with counting times on the order of a day.

III. CONCLUSIONS

Compact pulsed neutron sources are receiving increasing interest for a number of applications throughout the world. The LENS facility provides one example of how such a source can be realized for a combination of materials research and innovation in neutron instrumentation. The choice of a Be target with a proton energy of 13MeV allows "hands-on" maintenance of all components while providing sufficient neutron flux to support a variety of materials research programs.

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