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NEUTRONIC PERFORMANCE OF THE LENS TMR

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Abstract

The Low Energy Neutron Source (LENS) is based on Be(p,xn) reactions at proton energy up to 13 MeV. Its novel design employs a cylindrical light water reflector/moderator surrounding the Be target primary neutron source and a solid CH_4 cold neutron moderator downstream from the Be target that is coupled to the reflector. The design of the Target/Moderator/Reflector (TMR) assembly was optimized with MCNP and MCNPX Monte Carlo codes. The 12 x12 cm^2 surface area cold moderator is viewed by three 10x10cm^2 cross sectional area neutron beam tubes at -20, 0, and 20 degrees to the surface normal of the moderator. The optimum thickness of this coupled moderator for cold neutron yield is found to be 1 cm. The solid methane moderator can be cooled to temperatures below 10K with a closed-cycle He refrigerator to which the moderator is linked with a high-purity Al conducting rod. The system is designed with a flexible gas handling system to permit the study of a variety of moderator gas mixtures. The cryogenic moderator has been installed, and the facilty is producing neutrons using a 7 MeV proton beam. The expected neutronic performance of the TMR at full operating power is discussed and measurements of the neutron yield and spectra obtained with the present 7 MeV proton beam are reported.

1. Introduction

The Low Energy Neutron Source (LENS) at Indiana University Cyclotron Facility (IUCF) Low represents a prototype for the construction of a university scale pulsed cold neutron source. LENS was conceived as a facility that could fill a unique role in education and instrumentation development for neutron scattering within a university setting. The source employs (p,nx) reactions in Be to produce neutrons with a commercial linear accelerator. This mechanism is considerably less efficient than spallation for producing neutrons, however it has advantages in terms of both cost and the level of radiation produced at the source. The Be source itself produces only about 1 gamma for every 9 neutrons, and the maximum neutron energy is roughly 2 MeV below the incident proton energy. Components of the LENS TMR are then subjected to a considerably softer radiation environment even than seen at low-power spallation sources such as KENS or IPNS. Constructing a facility that is able to deliver adequate neutron flux to its instruments, while maintaining these radiological and financial advantages, places significant demands on the neutronic design of the source. In this paper we describe some of the novel aspects of the LENS design and report on initial characterization of the neutron beams produced. The facility is currently commissioning, and early experiments with cryogenic methane moderator have been completed. Further facility details may be found elsewhere in these proceedings [1].

One area where LENS offers unique advantages is in the experimental study of moderator designs and materials. Access to the moderator within several days after shutting down the proton beam should be possible even without extensive remote handling facilities for highly radioactive components, provided care is taken in the choice of materials used in the central region of the TMR. A significant design challenge is to construct a reflector that is flexible enough to accommodate changing moderator designs, does not contain elements that would provide undesirable activation, and provides adequate coupling to the moderator.

Presently the facility makes use of an ACCSYS PL-7 which was previously used at the IUCF as the cooler synchrotron pre-accelerator [2]. At the 7MeV proton energy delivered by this accelerator, a neutron yield of 10^{13} n/s/mA is available, but a factor of 3.3 greater yield is available at 13MeV [3]. Even higher yields accompany higher proton energies, but for energies above 13MeV activation of the target through the ^{9}Be(p,t) becomes a serious issue, so we have chosen to concentrate on the performance for energies of 13MeV and less. For MCNP simulations 13 MeV source term containing the neutron energy spectral (> 100 keV) and angular probability distributions was derived from experimental data [3,4]. In the final design the proton beam is incident at 45 degrees to the Be target normal (to reduce the thermal load on the target) and the neutron beam tubes are situated at -20,0, and 20 degrees to the moderator normal. The proton beam is steered onto the target by two bending magnets to avoid placing the accelerator in direct line of sight with the target. During out initial operations, the proton beam current is determined by turning off these bending magnets to direct the proton beam onto an instrumented beam stop.

In order to provide reasonable neutron flux for scattering experiments, LENS must run in a long-pulse mode and employ a coupled moderator. We have also chosen to focus on the production of cold (<5 meV) neutrons, as the relatively small dose to which the moderator is exposed in the LENS TMR should allow it moderator to run at significantly colder temperatures than is possible at spallation sources (IPNS for example). In our neutronic design, we concentrate on the response of the moderator/reflector assembly to an impulsive proton beam and make an effort to insure that that neutronics do not unduly lengthen the neutron pulse.

2. Neutronic Design

Since it will focus on cold neutrons, and has a relatively soft radiation field near its target, solid methane is the obvious choice for the cold source material in LENS. We have therefore chosen this material for our neutronic evaluation of the LENS TMR. At present for simulation of cold neutron source characteristics at very low temperatures there is limited data on S(α,β) kernels needed for the MCNP code although development work is progressing in this area at IUCF [5]. In our analysis we have used the 22K Methane kernel *smeth22k* available from [6]. The target moderator configuration was optimized with MCNP simulations to reduce the thermal load on the cold source and the fast neutron background in the neutron beam tubes while maximizing the cold neutron yield.

We initially conducted scoping calculations to identify materials and dimensions for the inner reflector. In Figure 1 we investigate the efficiency for methane of various thicknesses to cool incident fast neutrons of various energies directly to long-wavelengths (2meV), and find the unsurprising result that such a moderator should be on the order of 4 to 5 cm thick. We also note, however, that a much thinner methane layer is optimal for efficiently cooling thermal neutrons. In Figure 2 shows this in more detail by showing the efficiency to cool thermal neutrons (represented by a 100meV monoenergetic beam) to a variety of cold neutron energies. A thinner cold source has distinct advantages from a cryogenic point of view, since reducing the methane volume will lower the thermal load experienced by the moderator during operation. A primary task for the reflector at LENS is therefore to maximize the thermal flux used to feed the cryogenic methane. In this source, the reflector may be seen to act as a combination reflector/moderator, and the methane serves as a cold source whose task is to convert thermal neutrons to longer wavelengths.

We considered a number of materials for the reflector/moderator and performed calculations in MCNP to evaluate their ability to feed the methane moderator with neutrons in the energy range from 10 to 100meV. Figure 3 shows the probability for thermalizing neutrons into this energy band as a function of incident neutron energy for various reflector/moderator material choices. These results indicate that a light water reflector is ideal for cases where the primary neutron energies are 4MeV or less, which is essentially the case for a 7MeV proton beam at LENS (for which the maximum neutron energy is roughly 5MeV). For 13 MeV proton energy a Be reflector moderator may increase (by up to 40%) the reflected thermal neutron flux at the location of the coupled cryogenic moderator. However, water has the additional advantages of low cost and great flexibility in accommodating modifications associated with experimental moderator studies and therefore the design employs this material. Simulations indicate little gain in cold flux for a water radius greater than 20cm, but in order to maintain flexibility we have chosen a radius of 25cm. The larger dimension will also be more suitable for a Be reflector so this choice provides accommodation for a future upgrade with minimal changes to the rest of the TMR.

The MCNP geometry resulting from these scoping calculations is shown in figure 4. The configuration is a cylindrical 50 cm tall 50 cm diameter light water reflector surrounding a Be proton target and a 12x12x1 cm cryogenic methane moderator in s slab geometry. This design relies on strong coupling of water moderated thermal neutrons to the cryogenic cold moderator. The importance of this coupling can be seen in figure 5 where the long-time tail in the emission time distribution for the cold neutrons is seen to closely parallel the emission time for thermal neutrons. This figure essentially represents the impulse response of the target/reflector combination, and indicates that roughly 95% of the cold neutrons are emitted within 1ms of the proton pulse. The central water reflector is surrounded by a lead layer to act as a shield for the gammas produced by capture in the water, but a borated layer is provided in between the two to minimize activation of the lead. Outer layers of the TMR, which are composed of borated polyethylene with additional layer of lead, have no impact on the moderator performance but act as the primary shield for the source. The MCNP model includes vacuum and Al components from the cryogenic system, as well as a polyethylene volume just above the moderator which serves to limit leakage along the cryogenic utility penetration. Figure 6 shows the moderator lethargy intensity predicted by this model for various proton beam conditions. The curves shown correspond roughly to the beam conditions expected near the beginning of 2006, the beginning of 2007, and at the eventual 13MeV 32kW operating condition.

The moderator cryogenics system at LENS employs a Cryomech PT410 He refrigerator which is linked to the moderator by a high-purity Al conducting rod. The first stage of this refrigerator is used to cool a radiation shield and the vertical polyethylene plug shown in figure 4 above the methane (to temperatures around 35K). The cold head is offset from the moderator cavity to limit radiation exposure of the cryogenic system. Prior to its insertion in the TMR, this system's performance was evaluated with electric heaters placed on the moderator vessel to simulate radiation heating during operation. In this mode, a base temperature below 4K was achieved, and thermal loads as large as 5 W increased the vessel temperature to roughly 13K. MCNP calculations predict a total thermal load on the moderator, its vessel and the lower portions of the thermal link to be on the order of 2 W when the facility is running at 32kW beam power. We are therefore confident that the facility will be able to run with a moderator temperature of less than 15K when it enters operations. The moderator also uses a flexible gas handling system that will allow up to 4 separate gasses to be mixed into the moderator and can monitor moderator gases for radiation-induced cracking.

3. Results

The first neutrons were produced at LENS in December 2004, with a polyethylene plug filling the void in the reflector/moderator designed for vacuum can that will accommodate the cryogenic moderator and its affiliated systems when the facility enters operations. A 2cm thick polyethylene slab supported this plug in the region viewed by the neutron beamlines, and this surface is the one viewed by the instruments used to measure the neutron spectra. The absolute thermal neutron spectrum was measured using the foil activation normalized time of flight (TOF) method of neutron spectrometry detailed elsewhere [7,8]. A 3 Torr ^{3}He detector with 760 Torr N_2 quench gas manufactured by LND was employed in these measurements. The activation foil was indium, which was counted on a GeLi detector calibrated by a NIST-traceable multi-gamma standard. The proton beam current was determined by directing the beam onto an instrumented beam stop placed upstream of the Be target immediately prior to, and just after, the neutron spectra were collected. The facility does not yet have a real-time proton beam current monitor, however detectors within the TMR vault monitored any variations in the proton beam delivered during the run through changes to the gamma and neutron background in the vault.

With the present proton beam characteristics, the neutron beams at the instruments are unable to provide sufficient activation of a foil placed at the sample position. Therefore the normalizations were performed with the ^{3}He detector at a distance of 570 cm from the polyethylene surface (to provide adequate time of flight resolution and reduce room-return background) and the foils positioned 140 cm from the moderator. Using this method, the integrated thermal flux was determined to be $3x10^3$ n/cm^2/s at 570 cm from the moderator center. These measurements suggest a nominal efficiency for the ^{3}He detector and electronics of $4x10^{-4}$ at 25meV (the manufacturer's specification was for 10^{-3}). This measured thermal neutron yield from the polyethylene is then roughly a factor of two lower than expected, as demonstrated in figure 7. This level of agreement is reasonable, given the uncertainties in the nuclear data, the beam current actually delivered to the sample, and geometric details in the MCNP model.

The cryogenic methane produced the first cold neutron spectrum at LENS on 15 April, 2005. Representative data are shown in figure 8 along with a qualitative fit to two Maxwellian components. The fitted components have temperatures of 25K (with 53% integrated weight) and 160K (with 47% integrated weight). For these data the methane was held at 3.6K. This temperature was determined by measuring the vapor pressure of a small amount of helium that was condensed around the solid methane to enhance its thermal contact with the moderator vessel. Si diode thermometers were also available to monitor the temperature of the moderator during cool down and warm up, but these thermometers have not been calibrated to better than 0.5K. These thermometers will be replaced with more robust thermometry before the facility enters full power operation. MCNP simulations using the geometry of figure 4 also produce a spectrum consistent with two Maxwellians, one near 260 K (with an integrated weight of 30%) and one near 40K (70% integrated weight). The warmer neutrons predominantly come indirectly from the reflector/moderator via scattering off the front face of the methane. It is not clear at this point why the data shows a thermal component at a distinctly lower temperature than the simulation. This could reflect some inadequacy in the kernel employed for the simulation or perhaps it reflects a contribution from the low temperature polyethylene in the physical system (which is modeled by room temperature polyethylene in the simulation). The relatively large weight observed for the warm component in the measured spectrum may reflect incomplete filling of the moderator due to our inability to cycle through the freezing point multiple times. The lower temperature of the cold component of the spectrum is gratifying, and no doubt reflects the ability of our cryogenic system to hold the methane below the 22K relevant for the MCNP kernel we have used.

4. Conclusion

The LENS facility has produced its first neutrons and to date the performance of the system is within the range of expectations. In particular, the cryogenic moderator has demonstrated a neutron spectrum whose long wavelength tail fits to a 25K Maxwellian distribution. The measured spectrum also exhibits a contribution from a second Maxwellian at a somewhat higher temperature. MCNP model simulations are consistent with such a bimodal temperature distribution, but the temperatures and relative weights of the two components in the simulation differ from the measurement. At present, the cold neutron flux available is sufficient to begin commissioning of the first neutron scattering instruments at the facility. Facility commissioning will also include efforts to enhance the cold neutron flux from the moderator and measure emission time distributions as part of the instrument construction and commissioning process.

Acknowledgements

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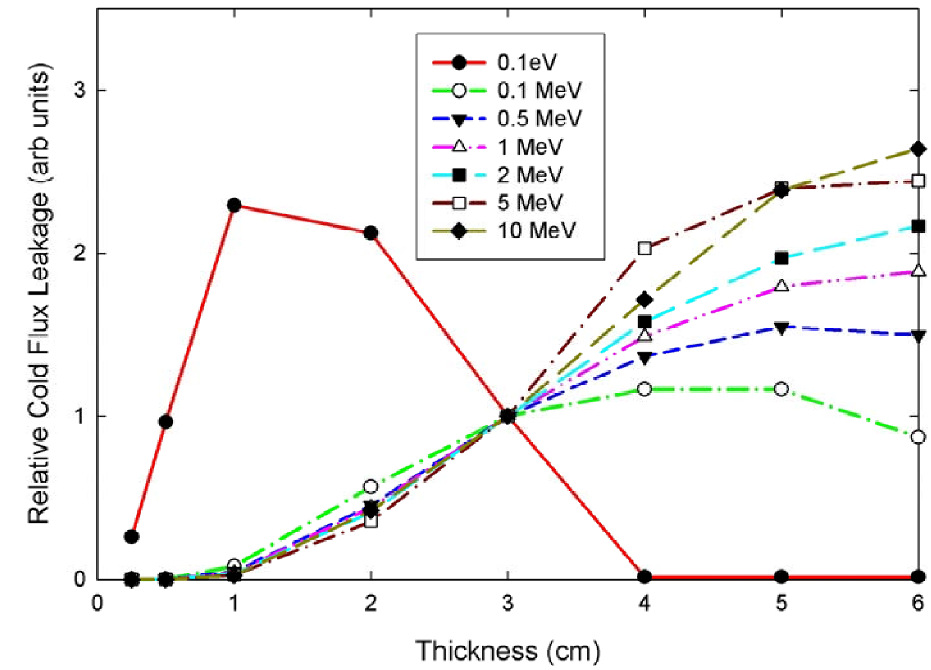

Figure 1: *Probability to produce 2 meV cold neutrons from monoenergtic source neutron groups at normal incidence on a 22K cold slab CH_4 moderator. The legend identifies the source neutrons. Neutron scattering cross section in hydrogen increase rapidly below 0.1 eV resulting in a rapid decrease in mean free path and effective optimum thickness of the cold moderator. All curves have been scaled to pass through 1 at 3cm in order to fit all curves onto a common vertical scale.*

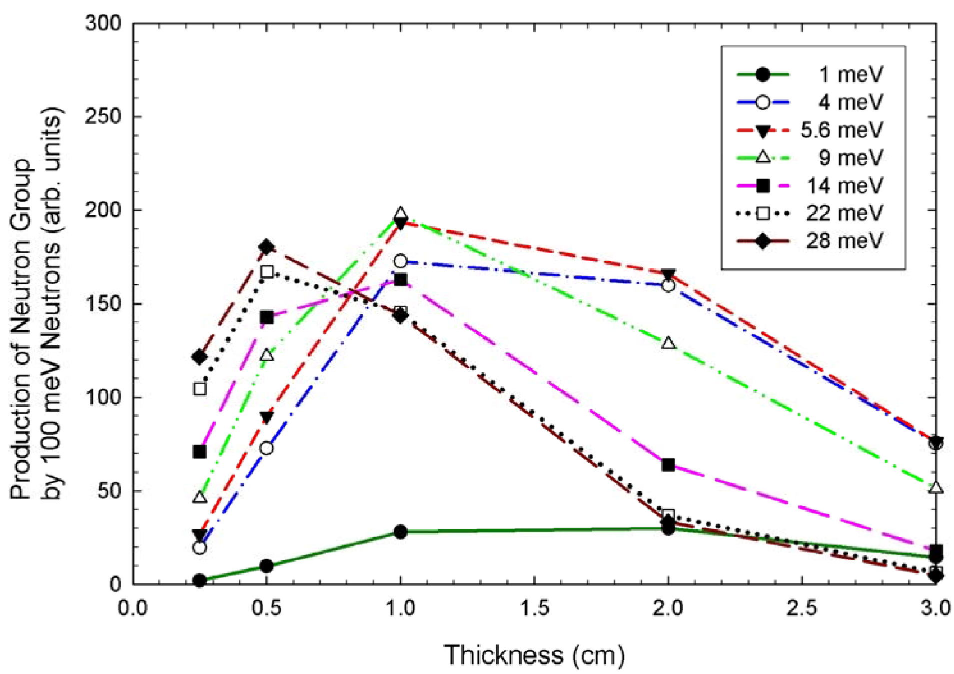

*Figure 2***:** *Probability for a cryogenic methane moderator to cool incident 100meV neutrons to various cold neutron energies as a function of methane thickness.*

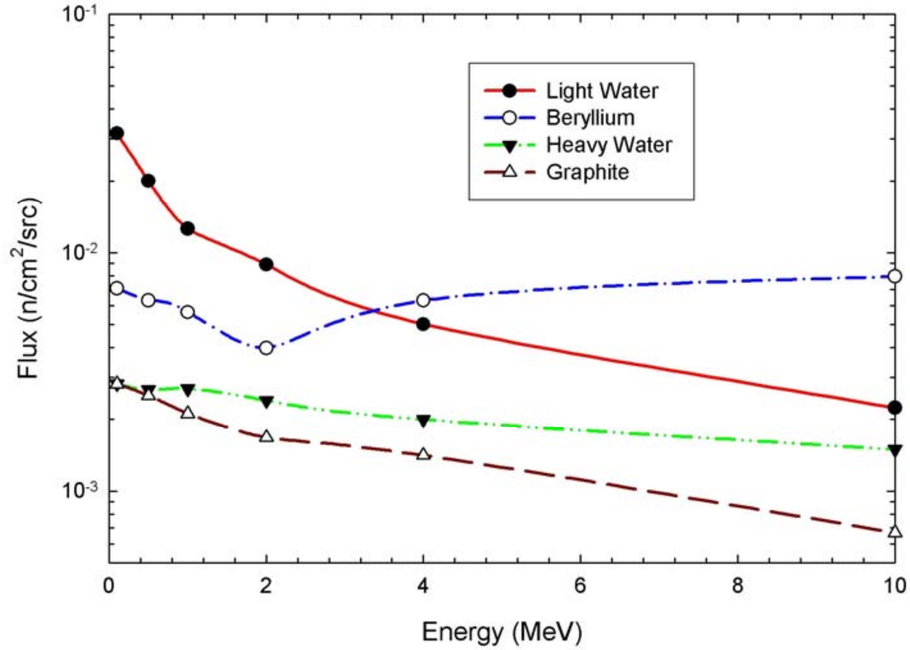

Figure 3 Probability for a 40 cm radius reflector of various compositions to thermalize fast neutrons of incident energy from 0.1 to 10 MeV. Water provides the optimal coupling to a methane cold source for neutron energies below 4 MeV.

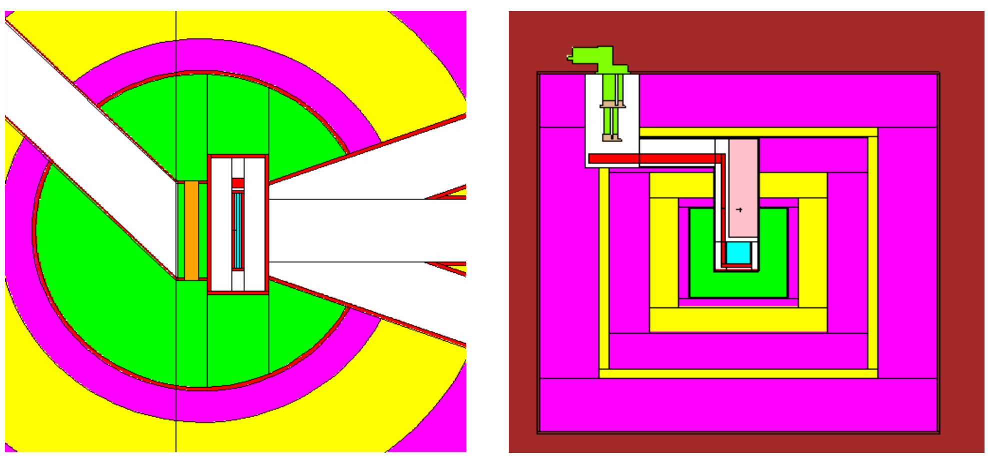

Figure 4 MCNP Simulation Geometry. The central (blue) methane cold source is surrounded by (green) water which is in turn surrounded by lead (yellow) and borated polyethylene (pink). The cryogenic system is modeled by a vacuum space (white), solid aluminum thermal link (red) and polyethylene plug (beige).

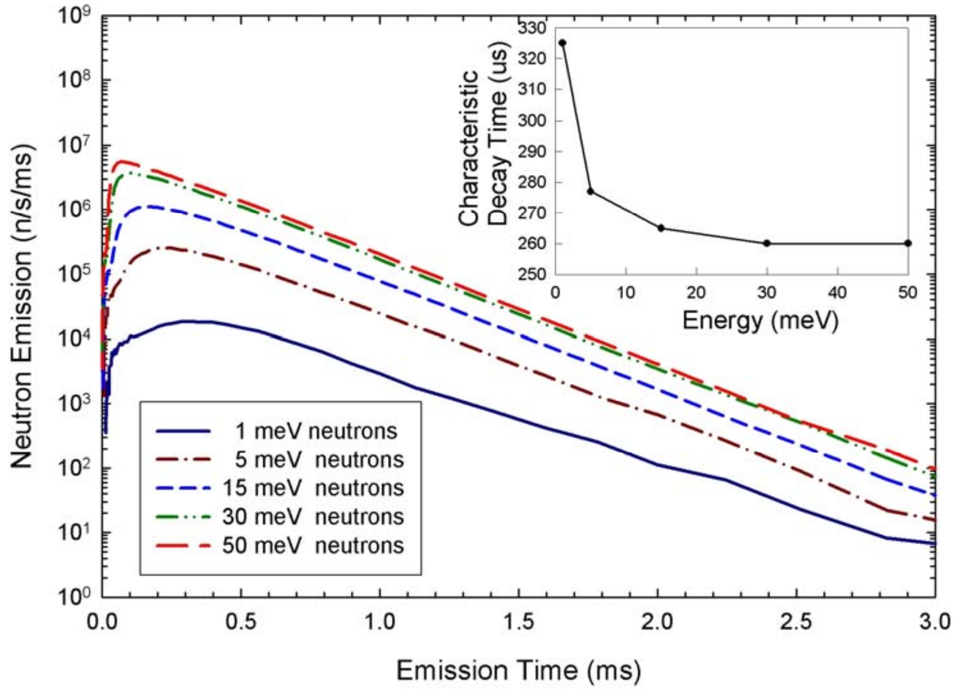

Figure 5 Temporal response of the LENS reflector/moderator system to a short proton pulse in the cold and thermal neutron energy range. Note that the long time tail of the cold (5meV) neutrons closely follows the thermal time distribution.

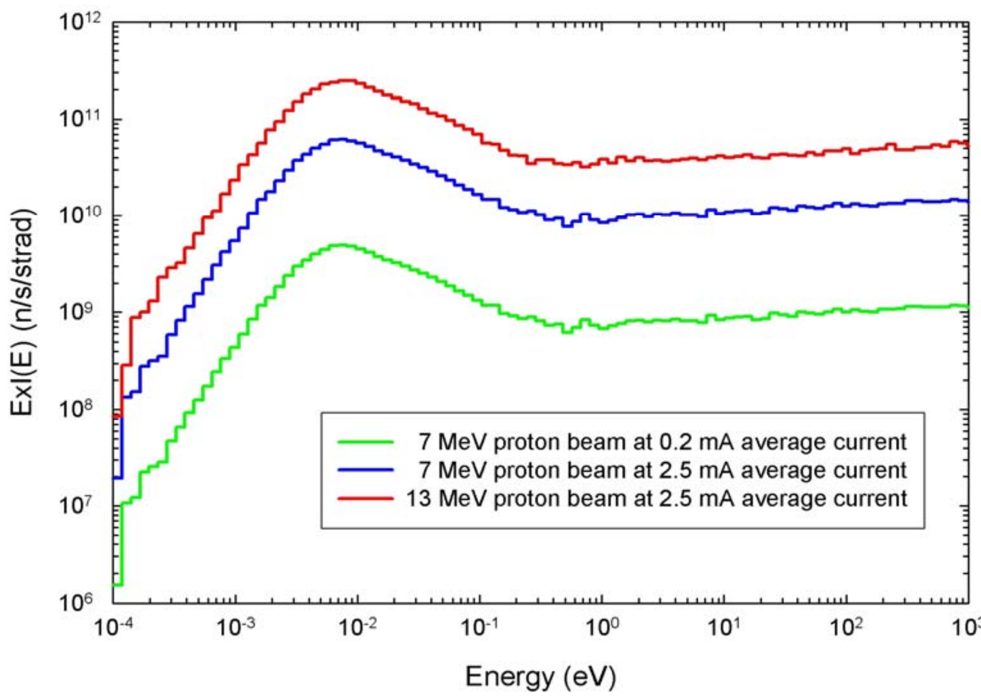

Figure 6 Simulated 22 K Moderator LENS Spectrum for three different proton operating conditions.

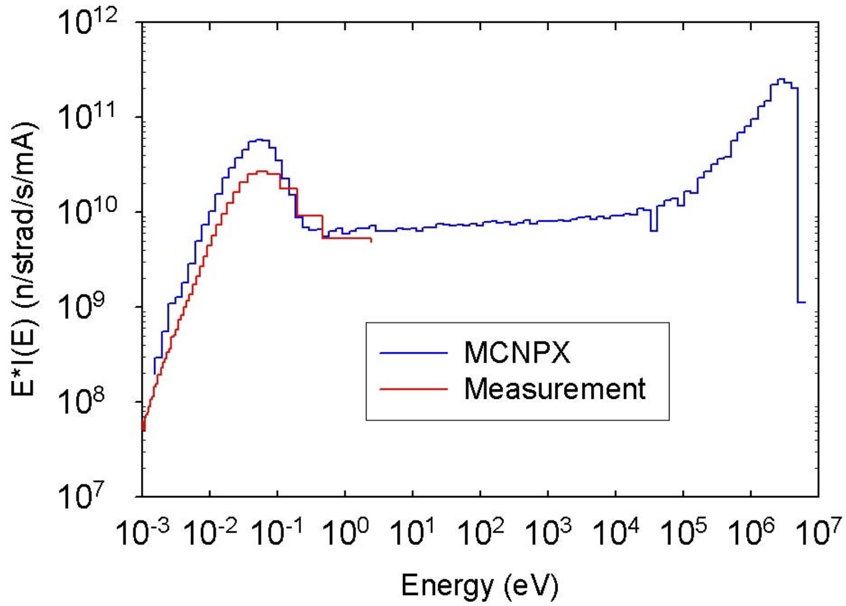

Figure 7 Thermal Neutron measurement compared to MCNP predictions for LENS when operated with a simple room temperature polyethylene moderator.

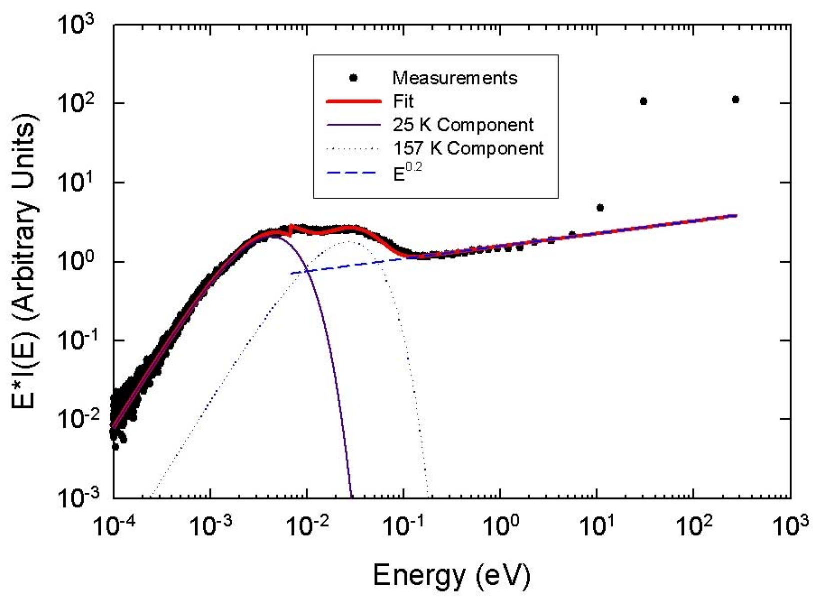

Figure 8 Spectrum collected with the methane moderator at a temperature of 3.6K with a thin ^{3}He detector. The curves represent the slowing-down and Maxwellian contributions to the fit.