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Spectral Intensity Benchmarking on IPNS Beamlines

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Abstract

The Intense Pulsed Neutron Source at Argonne National Laboratory provides cold and thermal neutrons using moderators of cryogenic (both solid and liquid) methane. Measurements of the neutron beam characteristics provide a means of monitoring facility performance and of assessing the effectiveness of upgrades both to the target/moderator/reflector assembly and to instrument beamlines. An additional goal of the present measurement program is the development of techniques for characterizing beamlines that contain neutron guides. We measured neutron energy spectra with standard time-of-flight techniques using both the in-situ beam monitors and portable beam characterization equipment from SNS. Cadmium-difference foil activation techniques provide absolute flux levels. We estimate the wavelength-dependent guide gain due to recent instrument upgrades on QENS and GPPD using the results from pairs of beamlines viewing the same moderator face. We also compare measurements for beamlines on the IPNS "F" and "H" moderators to the results of recent simulations. A detailed discussion of the data analysis procedures suggests ways to improve the measurements and to extend their usefulness to other facilities.

1. Introduction

Spallation neutron sources have proved to be important tools in the development of new materials for a wide variety of applications. In these facilities, fast neutrons created by proton-induced spallation interactions in a heavy-metal target thermalize in nearby moderators to provide beams of slow neutrons ($E_n \leq 1$ eV) for experiments. The absolute number and energy distribution of these neutrons establish a fundamental limit on the experimental resolution achievable from the neutron beam. Accurate knowledge of these quantities is required for the design of spallation source target/moderator/reflector systems and are also necessary to predict the performance of instruments located at a spallation source facility. Accurate measurements of neutron emission from moderators also allows the benchmarking of computational design tools, measurement of the performance of instruments following the addition of neutron mirrors or guides, and the ability to calculate the activity present in a sample following irradiation.

As part of a collaboration between IPNS and SNS on benchmarking measurements, we measured the neutron emission energy spectra for selected instrument beamlines at the IPNS facility using both in-situ beam monitors and portable beamline characterization equipment designed for the SNS CD4 commissioning measurements [1]. The results of these measurements are expected to lead to improvements in both measurement and computational techniques.

2. Procedures

The quantity measured in the present benchmark study is the energy-dependent intensity of the neutron beams. While this does not provide a complete description of the moderator's performance, it does provide a necessary starting point for further investigation, and provides information necessary for some scattering experiments, calculation of reaction rates in samples, etc. The neutron beam intensity $i(E)$ emitted from a moderator face, normalized by the accelerator beam current, corresponds to what in optics terminology is a normalized "luminous intensity." This intensity is related to a measured flux by

$$i(E) = \frac{L^2}{\langle I \rangle}\phi(E)_L \tag{2.1}$$

where $\varphi(E)$ is the time-averaged flux per unit energy at a distance L far from the moderator face, and $<I>$ is the time-averaged accelerator beam current. In general, the use of luminous intensity rather than flux as a metric permits the brightness of the moderator face to be specified independently of the length of the flight path. The units of $i(E)$ are then neutrons per steradian per second per electron-volt per microampere. The commonly-quoted measure of moderator coupling effectiveness is

$$[E \times i(E)]_{E=1\,eV} \tag{2.2}$$

Multiplying the intensity $i(E)$ by E results in a quantity that is proportional to the normalized counting rate seen in a thin $1/v$ detector placed at a distance L from the moderator surface, scaled by a factor which is independent of neutron energy. Thus $E \times i(E)$ is easily compared to a time-of-flight beam intensity measurement. This quantity can be directly calculated in Monte Carlo simulations [2,3,4] and thus provides a convenient comparison between measurement and calculation. We make the comparison at a neutron energy of 1 eV because at this energy the neutron energy spectrum still exhibits the $1/E$ dependence characteristic of the slowing-down region and is independent of the characteristics of the moderator.

A combination of gold foil activation and time-of-flight spectrum measurements provided absolutely normalized intensities for the various neutron beams [5]. Both the in-situ beam monitors and the SNS portable beamline characterization equipment utilize low-efficiency $1/v$ detectors operated in a counting mode to record the neutron TOF spectrum. Simultaneous cadmium-difference gold foil activation measurements provided the normalization factor for detector efficiency.

2.1 Theory

The time-averaged counting rate per unit time-of-flight at time-of-flight t at the beam monitor is

$$C(t) = A\,\eta(E)\phi_D(E)\frac{2E}{t} + B\,, \tag{2.3}$$

where E is the neutron energy corresponding to time-of-flight t, A is the area of the beam intercepted by the detector, $\eta(E)$ is the energy-dependent efficiency of the detector at energy E, $\phi_D(E)$ is the time-averaged flux per unit energy at the detector, and B is a steady background counting rate. For a thin $1/v$ detector, such as ^3He in ^4He or $^{10}BF_3$ in P-10, the efficiency can be expressed as

$$\eta(E) = k\lambda \tag{2.4}$$

where λ is the neutron wavelength corresponding to energy E, and k is a constant unique to each detector and electronic setup. Substituting Equation 2.4 into Equation 2.3, together with the deBroglie relation, gives

$$C(t) = E \times \phi_D(E)\frac{2hkA}{mL_D} + B \tag{2.5}$$

where h is Planck's constant, m is the neutron mass, and L_D is the flight path length between the moderator and detector. We can then define an absolute efficiency (that accounts for detector geometry and position as well as intrinsic efficiency)

$$K' = \frac{2hkA}{mL_D} \tag{2.6}$$

relating the flux at the detector position to the counting rate such that

$$\phi_D(E) = \frac{C(t) - B}{EK'} . \tag{2.7}$$

We can modify Equation 2.7 to relate the flux at the foil position to the net counting rate at the detector position,

$$\phi_F(E) = \frac{C(t) - B}{EK} \tag{2.8}$$

where K is a scaled absolute efficiency $K = K'\left(L_F^2 / L_D^2\right)$. This equation is especially useful, as the time-averaged counting rate per unit time-of-flight $C(t)$ is easily obtained from the beam monitor, the background B is a constant at all time-of-flight values, and the efficiency K will remain the same for any given detector, providing that the detector's configuration has not changed.

Finally, the quantity K can be evaluated directly from the detector and gold foil activation data using the expression

$$K = \frac{2 N_c N_b}{N_c R_b (1-\gamma) - N_b R_c} \int_{t'_{\min}}^{t'_{\max}} \left(1 - e^{-\Sigma_{Cd}(t') s} - \gamma\right) \sigma_{Au}(t') \frac{C(t') - B}{t'} dt' \tag{2.9}$$

where N_b, N_c are the number of atoms in the bare and cadmium-covered foils
R_b, R_c are the measured activation rates (saturation activities) of the bare and cadmium-covered foils
γ is the average neutron transmission through the cadmium cover above a selected energy
t'_{min}, t'_{max} are the limits of integration, corresponding to the shortest and longest flight times
$\Sigma_{Cd}(t')$ is the cadmium cover macroscopic total cross section, and s the physical cover thickness
and $\sigma_{Au}(t')$ is the ^{197}Au(n,γ) microscopic activation cross section.

2.2 IPNS System Description

The Intense Pulsed Neutron Source at Argonne National Laboratory is a pulsed spallation source that generates neutrons by accelerating protons to 450 MeV and directing them onto a target composed of light-water-cooled depleted uranium disks of diameter 10 cm and total length 20 cm. The IPNS accelerator system produces a time-averaged current of 15 μA in 70-ns pulses at a rate of 30 Hz. Figure 1 shows a cutaway view of the IPNS target, reflector, and moderators.

IPNS employs three cryogenic methane moderators, but measurements were only made on two of them ("F" and "H") for the present study. Both of these moderators are decoupled with cadmium. The "F" moderator is located beneath the upstream end of the target, and is filled with liquid methane at 100 K. The moderator is 10 cm x 10 cm x 4.5 cm thick and is viewed from both sides, with gadolinium poison plates located 1.6 cm beneath each of the viewed surfaces. The "H" moderator is located above the upstream end of the target, has a viewed face 10 cm wide x 10 cm high x 4.45 cm thick. The H moderator is filled with solid methane moderator and has a gadolinium poison plate located 2.2 cm beneath the viewed surface.

2.3 Foil Activation Counting

The activated gold foils were counted with a 7.62 cm x 7.62 cm NaI detector inside an enclosure shielded with 5 cm of lead on all sides. Energy and efficiency calibrations were performed with two recently-acquired NIST-traceable multi-gamma calibration sources. When possible, we counted each foil several times to determine the reproducibility of the results. The activation rate for each foil was determined using the net counts obtained in the 411.8-keV peak due to gamma emission during the decay of ^{198}Au, and then correcting for decay after irradiation and during the counting period.

In counting gold activation foils with a NaI spectroscopy system, one potential source of systematic error arises from 425.6-keV gamma rays produced by the decay of ^{196}Au. This species is formed in the reaction ^{197}Au(n,2n) by neutrons in the beam having energies greater than the threshold energy of 8.114 MeV. The two gamma rays are too close in energy to be effectively distinguished from each other using a

NaI detector. To determine the importance of this effect in our present investigation, one foil that was irradiated on the SEPD beamline (chosen because it lies in the forward direction with respect to the incident proton beam, and thus would have a higher proportion of high-energy neutrons) was counted with a HPGe detector (a portable cryo-cooled ORTEC Detective). The resulting gamma spectrum, shown in Figure 2, exhibits no trace of the ^{196}Au peak. We therefore conclude that our measurements contain no significant contribution from the high-energy activation of ^{197}Au.

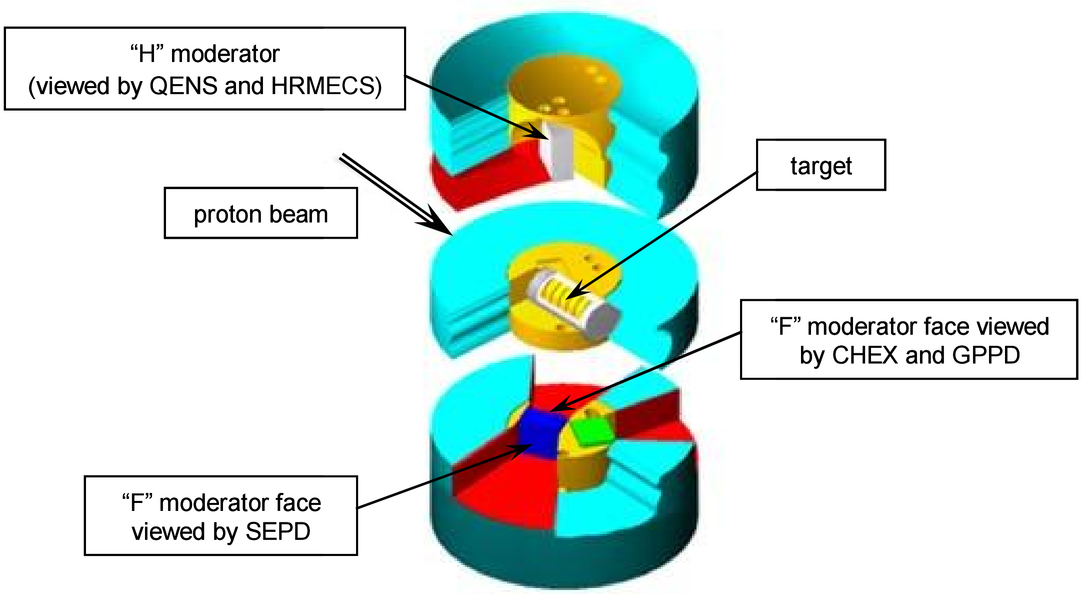

Figure 1. Cutaway view of the IPNS target, reflector, and moderator assembly. In this figure, protons are incident on the target from the left rear.

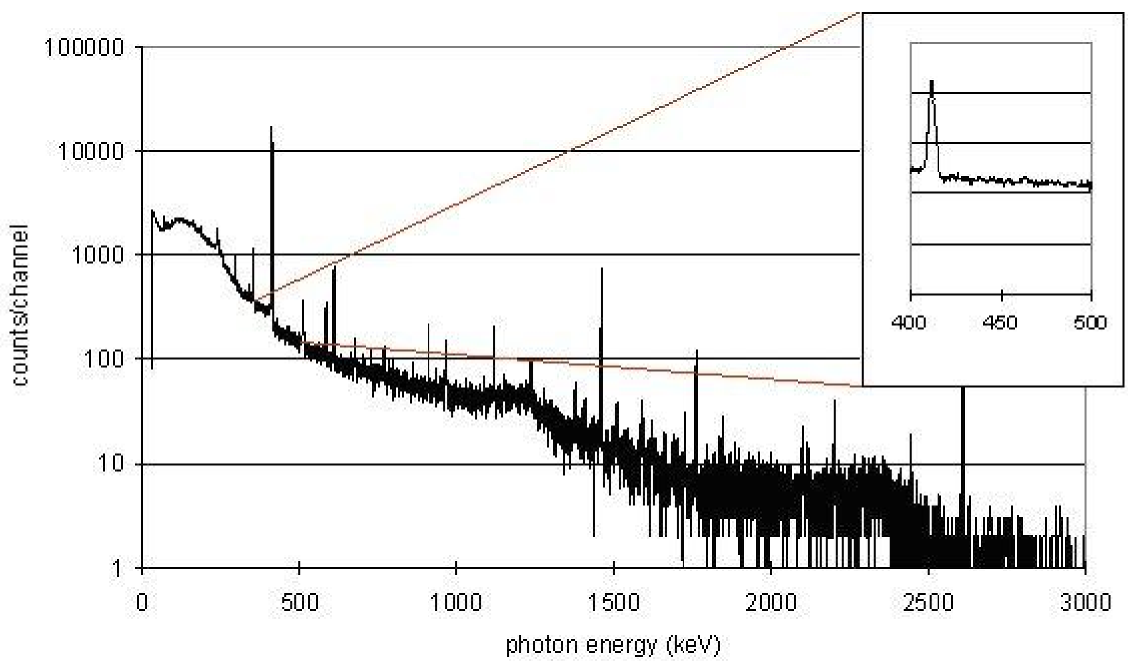

Figure 2: HPGE gamma spectrum from gold foil irradiated in IPNS SEPD beamline. Inset shows detail of energy spectrum near 411.8-keV ^{198}Au peak.

Cadmium effectively absorbs almost all neutrons with energies below ~ 0.5 eV. The gold foil cadmium difference method has traditionally been employed in flux characterization of reactor spectra which have a characteristically large sub-cadmium maxwellian component. Difficulties arise in using the gold foil cadmium difference method with the typically undermoderated spallation neutron beams because of the relatively low population of sub-cadmium energy neutrons and the presence of a large 4.8-eV absorption resonance in gold. These two factors cause the saturation activities of the bare and cadmium-covered gold foils (R_b and R_c in Equation 2.9) to be very similar. The accuracy of Equation 2.9 is dependent on a statistically significant difference that frequently requires the subtraction of two nearly equal quantities.

For this reason, other foil materials are being considered to increase the difference between bare and cadmium-covered foil activities. Dysprosium is an interesting candidate foil material because ^{164}Dy, which has an abundance of 28.18%, is a pure $1/v$ absorber up to 100 keV. The ^{164}Dy(n,γ)^{165}Dy reaction yields a gamma ray of 361.7 keV, but this energy has a branching ratio (photons emitted per decay) of only 0.0084. Other gamma rays have higher branching ratios, particularly the 94.7-keV (0.03578) and the 46.77+47.55-keV (0.072) gamma rays, but we had difficulties in determining the counting efficiency of our spectroscopy system at these low energies. Dysprosium foils were counted with the same spectroscopy system as the gold foils and analyzed in a parallel manner.

2.5 Gamma Factor Measurement

An interesting parameter in the data analysis is the value of γ, the average value of neutron attenuation by the cadmium cover for all energies above some selected energy, which is typically about 10 eV. While $\exp(-\Sigma_{Cd}\cdot s)$ is always less than one, and thus the quantity $1 - \exp(-\Sigma_{Cd}\cdot s)$ would be small but positive, Monte Carlo modeling suggests that γ might actually have a negative value due to in-scattering effects in the cadmium [1]. We conducted an experiment designed to provide a better idea of the value and sign of γ. Six foils, three gold and three dysprosium, were placed in the CHEX beamline and irradiated for a period of six days. For each type of foil, there was one bare foil, one covered by 0.5 mm cadmium (the thickness used in our difference measurements), and one covered by 2 mm cadmium. All foils were placed behind a ceramic plate of approximate composition 75% B_4C and 25% SiC having total thickness 0.635 cm. The plate reduced the amount of activation due to low-energy neutrons and allowed us to focus on the effects of neutrons having energy greater than a few eV. Table 1 shows the saturation activities resulting from this foil irradiation. The uncertainties listed are those from the gamma spectroscopy only.

The gold foil results indicate that γ is positive with a value of perhaps a few percent. The dysprosium foil data are inconclusive, since the observed changes are less than the uncertainty in counting statistics. This is due to the small mass of Dy foils used and the short half-life of the ^{165}Dy isotope. We have used γ = 0.0014 in our analysis, which comes from the Monte Carlo modeling described above.

Table 1: Results of Gamma Factor Measurement.

Foil Type	Cover	Cover Thickness [mm]	Foil Mass [mg]	Specific Saturation Activity [Bq/mg]	γ [%]	Uncertainty [%]
Au	none	-	18.68	14.94	-	0.12
Au	Cd	0.5	20.16	14.48	3.1	0.10
Au	Cd	2.0	19.94	14.79	0.95	0.09
Dy	none	-	11.75	1.69	-	8.87
Dy	Cd	0.5	11.75	1.70	- 1.0	12.2
Dy	Cd	2.0	11.75	1.88	- 11.6	26.5

3. Results and Discussion

3.1 IPNS "F" Moderator

Measurements were made on the CHEX and GPPD beamlines, which view the IPNS "F" moderator, in December 2004 using both the IPNS in-situ beam monitors and the SNS portable beamline monitor. A companion measurement using only the in-situ beam monitor was made on the SEPD beamline in February 2005. The GPPD and SEPD instruments view opposite sides of the "F" moderator along a line perpendicular to the moderator surface, while CHEX views the "F" moderator from the same face as GPPD but at an angle 18° further upstream. The analyzed results for the CHEX and SEPD beamlines, which have direct views of their respective moderator faces, are shown in Figure 3. The results from the IPNS in-situ beam monitors (labeled in-situ) and the SNS portable beamline monitor (labeled portable) agree very well with each other. The 1-eV coupling values for these beamlines are 1.22×10^{10} n/ster/s/μA for CHEX (in-situ), 1.19×10^{10} n/ster/s/μA for CHEX (portable), and 1.07×10^{10} n/ster/s/μA for SEPD (in-situ).

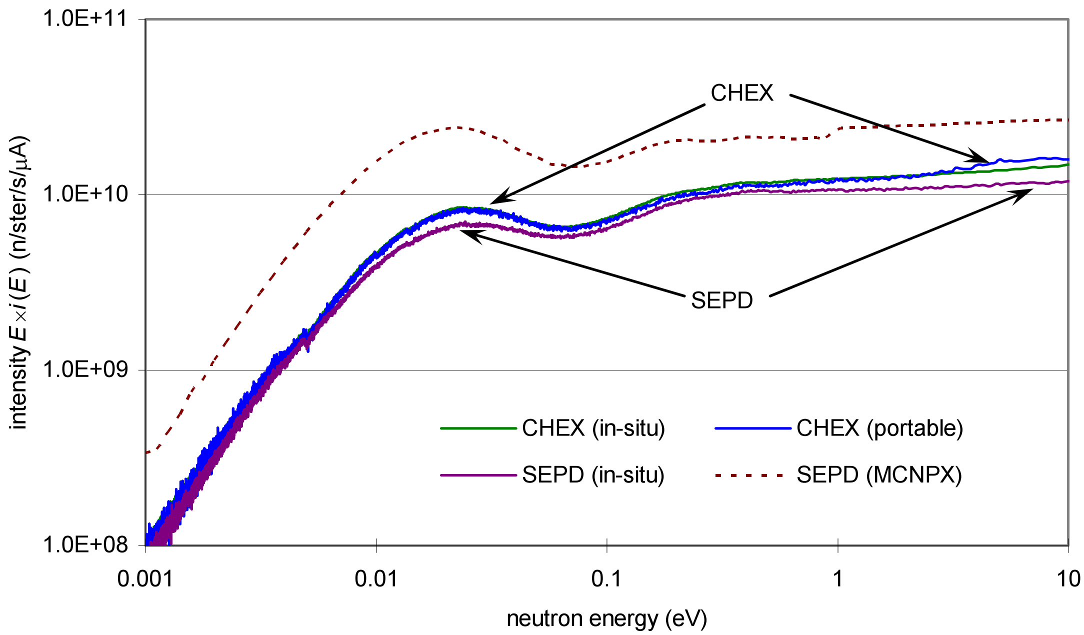

Figure 3. Neutron spectral intensity from the IPNS "F" moderator.

Also shown in Figure 3 is the result of an MCNPX simulation of the neutron intensity spectrum for the SEPD beamline. While in previous measurements we have seen good agreement between measurements and simulations for the "F" moderator, the measurements are now lower than the simulations by about a factor of two. We are not certain at present what causes this discrepancy, but since the two measurements agree well it is probably not due to the performance of either detector/electronics combination. It may well be due to an error is data analysis of either the counting data or the foil activation, since both the IPNS and SNS data sets were processed using the same methods and using the same foil activation data.

Our data for the GPPD beamline, in terms of neutron flux at the sample position, are shown in Figure 4. The data taken with the SNS portable beamline monitor and those taken with the in-situ beam monitor are in close agreement; for clarity, only the curve for the portable monitor is shown. Also shown in Figure 4 is an estimate of the neutron flux at the GPPD sample position before the recent upgrade (that is, at 20 m flight path and with no neutron guide). These estimates are scaled from the CHEX intensity measurements described above. Because of the presence of the neutron guide, the extension of our flux measurement to moderator intensity is not as straightforward as in the case of CHEX and SEPD. The new GPPD configuration does not have the same $1/E$ intensity as does the CHEX beamline. This is because the neutron guide views the entire moderator in the vertical plane but only the central section of the moderator in the horizontal plane.

Figure 5 shows the wavelength-dependent effective instrument flux gain for GPPD, which instrument personnel define as the ratio of the neutron energy spectrum in the present instrument configuration to the spectrum at the sample position before the upgrade. This definition includes the effects of both the inclusion of the neutron guide and the longer flight path. Using this definition, our experimental data show a guide gain approaching 5.5 for longer wavelengths (greater than 3 Å). Neutron scattering data taken on GPPD (shown as open diamonds) indicate a long-wavelength guide gain of about 6.1. These two measurements are consistent within our experimental error.

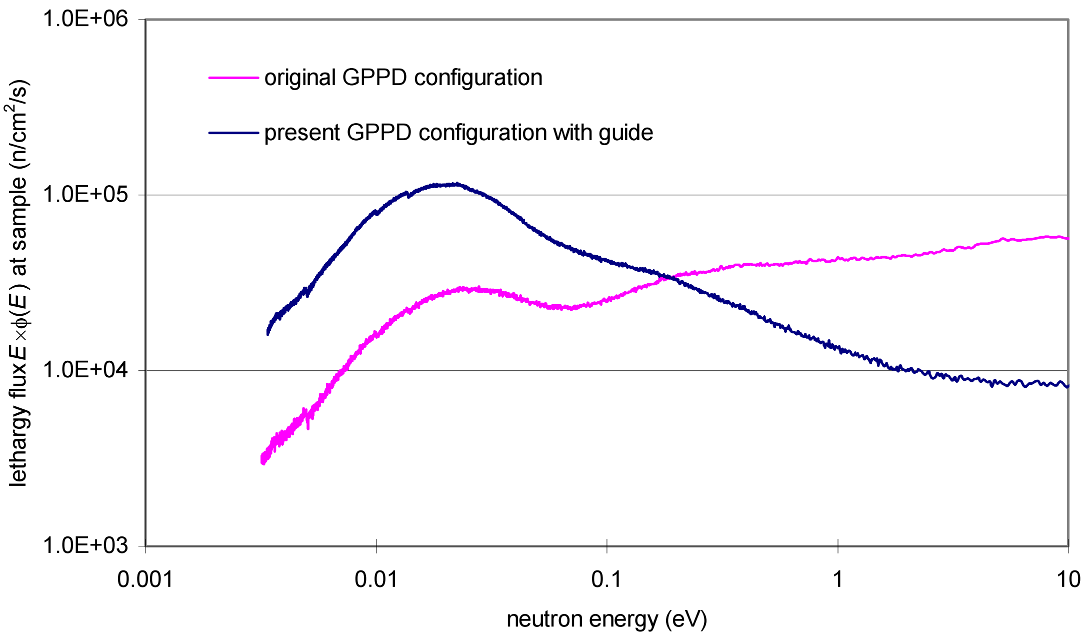

Figure 4. Neutron flux at sample position for previous and present configurations of GPPD.

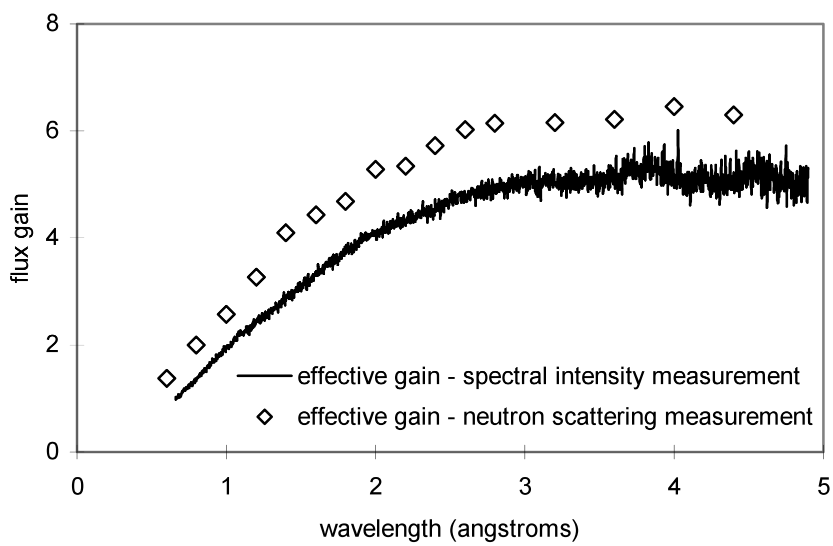

Figure 5. Wavelength-dependent flux gain for GPPD instrument upgrade.

3.2 IPNS "H" Moderator

Measurements were made on the QENS and HRMECS beamlines, which view the IPNS "H" moderator, in February 2005. QENS views the "H" moderator along a line normal to the moderator surface, while HRMECS views the "H" moderator at an angle 18º further upstream. Figure 6 shows the results of neutron intensity spectrum measurements on the IPNS "H" moderator. The measurements on HRMECS, shown in Figure 6, agree well up to an energy of about 0.1 eV. Above this energy the two data sets diverge due to (i) the sensitivity of the SNS portable monitor detector and electronics to the prompt gamma flash coming from the moderator at t = 0, and (ii) an anomalous falloff of the data taken with the IPNS in-situ beam monitor with increasing energy. The "notch" in the HRMECS spectra just below 0.01 eV is caused by the HRMECS T0 chopper. The chopper could not be operated stably at frequencies below 60 Hz (twice the pulse repetition rate) and thus obstructed the neutron beam at the beginning and middle of each pulse. The figure also shows the spectral intensity measured using the QENS in-situ beam monitor. The spectral intensities for these beamlines at an energy of 100 meV are 1.68×10^{10} n/sr/s/μA for QENS (in-situ), 1.20×10^{10} n/ster/s/μA for HRMECS (in-situ), and 1.12×10^{10} n/ster/s/μA for HRMECS (portable).

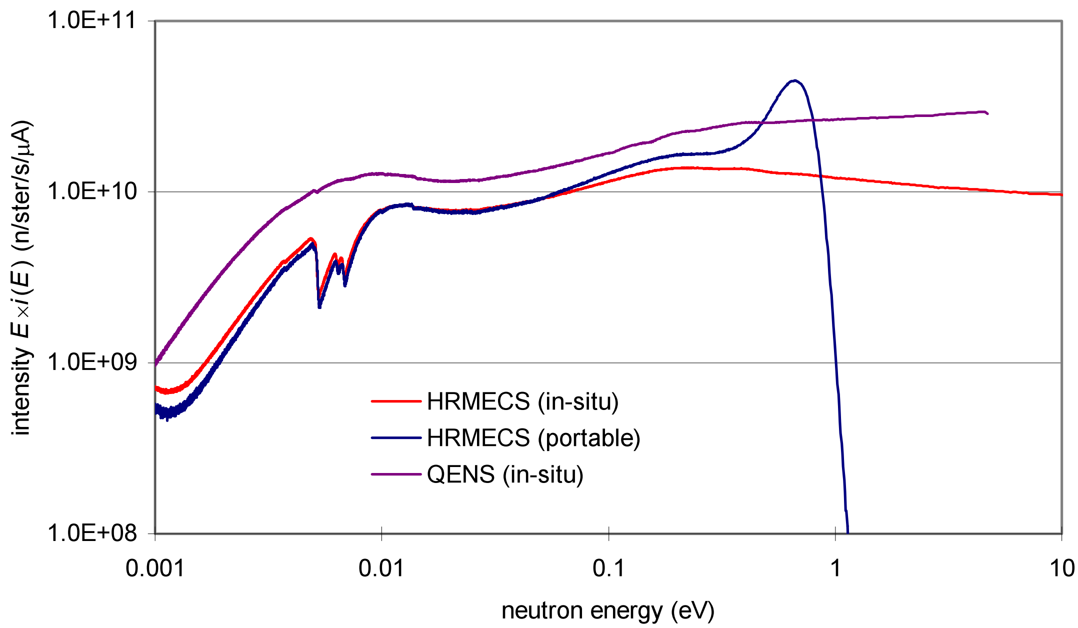

Figure 6. Neutron spectral intensity from the IPNS "H" moderator.

Figure 7 shows the spectral intensity for the QENS beamline, measured using both the in-situ and portable beam monitors. We cannot explain the anomalous peak in the QENS portable beam monitor measurement at ~200 meV. The peak at ~2 eV appears to be the same after-effect of the prompt flash we have seen in our other datasets. We continue to search for a reason for the oddly-shaped peak around 200 meV. The spectral intensity measured with the in-situ monitor agrees well with the results of a recent MCNPX simulation over an energy range 30 meV ≤ E ≤ 1 eV. However, the two spectra diverge below 30 meV, with the measured data showing a lower thermalization and a higher spectral temperature than the simulation.

A supermirror funnel guide was installed on QENS in the latter half of 2003 [6]. Since the in-situ beam monitor is located in front of the guide and the portable beam monitor was located after the guide, we can use the neutron flux measurements from the two monitors to estimate the guide's wavelength-dependent gain. The absolutely-normalized flux from the QENS in-situ monitor could not be used directly for this calculation, so we re-normalized the data from the QENS in-situ monitor to bring the curve into agreement with the HRMECS (in-situ) data at 100 meV. The calculated guide gain, shown in Figure 8, rises to about 3 at a wavelength just over 5 Å, and then slowly decreases to about 2.5 at 15 Å. These data are consistent with the results of a single neutron scattering measurement made with 4 meV neutrons shortly after the guide was commissioned.

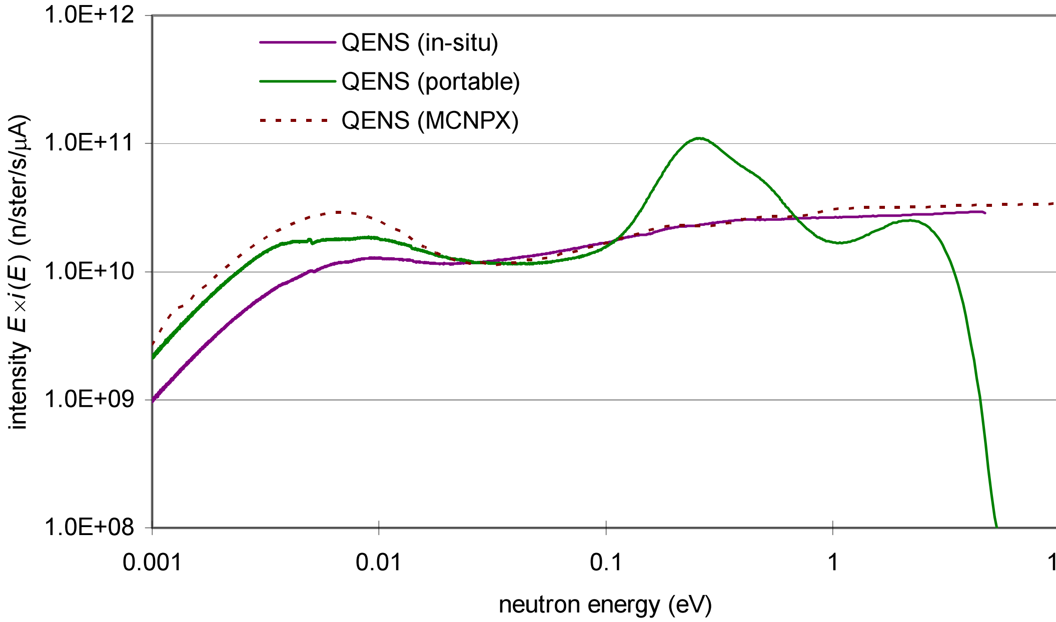

Figure 7. Results of neutron spectral intensity measurements on the IPNS "H" moderator.

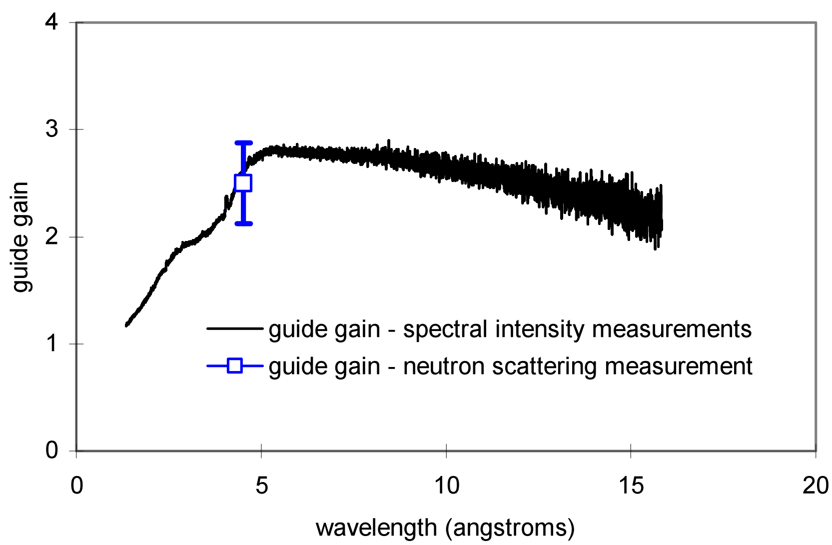

Figure 8. Wavelength-dependent gain for QENS converging funnel neutron guide.

4. Conclusions and Future Directions

The measurements we have made using the SNS portable monitoring equipment and the in situ beam monitors agree well, and provide reasonable spectral intensities for the IPNS beamlines that we characterized. These measurements do not, unfortunately, agree with Monte Carlo simulations for those beamlines, and we are exploring the origins of this disagreement. Our efficiency calibration procedures appear to work fairly well on both unobstructed and chopped beams, and the resulting normalized spectral intensities appear well-behaved, if slightly lower than we expect from simulations. We feel that further investigations are necessary before we can use these procedures for guided neutron beamlines in a routine manner. However, the efficiencies we calculate should still be applicable to guided beams, with the proviso that the spectrum measured represents an integration over the entire beam footprint, not just the sample location.

Acknowledgements

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