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.

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31 1. Introduction

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

54 Reflector-filters, both polycrystalline and single-crystal, were tested on an
55 unreflected pulsed neutron source at the I. V. Kurchatov Institute of Atomic
56 Energy, [3, 4] indicating gains approaching a factor two at long wavelengths
57 from 40 mm layers of beryllium and quartz, respectively, placed adjacent to the
58 moderator, covering the viewed moderator area as well as significant additional
59 solid angle. As such, the reflector-filters tested there did not distinguish between
60 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 beam-lines), 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

90 reflector-filter will scatter many neutrons with wavelengths less than that of the
 91 so-called Bragg edge at 4 Å (5 meV), but it is very nearly transparent above
 92 that wavelength. This property of beryllium is frequently exploited as a beam-
 93 line filter, [13] taking advantage of the change in the scattering cross section
 94 from some 6 barns per atom below 4 Å to less than 0.005 barns per atom above
 95 that wavelength (cross sections from ENDF/B-VII.0). As the reflector-filter
 96 returns neutrons below 4 Å to the moderator and increases the total neutron
 97 density therein, the neutrons have a much higher chance of being emitted at
 98 wavelengths above the Bragg edge than would otherwise be the case.

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

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

117 As a corollary, a comparison of the wavelength-dependent gain factors of the
 118 polycrystalline reflector-filter and the single-crystal reflector-filter (relative to a
 119 conventional moderator) should allow us to proportionally attribute the neutron
 120 emission gains from that polycrystalline reflector-filter to the wavelength ranges

below 1 Å and from 1–4 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 1–4 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 1–4 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 μ s 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 Figure 1. When operated as

Figure 1: Horizontal cross section through LENS target-moderator-reflector. The green box in the middle represents the polyethylene moderator, while the blue box represents the corundum (or empty) reflector-filter.

149 a moderator test facility, the moderator usually used in LENS is removed, and
 150 test moderator assemblies can be sequentially installed.

151 3.2. Instrumentation

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

156 The SANS beam-line beam monitor is a thin low-density ^3He detector posi-
 157 tioned (5.25 ± 0.01) m downstream from the moderator surface along the SANS
 158 beam line, which is 20° away from the moderator surface normal, as shown in
 159 Figure 1. This detector provides neutron energy spectra via time-of-flight.

160 The emission time analyzer is positioned in the SANS sample area during

161 moderator studies. A high mosaicity 10 K germanium single crystal in the
 162 SANS sample position at 8.50 m diffracts neutrons from the (nnn) series into
 163 a scintillator detector positioned in time focused geometry at a nominal Bragg
 164 angle of $2\theta \approx 112^\circ$. [15] The emission time analyzer provides the emission time
 165 distribution (sometimes called the pulse shape) for several different neutron
 166 energies simultaneously.

167 3.3. Test Moderator / Reflector-Filter Assemblies

168 For these experiments we used a moderator of 25 mm thick virgin high-
 169 density polyethylene, 110 mm by 110 mm on the face, transversely penetrated by
 170 5 mm diameter thoroughgoing aluminum rods for thermal conductivity, shown
 in Figure 2. The aluminum rods displace approximately 23% of the polyethy-

Figure 2: Photograph of polyethylene moderator.

171
 172 lene volume, giving a full-density effective thickness of approximately 19 mm,
 173 while significantly flattening the temperature distribution within the moderator
 174 at low temperature. The reflector-filter test objects were mounted on the front

175 face of the moderator, in identical aluminum vessels, each 51 mm by 102 mm
176 by 102 mm. The reflector-filter mounting, on the same cold platform as the
177 moderator itself, is not strictly necessary for the characterization of a reflector-
178 filter. Indeed, it precludes separate control of the temperature of the moderator
179 and the reflector-filter. However, in these studies we were primarily interested
180 in achieving the lowest practical temperatures in both moderator and reflector-
181 filter, so no separate control was necessary. The vacuum vessel containing the
182 cryogenic apparatus can be wrapped with absorbing material to decouple the
183 moderator from the long-lived thermalized neutron population within the reflec-
184 tor. For these studies, that decoupler was left off, as our tests were intended to
185 understand the performance of the single-crystal reflector-filter for moderators
186 optimized for long-wavelength intensity, which are typically coupled moderators.

187 The properties of an ideal material for a single-crystal reflector-filter are
188 similar to those of a conventional reflector-filter: high coherent scattering cross
189 section and low incoherent scattering and absorption cross sections. While beryl-
190 lium, as used in the Lujan Center reflector-filter, meets these criteria, it is not
191 easily available in large single crystals. Graphite also has a favorable cross
192 section, [2] but is quite expensive in the size and quality needed for our demon-
193 stration. We chose to use single crystal corundum (Al_2O_3) to test the single
194 crystal reflector-filter concept. The test apparatus we used limited the total
195 volume available for a reflector-filter (either single-crystal or polycrystalline) to
196 some 50.8 mm thickness, well below optimum, but sufficient for this proof of
197 concept. While corundum has a higher capture cross section than desirable, we
198 believe we can correct for this effect.

199 The single crystal reflector filter was constructed from four single crystal
200 corundum blocks, each 12.7 mm thick and 102 mm by 102 mm, which were
201 stacked with the same crystal orientation and positioned at the front face of the
202 polyethylene moderator. As previously stated, the physical constraints near the
203 LENS target preclude a test with a filter of optimal thickness—we describe be-
204 low how we extrapolate from this geometry-limited experiment to the expected
205 performance of more optimized reflector-filters. The crystallographic orientation

206 was confirmed, and the mosaic distribution measured, using the CG1B neutron
 207 diffractometer at HFIR [16]. The crystal blocks had mosaic of roughly 0.17° .
 208 Each crystal block was oriented with the c -axis (as measured by the $\langle 006 \rangle$ re-
 209 flection) emerging within 1° of the normal to the large face. For each crystal
 210 block we identified the orientation of the $\langle \bar{3}30 \rangle$ reflection to be within 4° of one
 211 of the smaller side faces. We named this face the y -face. The $\langle 110 \rangle$ vector thus
 212 emerges nearly normal to the x -face, with the $\langle 006 \rangle$ vector (the z -face) toward
 213 the viewer.

214 We tested four cases—the actual single crystal corundum reflector filter was
 215 tested twice. In both configurations using the single-crystal reflector-filter, the
 216 crystal lattice was oriented with the c -axis emerging along the nominal moder-
 217 ator normal. In the configuration we describe below as y -up, the $\langle \bar{3}30 \rangle$ pointed
 218 up and the SANS beam-line used for characterization emerges approximately
 219 along the $\langle \bar{1}\bar{1}9 \rangle$ direction. In the configuration we describe as x -up, the $\langle 110 \rangle$
 220 pointed up, and the SANS beam-line emerges approximately along $\langle \bar{1}110 \rangle$. The
 221 two remaining cases included one where the crystals were replaced with corun-
 222 dum powder (99.99% pure with particle size between 0.5 and 1 micron, loaded
 223 into an aluminum cell in a helium environment, packed to around 25% theo-
 224 retical density), and one where the aluminum casing containing the crystal or
 225 powder was left empty (i.e. vacuum).

226 Each of the four different configurations was first measured at ambient room
 227 temperature (~ 300 K during these experiments) and then at 75 K without mod-
 228 ification to the experimental setup (only the temperature was changed). Only
 229 the low-temperature results are described below, as our primary interest for
 230 these experiments was in long-wavelength neutron intensity gains. We antici-
 231 pated possibly significant differences between the x -up and y -up configurations
 232 as the mosaicity of the corundum might result in significant Bragg effects being
 233 visible in the transmitted spectra. [17] However, we saw no particular differ-
 234 ence between the orientations, and as the x -up measurement suffered from poor
 235 statistics relative to the y -up measurement, we report below only the y -up re-
 236 sults.

237 4. Analysis

238 4.1. Normalization

239 Our data normalization is based on the number of Q-pulses obtained by a
240 measurement of the proton current by a transformer in the proton beam pipe.
241 Each Q-pulse represents 10 nC of proton beam charge passing through the trans-
242 former. The recorded data (in counts per time-of-flight bin) from the $1/v$ -SANS
243 beam monitor of known efficiency (4.5×10^{-4} counts per neutron at 1 Å), when
244 normalized, provide wavelength spectra in neutrons per Å per nC. The recorded
245 data from the emission time analyzer cannot easily be absolutely normalized,
246 but can easily be normalized to counts per microsecond per nC enabling rel-
247 ative comparisons. It should be noted that the time in this representation is
248 time-of-flight, not time of exposure, and we use microsecond rather than second
249 to emphasize this distinction. Further details of data analysis can be found
250 elsewhere. [18]

251 4.2. Spectral Gain

252 The measured spectra are shown in Figure 3. The spectra shown in Figure 3
253 from the single crystal and powder measurements, when divided by the spectrum
254 from the empty reflector-filter measurement (that is, the spectrum from the
255 bare moderator), produce the gain factors $G_p(\lambda)$ for the polycrystalline powder
256 reflector-filter and $G_y(\lambda)$ for the y -up single-crystal reflector-filter shown in Fig-
257 ure 4. Note that the (powder) polycrystalline reflector-filter has approximately
258 one quarter of the neutronic thickness of the single-crystal reflector-filter, due
259 to lower density. If the two samples had the same neutronic thickness, we would
260 expect the suppression of short-wavelength neutron emission to be identical.

261 The gain factors shown in Figure 4 show the effect of the polycrystalline
262 reflector-filter and the single-crystal reflector-filter. We do observe suppression
263 of short-wavelength neutrons in the beam from the single crystal case, and
264 transmission gradually sets in in the range from 0.3 Å to 1 Å as expected.
265 In the less dense powder sample there is still a suppression of fast neutrons

Figure 3: Measured neutron spectra showing suppression of short wavelength neutrons by 75 K reflector-filters.

266 and the transmission sets in suddenly at the Bragg edge around 4 Å. Another
 267 effect, previously observed from polycrystalline reflector-filters, is apparent in
 268 the powder case, namely the feature around 1.5 Å. [1, 8] This feature appears
 269 in both calculated and measured polycrystalline reflector-filter results for the
 270 beryllium implementation at the Lujan Center and in our measured results here.
 271 We considered whether it might be related to some thermalized component in
 272 the reflector-filter itself, but this seems unlikely as the feature appears at too low
 273 of a wavelength (around 1.5 Å, implying a spectral temperature of around 400 K
 274 from a medium at 70 K), and is significantly narrower in wavelength spread than
 275 would be expected from a Maxwellian distribution in any event. Similarly, we
 276 do not think it related to a thermalized population in the reflector, appearing
 277 in the emitted beam after a single scattering within the reflector-filter. With
 278 these measurements, we have confirmed that it is not an artifact of either the
 279 Lujan Center geometry, or of beryllium itself, and we hope to address its origins
 280 in further studies, both experimental and computational.

Figure 4: Measured gain factors for the 75 K polycrystalline and single-crystal reflector-filters studied.

281 The single-crystal and polycrystalline reflector-filters measured have signifi-
 282 cantly different neutronic thickness due to a large difference in density (approx-
 283 imately a factor four). To be able to compare the measurements we assume that,
 284 were the polycrystalline powder to have the same density as the single crystal,
 285 then it would behave identically at wavelengths below some $0.3 \text{ \AA}$, that is, where
 286 structure and orientation effects are negligible. We correct the gain factor of the
 287 polycrystalline measurement by treating the gain factor as though it arises from
 288 a repeated series of filters, raising it to a power a such that $G_p^a(\lambda_0) = G_y(\lambda_0)$ for
 289 $\lambda \approx 0.1 \text{ \AA}$. We apply this correction over the entire wavelength range, assuming
 290 that the model of a repeated series of filters is uniformly valid.

291 By fitting constants to the gain factors at short wavelengths shown in Fig-
 292 ure 4, we find $G_y(\lambda_0) = 0.566 \pm 0.015$ and $G_p(\lambda_0) = 0.818 \pm 0.017$, such that
 293 $a = 2.83 \pm 0.02$, as applied in Figure 5. Though we believe this to be a good
 294 approximation, we would only be able to verify the correction by redoing the
 295 experiment using a polycrystalline corundum reflector-filter of equal dimension

Figure 5: Reflector-filter (75 K) gain factors corrected for different neutronic thickness.

296 and density as the single crystal reflector-filter. The apparent gain factor a short
 297 wavelength, $G_y(\lambda_0) = 0.566 \pm 0.015$, is significantly higher than the transmission
 298 of a comparable filter (as opposed to a reflector-filter), for which values from the
 299 literature range over 0.15–0.35. [19–22] The significant variation in the litera-
 300 ture is not something we can address at this point, but our apparent gain factor
 301 $G_y(\lambda_0)$ is larger yet, indicating that the reflector-filter does indeed boost the
 302 intensity within the moderator and at the moderator surface by a significant
 303 amount. Strictly speaking, while we can also assume that the reflector-filter
 304 provides in-scattering to the beam from the reflector itself, regardless of the
 305 intensity within moderator, as well as out-scattering from the beam, we cannot
 306 here distinguish among these effects.

307 It is worth noting that the above comparison also yields an effective esti-
 308 mate of the polycrystalline powder density relative to the single-crystal density;
 309 $\rho_p = \rho_y/a$. Using the corundum single-crystal density of 4.03 g/cm^3 we would
 310 estimate the effective powder density to be 1.42 g/cm^3 , significantly higher than
 311 the measured density of 1.06 g/cm^3 . That is, the powder appears to have *more*

312 of an effect compared to the thicker single-crystal than its relative density would
 313 indicate. We note that the additional scattering power at 0.1 Å could be ex-
 314 plained by this additional (unrealistic) 0.36 g/cm³ of additional corundum, or
 315 equally by 0.02 g/cm³ of water within the corundum powder. Water contami-
 316 nation seems much more plausible. However, that much water would represent
 317 an effective 0.1 cm thickness of water or water ice, which might be expected to
 318 have significant effect at long wavelengths.

319 Figure 5 shows clearly the benefit (increased gain / reduced penalty) of the
 320 single-crystal reflector-filter relative to the polycrystalline reflector-filter in the
 321 0.4–4 Å range, and their similarity at long wavelengths. What Figure 5 also
 322 shows is that both reflector-filters are significantly compromised by capture in
 323 the corundum (primarily in the aluminum), as can be seen by the fall-off in
 324 the gain factor at long wavelengths for both reflector-filters. For a produc-
 325 tion reflector-filter (whether polycrystalline or single-crystal), one would choose
 326 a material with low absorption, such as graphite, diamond, enriched lithium
 327 fluoride, beryllium fluoride, enriched lead, or bismuth. To estimate the gain
 328 factor of an ideal reflector-filter, polycrystalline or single-crystal, we eliminate
 329 the absorption effects by dividing the adjusted gain factors shown in Figure 5
 330 for the single crystal reflector-filter and polycrystalline reflector-filter by the
 331 transmission factors (against capture) of a 50.8-mm slab of corundum of den-
 332 sity 4.03 g/cm³ and 1.06 g/cm³ respectively. To do so, we assume $1/v$ behavior
 333 for both the aluminum and oxygen capture cross sections, with microscopic cap-
 334 ture cross sections of 0.233 b and 0.0002 b, respectively. [23] These observed gain
 335 factors $G(\lambda)$, corrected for capture and for full density across 50.8 mm thickness
 336 and defined as $G'(\lambda)$, appear in Figure 6.

337 Figure 6 clearly shows that low-capture polycrystalline and single crystal
 338 reflector-filters would comparable in gain at long wavelengths, and in suppres-
 339 sion at short wavelengths, while the single crystal reflector-filter regains the
 340 intermediate wavelength neutron emission lost in the polycrystalline reflector-
 341 filter. That is, the single-crystal reflector-filter retains all the long-wavelength
 342 advantages of the polycrystalline reflector-filter, without suppressing potentially

Figure 6: Reflector-filter (75 K) gain factors corrected for density and capture.

important intermediate wavelength neutrons. Even without the scaling argument applied to $G_p(\lambda_0)$, the fact that $G_y(\lambda_0)$ is larger than a filter transmission at the same wavelength confirms our hypothesis that the gains from a reflector-filter, whether polycrystalline or single-crystal, accrue from effects on neutrons of wavelength less than 0.1 Å rather than on neutrons of 1–4 Å.

The magnitude of the gains shown in Figure 6 are modest, around 10% at wavelengths longer than the Bragg edge. The LENS facility is somewhat constrained in the room available for a reflector-filter, precluding prototypical tests. However, the gains shown in Figure 6 indicate that a single-crystal reflector-filter with the same (coherent) scattering cross section as 200 mm of corundum and negligible capture could provide gains of 50% at long wavelengths and intermediate wavelengths at the same time, while suppressing background fast neutrons. By extension, a single-crystal reflector-filter with the same scattering power as the beryllium reflector-filter implemented at the Lujan Center could extend the observed factor two gain in neutron intensity for greater than 4 Å to as low as 1 Å wavelength.

4.3. Emission Time Analysis

The previous section indicates that the single-crystal reflector-filter increases the wavelength-dependent intensity in a neutron beam in the desired 1–4 Å region as compared to an unfiltered beam, while retaining the long-wavelength gains we expect from the proven polycrystalline reflector-filter. This effect is exactly, if quantitatively, what is desired from the single-crystal reflector-filter. We can use the wavelength-dependent emission-time distributions, which we measured at the same time as the spectra, to further explore the nature and origins of the effect.

If we ignore the corrections for neutronic thickness and absorption made in the previous section, the gain factors $G_p(\lambda)$ for the polycrystalline reflector-filter and $G_y(\lambda)$ for the single-crystal reflector-filter are equal to 0.90 and 1.05, respectively, at the 1.81 Å wavelength corresponding to the third-order reflection measured in the emission time analyzer. The emission time distributions as measured at 1.81 Å appear in Figure 7. The gain factors (0.90 and 1.05)

Figure 7: Emission time distributions for 1.81 Å neutrons as measured (without density or capture correction) at 75 K.

mentioned above are the ratio of the spectra, and approximately corresponds to the ratio of the integrals of these emission time distributions. It is clear from Figure 7 that the intensity change at 1.81 Å occurs primarily in the peak of that distribution. That is, the 5% gain from the single-crystal reflector-filter as integrated over the emission time distribution is really a 10% increase in the peak of the distribution. The long-time tails (around 200 μs after the peak) are unchanged. Similarly, the 10% loss imposed by the polycrystalline reflector-filter (as compared to the unfiltered system) is really a 30% loss in peak intensity. Again, the long-time tails are unchanged.

The uncorrected spectral gain at 1.81 Å, 5%, is not large. But all that gain occurs in the peak of the emission time distribution, and is therefore a gain not only in time-integrated intensity, but also in peak intensity and in available time-of-flight resolution. Instruments for which the only parameter of interest is integrated intensity at a given wavelength will see a modest gain (5%). Instruments (such as chopper spectrometers) for which the appropriate metric is instantaneous (peak) intensity will see a more significant gain (10%). Resolution-driven instruments (such as powder diffractometers) with more complicated figures-of-merit which increase with either peak or integrated intensity and also increase with *decreasing* pulse width will benefit more strongly yet. By looking at the emission time distributions, we can see that the benefit of the single-crystal reflector-filter is even greater than what is indicated solely by the ratios of spectral intensities shown previously. The emission time distributions at 1.35 Å and 1.08 Å show similar effects.

Additionally, the emission time distribution comparison indicates that the action of either reflector-filter does not change the storage time of the moderator-reflector system—further support that the single-crystal reflector-filter gain arises from short-lived epithermal and fast neutron populations being returned to the moderator rather than from a thermal neutron population bouncing back and forth. Finally, we also see that while the polycrystalline reflector-filter does not change the storage time of the moderator-reflector system, it does suppress the peak intensity. From this observation we conclude that the intermediate-

wavelength neutrons “lost” from the effects of the polycrystalline reflector-filter are not returned to the moderator, and perhaps subsequently emitted at long wavelengths; they are simply lost to the emitted neutron beam.

5. Conclusion

We have successfully demonstrated single-crystal and polycrystalline reflector-filters at LENS. Comparative time-of-flight study reveals that the single-crystal reflector-filter augments intermediate wavelength neutrons as hoped. Our measurements show that the intermediate wavelength neutrons allowed through the single-crystal reflector-filter do not detract from the cold neutron intensity, indicating that the reflector-filter benefit (whether single-crystal or polycrystalline) derives primarily from suppressing fast neutrons of no use to the instruments viewing that moderator.

The reflector-filters we tested in the LENS facility do not provide significant gains for LENS itself. In the first place, corundum, with its high capture cross section, is not an ideal reflector-filter material. In the second place, the LENS geometry, in order to permit easy access to and rapid exchange of test moderators, does not provide sufficient space for an optimized reflector-filter. Our experiments were intended to demonstrate the concept prior to optimizing a single-crystal reflector-filter for a particular application.

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