A New Polarized Neutron Interferometry Facility at the NCNR

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Abstract

A new monochromatic beamline and facility has been installed at the National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) devoted to neutron interferometry in the research areas of spin control, spin manipulation, quantum mechanics, quantum information science, spintronics, and material science. This facility is possible in-part because of advances in decoherence free subspace interferometer designs that have demonstrated consistent contrast in the presence of vibrational noise; a major environmental constraint that has prevented neutron interferometry from being applied at other neutron facilities. Neutron interferometry measures the phase difference between a neutron wave function propagating along two spatially separated paths. It is a practical example of self interference and due to its modest path separation of a few centimeters allows the insertion of samples and macroscopic neutron spin rotators. Phase shifts can be caused by gravitational, magnetic and nuclear interactions as well as purely quantum mechanical effects making interferometer a robust tool in neutron research. This new facility is located in the guide hall of the NCNR upstream of the existing Neutron Interferometer and Optics Facility (NIOF) and has several advantages over the NIOF including higher incident flux, better neutron polarization, and increased accessibility.

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The long term goal for the new facility is to be a user supported beamline and make neutron interferometer more generally available to the scientific community. This paper addresses both the capabilities and characteristics of the new beamline.

14 *Keywords:* Neutron interferometry; Polarized neutrons; Quantum information
15 science

16 **1. Introduction**

17 The National Institute of Standards and Technology (NIST) Center for Neu-
18 tron Research (NCNR) located in the Gaithersburg, MD is a user-focused fa-
19 cility [1] that provides thermal and cold neutrons beams for a wide variety
20 of applications. These include materials science, the study of polymers, bi-
21 ological science, neutron standards and dosimetry studies, and fundamental
22 physics research. Neutrons are used in research applications because they in-
23 teract differently than light/electron beam techniques, can deeply penetrate
24 materials, have wavelengths that coincide with material lattice spacing, exhibit
25 isotope-dependent scattering that is especially strong in the case of hydrogen,
26 and through their magnetic dipole moment interact with magnetic materials.

27 For many of these research areas cold neutrons which have an energy below
28 25 meV (corresponding to wavelengths λ longer than 0.18 nm) are preferable.
29 To maximize cold neutron flux, thermal neutrons with $\lambda < 0.18$ nm produced
30 by the reactor are cooled by a liquid hydrogen (LH) cold source [2]. A large
31 number of the instruments at the NCNR are located in the guide hall where
32 the cold neutrons leaving the LH source have been transported tens of meters
33 using evacuated neutron guides (NG). With the addition of a new interferom-
34 etry beamline, the Neutron Interferometry and Optics Facilities (NIOFs) are
35 now the second and third instruments located downstream of the cold source
36 on NG-7. The location of both interferometer facilities are highlighted in Fig. 1
37 that shows the layout of the NCNR. The neutron interferometry (NI) program
38 at the NCNR has a history of successful measurements of nuclear constants and

Figure 1: Layout of the NCNR. The reactor core (purple) is surrounded by several instruments (labeled as BT#) requiring higher energy neutrons. The cold source (hidden) is located at the intersection of the NG guides. The NIOFa beamline resides on NG7 and is upstream of existing beamline NIOF.

neutron phase effects (see Table 1). These include demonstration of the 4π periodicity of neutron wave function [3], precision coherent and incoherent scattering length measurements [4–7], measuring vertical coherence [8], demonstrating contrast in the presence of zero entanglement but non-zero Quantum Discord [9], and more applied experiments including phase contrast imaging [10, 11] and measuring the density of thin films [12]. More recently, proposed experiments have needed both high neutron polarization and precise spin manipulation. Although polarized neutrons have been used at the NIOF it is in some ways not ideally suited for these types of experiments. One obstacle in neutron interferometry is its sensitivity to the environment. The path length inside a neutron interferometer is on the order of 10 cm long and it takes a neutron approximately $50 \mu\text{s}$ to travel that distance over which it undergoes greater than 10^8 oscillations. This relatively long (compare to light that in the same time can travel 15 km) flight time is the reason why neutron interferometers are extremely sensitive to external disturbances such as thermal instabilities, thermal gradients, vibrational noise, and acoustical noise. To preserve long-term phase stability at the older NIOF, the neutron interferometer is housed in a massive,

thermal, acoustical, and vibration isolated hutch (see Fig. 2) that has its own foundation separate from the rest of the building [21]. The hutch constrains the neutron interferometer 9 m away from the neutron guide and this contributes to the low neutron rates in the detector on the order of 10s^{-1} . When using neutron polarizers that have a maximum transmission of 40% this count rate

Experiment	Year	Institutions	Ref.
X-ray determination of deformation	94	UMC NIST	[13]
b (coherent) of ^{nat}Si	98	HMI LANL NPIC NPIR UMC NIST	[14]
Search for quantum entanglement in $\text{H}_2\text{O-D}_2\text{O}$	99	HMI LANL UMC NIST	[5]
Neutron phase contrast imaging	99	DUKE UMC NIST	[10]
Measurement of thin film density	99	NIST	[12]
4π -Periodicity of the spinor wave function	00	HMI LANL UMC NIST	[3]
b (coherent) of ^1H	03	IU LANL UMC UNCW NIST	[6]
b (coherent) of ^2H	03	IU LANL UMC UNCW NIST	[6, 15]
b (coherent) of ^3He	04	IU NCS UMC UNCW NIST	[4]
Reciprocal space neutron imaging	07	MIT TU NIST	[11]
Vertical coherence length	08	MIT TU NIST	[8]
Decoherence-free interferometer	09-11	IQC MIT PI UW NIST	[16, 17]
b (incoherent) of ^3He	09-14	IU TU IQC UIUC UNCW NIST	[7, 18]
Heatless neutron spin rotators	12	IQC PI MIT NIST	[19]
Quantum discord	14	IQC PI UW MIT NIST	[9]
Neutron OAM	15	BU JQI IQC NIST PI UW	[20]

Table 1: List of NI experiments done at or with the collaboration of the National Institute of Standards and Technology (**NIST**). Institutions are Boston University (**BU**), Duke University (**DUKE**), Indiana University (**IU**), Institute for Quantum Computing (**IQC**), Joint Quantum Institute (**JQI**), Los Alamos National Laboratory (**LANL**), Massachusetts Institute of Technology (**MIT**), University Missouri-Columbia (**UMC**), Nuclear Physics Institute Czech (**NPIC**), Nuclear Physics Institute Russia (**NPIR**), Perimeter Institute for Theoretical Physics (**PI**), University North Carolina-Wilmington (**UNCW**), University of Waterloo (**UW**), University of Illinois at Urbana-Champaign (**UIUC**), University of Maryland (**UMD**), and Tulane University (**TU**).

Figure 2: An artist's depiction of the hutch at the NIOF showing the nested-layers and vibration isolation system.

61 drops even further. To compensate for poor initial statistics many NI experi-
 62 ments need to be run for many months and insuring experimental (especially
 63 environmental) conditions over that long span of time can be challenging.

64 In 2010 the NCNR underwent an expansion project adding an additional
 65 guide hall with four new state-of-the-art neutron guides (see Fig. 1). During
 66 the yearlong reactor shutdown required for this expansion, a new beamline just
 67 upstream of the NIOF was installed. This new facility, designated as NIOFa,
 68 benefits from higher flux at the expense of some long-term phase stability. Con-
 69 struction of this facility is in-part due to the recent advances in neutron inter-
 70 ferometer design. A decoherence free subspace (DFS) neutron interferometer
 71 has shown to be insensitive to vibrational frequencies up to 22 Hz [16]. The new
 72 facility has improved neutron polarimetry capabilities, increased ease-of-access,
 73 a designated cryostat, and environmental temperature control. Further it will
 74 expand the capabilities, some of which are not feasible in the NIOF beamline,
 75 of the neutron interferometry program at NIST. The new facility will focus on:
 76 spin-based neutron interferometry, testing of quantum mechanics, spintronics,
 77 neutron spin manipulation, material research and quantum information science.

78 This paper covers aspects and characteristics of the new NIOFa facility. For
79 improved understanding of NI applications this includes a general treatment of
80 spin-based neutron interferometry. Detailing the changes to the older beamline,
81 see the companion paper to this one [22].

82 2. Neutron Interferometry

83 2.1. Neutron Optics

84 Neutron optics exploits the wave-like properties of neutrons and describes
85 the neutrons interaction with materials. In general it is analogous to optics
86 describing light propagation and shares many of the same concepts like diffrac-
87 tion, interference, coherence, and refraction (see Table 2). When a neutron with
88 initial momentum $k_0 = \sqrt{2m_n E_0}/\hbar$ passes through a medium (as depicted in
89 Fig. 3) its momentum changes to $K = nk_0$. Here E_0 is initial energy, m_n the
90 mass of the neutron and n is the index of refraction which one can write as

$$n = \frac{K}{k_0} = \sqrt{\frac{2m_n(E_0 - V)}{2m_n E_0}} \approx 1 - \frac{V}{2E_0}. \quad (1)$$

91 The potential V can represent any neutron interaction as the neutron couples to
92 the strong, weak, electromagnetic and gravitational forces. The approximation
93 in Eqn. (1) is valid because the effective potential for neutrons is $\approx 10^{-6}E_0$.

Property	Photon	Neutron
Mass	0	$m_n = 1.674928(1) \times 10^{-27}$ kg
Spin	$\hbar$	$\frac{1}{2}\hbar$
Magnetic Dipole Moment	0	$\mu_n = -9.66237055(71) \times 10^{-27}$ J/T
Equation	$\nabla^2 \psi(\mathbf{r}, t) = \frac{1}{c} \frac{\delta^2 \psi(\mathbf{r}, t)}{\delta t^2}$	$H\psi(\mathbf{r}, t) = i\hbar \frac{\delta \psi(\mathbf{r}, t)}{\delta t}$
Energy	$E = \hbar k c$	$E = \frac{\hbar^2 k^2}{2m_n}$
$n(\text{H}_2\text{O}) - 1$	0.33	2.88×10^{-7}
Velocity	c	$v = \frac{3956}{\lambda[m]} \times 10^{-10}$ m/s
Rest Mass	0	$E = m_n c^2 = 939.6$ MeV

Table 2: Comparison between light and neutron properties. A similar table can be found in [23]. Values are taken from the latest PDG summaries [24]. $n(\text{H}_2\text{O})$ is the index of refraction for water. Calculated values for the neutron are expressed for the thermal neutron wavelength of 0.18 nm.

Figure 3: A neutron passing through a medium can be described by an index of refraction n and potential V changing the incident wavevector k_0 to K . The angle of refraction is exaggerated as $n \approx 1$.

94 Note that one of the other major differences between light and neutron optics,
 95 other than the magnitude of n , is that

$$n = \frac{K}{k_0} \propto \frac{1}{v_{\text{med}}} \quad (\text{photon}) \quad (2)$$

96 and

$$n = \frac{K}{k_0} \propto v_{\text{med}} \quad (\text{neutron}) \quad (3)$$

97 where v_{med} is the velocity inside the medium. The relevant potential for a
 98 neutron interaction with a sample material is called the Fermi pseudopotential

99 and is given by

$$V_{\text{nuc}} = \frac{2\pi\hbar^2}{m_n}Nb \quad (4)$$

100 where N is the atomic density and b is the scattering length. The scattering
101 length is a property of the interaction, varies per isotope, and is typically on the
102 order of a few femtometers. Further, b is a complex number where $b = b' + ib''$.
103 The scattering cross section σ_s is given simply by $\sigma_s = 4\pi|b|^2$. The imaginary
104 part b'' is related to the neutron absorption cross section

$$\sigma_a = \frac{4\pi}{k_0}b''. \quad (5)$$

105 Neutron absorption in a material can be described by the transmission of a
106 neutron beam with an incident intensity I_0 [25] by

$$I = I_0 e^{-\sigma_a N D}. \quad (6)$$

107 The real part of neutron scattering lengths are overwhelmingly positive with
108 some notable exceptions like ^1H , ^{48}Ti , and ^{62}Ni . One of the primary means of
109 measuring b has been NI which has measured over fifty isotopes (many to high
110 precision).

111 2.2. Interferometry

112 A single crystal neutron interferometer consists of a silicon crystal that has
113 been machined to produce several parallel blades on a common base. This
114 ensures arcsecond alignment of lattice planes of each blade relative to each
115 other; a stringent requirement of Bragg diffraction. Shown in Fig. 4 are the
116 interferometers available at NIST. Properties for these interferometers are listed
117 in Table 3. A single crystal neutron interferometer is conceptually analogous to
118 an optical Mach-Zehnder interferometer. However, instead of mirrors a neutron

119 interferometer uses beam splitters and Bragg diffraction defined by

$$n\lambda = 2d \sin \theta_B \quad (7)$$

120 to separate the neutron into 2 paths. It is important to note that this separation
 121 happens for each individual neutron's wavefunction (counts rates are low enough
 122 to guarantee that here is only one neutron at a time inside the interferometer).
 123 In Eqn. 7 n is the order of reflection, d is the lattice spacing of the crystal and θ_B
 124 is the Bragg angle. For silicon $d = (0.543 \text{ nm})/\sqrt{h^2 + l^2 + k^2}$ [26] where h, k, l
 125 are the Miller indices for a particular lattice. Silicon has a diamond-structure
 126 lattice and many reflections are forbidden. Valid reflections are

$$h, k, l = \begin{cases} \text{all odd} \\ \text{all even with } h + k + l = 4m \end{cases}$$

127 where m is an integer. The most widely used lattice planes are (220) and (111).
 128 Wavelengths used for neutron interferometry experiments at NIST fall between
 129 0.2 nm and 0.5 nm. The most commonly used are 0.271 nm and 0.235 nm.

130 Figure 6 shows a schematic of a neutron interferometer. A neutron entering
 131 the first blade (splitter) of the interferometer is coherently split into two spa-
 132 tially separated paths labeled as path I and path II. Neutrons along path I and
 133 path II are again Bragg diffracted by the middle blade(s) (mirror) and interfere

	Lattice	λ Range	Max. Contrast	B_w	B_h	B_{s1}	B_{s2}
Type	Vector	(nm)	(%)	(mm)	(mm)	(mm)	(mm)
1 Skew	(111)	0.33 – 0.49	—	2.5	30.0	20.0	36.6
2 Skew	(111)	0.22 – 0.30	34	1.5	40.0	14.1	82.0
3 Skew	(220)	1.00 – 0.30	—	2.0	30.0	32.0	25.4
4 LLL	(111)	0.00 – 0.50	—	2.0	25.0	41.5	—
5 LLL	(111)	0.00 – 0.50	90	2.5	30.4	39.6	—
6 LLL	(220)	0.00 – 0.20	—	2.5	15.5	34.5	—
7 Skew	(220)	0.22 – 0.25	85	2.8	25.4	16.0	30.5
8 DFS	(220)	0.00 – 0.33	25	1.0	16.0	10.0	20.0
9 LLL	(111)	0.00 – 0.54	30	1.0	15.0	10.0	—

Table 3: Properties of the interferometers located at NIST shown in Fig. 4. Geometry blade width, height and separation are defined in Fig. 5. The maximum contrast is the largest value that has been observed for any wavelength. Interferometers with contrasts unspecified have either not been used in the last 15 years at NIST and/or are believed to be $< 10\%$.

Figure 4: The single crystal interferometers at NIST (formerly the National Bureau of Standards). Their properties are given in Table 3. Many of the interferometers shown here were fabricated by C. Holmes and S. Potts at the U. of Missouri-Columbia machine shop under the supervision of S. A. Werner.

134 in the final blade (analyzer) of the interferometer. The two beams exiting the
 135 interferometer are historically labeled the O- and H-beams. Neutrons are de-
 136 tected with 100 % efficiency by cylindrical ^3He filled proportional counters. The
 137 intensities measured by the detectors can be written as

$$I_O = A[1 + C \cos(\Delta\phi)] \quad (8)$$

$$I_H = A[B - C \cos(\Delta\phi)]. \quad (9)$$

138 In principle, the values of the parameters A , B , and C can be determined by
 139 calculation of the reflection and transmission coefficients along the 2 paths as
 140 the neutron Bragg diffracts in the silicon crystal. In practice, however, these
 141 parameters are extracted from fits to the data. Notice that in the interferometer

Figure 5: Geometries of a skew and LLL neutron interferometer. (a) Top view of skew symmetric neutron interferometer, where B_{s1} and B_{s2} (for the case of Skew and DFS geometries) are the blade separations. (b) Side view of a LLL interferometer showing blade height B_h , width B_w , and separation B_{s1} .

142 $I_O + I_H = \text{constant}$ as neutrons are not absorbed in the silicon crystal. The
 143 phase $\Delta\phi$ is path-integral phase difference between the two paths. In practice
 144 $\Delta\phi = \Delta\phi_V + \Delta\phi_0$ where $\Delta\phi_V$ is the phase shift caused by a sample (or other
 145 interaction). For instance, when the phase shift $\Delta\phi_V$ is caused by a sample
 146 located in path 2 one may write

$$\begin{aligned}\Delta\phi_{\text{sample}} &= \int_{\text{I}} k_0 ds - \int_{\text{II}} n k_0 ds \\ &\approx \int_{\text{II}} \frac{V}{2E_0} ds = \int_{\text{II}} N b \lambda ds = -N b \lambda D\end{aligned}\quad (10)$$

147 where N , b , and D are number density, scattering length and the effective
 148 thickness of the sample. The phase $\Delta\phi_0$ is the an initial phase difference between
 149 the paths that can vary depending on experimental conditions. If the sample
 150 absorbs neutrons then Eq. 8 is modified using Eqns. 6 as

$$I_O = \frac{A}{2} [(1 + e^{-\sigma_a N D}) + 2e^{-\sigma_a N D/2} C \cos(\Delta\phi)]. \quad (11)$$

151 Although the amplitude of I_H transforms in the same way as in Eq. 11, to

Figure 6: A diagram of a three blade interferometer. The incident neutron beam, which can be polarized in either spin state using a supermirror and precession coil spin flipper, enters the interferometer from the left. The ‘splitter’ blade of the crystal separates the neutron into 2 separate paths which are reflected using a ‘mirror’ blade toward the ‘analyzer’ blade where they interfere with each other. The neutron intensity is measured via proportional ^3He detectors.

152 transform the B term in Eq. 9 it would become necessary to express it as
 153 individual reflection and transmission coefficients; a complication that is omitted
 154 here.

In addition to the interaction to be probed ($\Delta\phi_V$) and the intrinsic phase of the interferometer ($\Delta\phi_0$) one often adds a variable ‘control’ sample called a phase flag. At the Neutron Interferometer and Optics Facilities (NIOFs) the phase flag is a 50 mm $\times$ 50 mm $\times$ 1.5 mm optically flat piece of fused quartz. By rotating the phase flag, one creates a phase shift due to the geometrical difference in optical path lengths between the paths of

$$\begin{aligned}\Delta\phi_{\text{p.f.}}(\delta) &= -N_{\text{p.f.}}b_{\text{p.f.}}\lambda D_{\text{p.f.}}\left[\frac{1}{\cos(\theta_B + \delta)} - \frac{1}{\cos(\theta_B - \delta)}\right] \\ &= -N_{\text{p.f.}}b_{\text{p.f.}}\lambda D_{\text{p.f.}}\left[\frac{2\sin(\delta)\sin(\theta_B)}{\cos^2(\theta_B) - \sin^2(\delta)}\right]\end{aligned}\quad (12)$$

155 where $N_{\text{p.f.}}$, $D_{\text{p.f.}}$, and $b_{\text{p.f.}}$ are the number density, thickness, and average
 156 scattering length of the phase flag, respectively. The angle δ is the angle of
 157 phase flag from its initial position parallel to the blades (see Fig. 6). Rotating
 158 a phase flag a few degrees produces interferograms like the ones seen in Fig. 7

159 and allows a fitted determination of each of the coefficients given in Eqns. 8 and
 160 9.

161 The neutron is spin 1/2 particle with a magnetic dipole moment (MDM) of
 162 $\mu_n = -9.66 \times 10^{-27}$ J/T (the minus sign indicates that the neutron's spin and
 163 MDM are anti-aligned). Thus the neutron can be polarized and analyzed using
 164 a variety of methods such as Stern-Gerlach magnets, supermirrors, polarized
 165 ^3He spin filters, and Huelser crystals. Typically these devices reach neutron
 166 polarizations P_n better than 90 % for monochromatic neutron beams. Once
 167 polarized, the neutron's polarization can be manipulated with nearly 100 %
 168 efficiency using standard neutron flippers of which there are many designs: RF
 169 coils [27, 28], DC driven precession spin flippers [29, 30], and thin films [19] to
 170 name a few. The phase shift caused by magnetic fields can be quite complicated
 171 as the overall phase shift is both dependent on the type (static vs time varying)
 172 and magnitude of the magnetic field as well as the specific spacial evolution of
 173 the neutron's spin around a spin sphere [30]. In its simplest form the magnetic
 174 potential

$$V_{\text{mag}} = -\mu_n \boldsymbol{\sigma}_i \cdot \mathbf{B} \quad (13)$$

175 is a function of Pauli matrices $\boldsymbol{\sigma}_i$ and the magnetic field $\mathbf{B}$. When the neu-
 176 tron spin is aligned parallel or anti-parallel to the magnetic field, this potential
 177 produces a phase shift of

$$\Delta\phi_{\text{mag}} = \pm \frac{1}{\hbar} \int_{II} \frac{\mu_n B}{2E} ds = \pm \frac{2\pi\mu_n \lambda m_n B D}{h^2} \quad (14)$$

178 Besides magnetic and nuclear interactions, there are numerous other potentials,
 179 that are listed in Table 4, including gravity, Sagnac (Coriolis), and Aharonov-
 180 Casher.

Figure 7: An interferogram showing I_O (red circles) and I_H (blue squares) where the lines are the fits using Eqs. 8 & 9. The phase shift $\Delta\phi_{\text{sample}}$ is measured comparing the sample in (solid) and out (dotted) positions for a sample with appreciable scattering losses. The uncertainties are purely statistical.

3. NIOFa Facility Design

3.1. Guide modifications

At the NCNR neutrons are produced in the reactor core by fission of ^{235}U and moderated to thermal energies using heavy water. Typically the reactor operates at full power for 38-day periods followed by 10 day maintenance breaks. For neutron instruments like the Neutron Interferometer and Optics Facility

Interaction	Potential	Phase shift $[\phi]$	Reference
Nuclear	$2\pi\hbar^2 b\delta(\mathbf{r})/m_n$	$-ND\lambda b$	[31]
Magnetic	$-\boldsymbol{\mu}_n \cdot \mathbf{B}(\mathbf{r})$	$\pm\mu_n B m_n \lambda D / (2\pi\hbar^2)$	[31]
Gravitational	$m_n \mathbf{g} \cdot \mathbf{r}$	$m_n^2 g \lambda A \sin(\alpha) / (2\pi\hbar^2)$	[32]
Coriolis	$-\hbar\boldsymbol{\omega} \cdot (\mathbf{r} \times \mathbf{k})$	$(2m_n/\hbar)\boldsymbol{\omega} \cdot \mathbf{A}$	[33]
Aharonov-Casher	$-\boldsymbol{\mu}_n \cdot (\mathbf{v} \times \mathbf{E})/c$	$\pm\{2\mu_n/(\hbar c)\}\mathbf{E} \cdot \mathbf{D}$	[34]
Scalar Aharonov-Bohm	$-\boldsymbol{\mu}_n \cdot \mathbf{B}(t)$	$\pm\mu_n B t/\hbar$	[35]
Berry		$\Omega/2$	[36]

Table 4: The phase shift caused for many interactions. The definitions of the undefined symbols can be found in the references. (Table reproduced from [23])

187 (NIOF) located in the Guide Hall, these thermal neutrons pass through a liquid
 188 hydrogen (LH) cold source. The LH source decreases the peak of the Maxwell-
 189 Boltzmann energy distribution to a temperature of 40 K; thus becoming what
 190 are called cold neutrons¹. Cold neutrons are then transported to the various in-
 191 struments by rectangular neutron guides. The older guides labeled NG1 through
 192 NG7 are made of glass. The inside of the glass guides are coated with ⁵⁸Ni. This
 193 allows for increased neutron transmission as ⁵⁸Ni has a relatively large critical
 194 angle of $\theta_c^2 = 0.34 \text{ mrad per meV}$ and thus minimizes neutron transport losses
 195 compare to naked glass. The NG7 guide, which houses both the NIOF and the
 196 new NIOFa, is internally 15 cm tall and 6 cm wide at the location of beam exit.

197 Before the upgrade, a single pyrolytic graphite PG(002) monochromator that
 198 was internal to the guide was used to provide neutrons to the NIOF hutch. A
 199 PG crystal, which has a hexagonal lattice structure, Bragg diffracts neutrons of
 200 the desired energy. The pyrolytic graphite crystals used at the NIOFa has an
 201 angular variation of 0.5° in lattice vector direction; a feature that is otherwise
 202 known as a mosaic η . A mosaic crystal allows a greater intensity to be reflected
 203 relative to a perfect crystal where $\eta = 0$.

204 For the new facility, a 150 mm portion of NG7 guide was removed and two
 205 pyrolytic graphite PG(002) monochromators were installed in the lower half
 206 of the NG7 guide (see Fig. 8). The upper half of the guide is reserved for a
 207 small angle neutron scattering (SANS) instrument located at the end position of
 208 NG7. The guide windows are magnesium foils $900 \mu\text{m}$ thick. Both PG crystals
 209 are 50 mm tall by 40 mm wide. Since these monochromators along with their
 210 stages and supports are located outside of the guide, they can be more conve-
 211 niently maintained. The two reflected beams from the monochromators cross as
 212 the upstream monochromator provides neutrons for the NIOF and downstream
 213 monochromator for the NIOFa. At the NIOFa beamline the PG monochroma-
 214 tor provides a fixed 0.44 nm neutron beam ($\theta_B = 41^\circ$). This wavelength was

¹This is higher than the LH temperature of 20 K since the neutrons are not in equilibrium with the cold source.

215 chosen to maximize the neutron intensity as it is near the peak of the Maxwell-
216 Boltzmann distribution provided by the LH cold source.

217 The NIOFa was installed in an area upstream of the hutch; in a space that
218 was reserved for the NIOF since its installation in 1994. This area was planned
219 into the original NIOF design to allow for a large range of neutron wavelengths
220 to be accessible. The NIOF uses a double monochromator system to reflect
221 neutrons parallel to the neutron guide and into the hutch. Although the first
222 monochromator is a fixed position relative to the guide; the second vertically-
223 focusing monochromator is on a 1.8 m travel translation stage. This translation
224 stage can be kinematically placed along several positions on the floor allowing
225 wavelengths from 0.2 nm with $\theta_B = 17.3^\circ$ to 0.47 nm with $\theta_B = 45.0^\circ$ (the rela-
226 tive angle of the reflected beam to the guide is $2\theta_B$). However, with the addition
227 of the new facility, the NIOF facility can only access neutrons from 0.2 nm to
228 0.31 nm without impacting the NIOFa beamline. The NIOF retains the capa-
229 bility of using 0.32 nm to 0.47 nm neutrons but in that case both facilities can
230 not run simultaneously.

231 3.2. Description of new beamline

232 A schematic of the new beamline can be seen in Fig. 9. Cold 0.44 nm neu-
233 trons coming from reactor are reflected out of the NG7 guide by the downstream
234 monochromator PG(002) labeled as Mon2. Both Mon1 and Mon2 are directly
235 coupled to a nema true [37] planetary gearhead with 100:1 ratio and stepper
236 motor². The output shafts of the motors are coupled to an incremental en-
237 coder³ with 8192 counts per revolution. Tilt of the monochromators is achieved
238 through motorized⁴ goniometers⁵. In order to minimize activation of the crystal
239 mounting, the PG crystals are mounted using a thin, slotted aluminum pieces,
240 the top of which sit 2 mm below the guide.

²model # NT17-100-H-34-615-557-D769

³model # 15T-02SF-8192N5RHV-F00

⁴Faulhaber model # AM1524-A-0.25-15.5-6 15/8 900:1

⁵model # NT66-525 (Mon2) and model # NT66-531 (Mon1)

Figure 8: The current setup with a guide cut of 150 mm where there are two identical PG(002) monochromator crystals.

241 Paraffin wax and steel shot-filled-steel walls (the teal shielding in Fig. 9)
 242 surround the neutron guides for radiation safety and to minimize backgrounds.
 243 This shielding extends 1.98 m high and is approximately 318 mm thick in total.
 244 At the NIOF there is a 177 mm high by 571 mm long rectangular hole in the
 245 back (guide side) of the shielding centered on the beamline. The beamline itself
 246 is 120 cm from the floor. To reduce backgrounds, a 6.35 mm-thick, neutron-
 247 absorbing boral plate was installed between the guide and the shielding. This
 248 boral plate has a 100 mm long by 62 mm high rectangular hole that allows
 249 neutrons from Mon1 and Mon2 to pass. Between the boral and the shielding
 250 wall is 50.8 mm of lead that has a slightly larger rectangular hole than the boral
 251 plate allowing neutrons to pass through unobstructed.

252 A 412.8 mm gap exists between the two shielding walls at the interferometer
 253 facility. This gap contains a rotatable collimator which is called the “Drum”.
 254 The Drum was originally built with the NIOF and can be translated so that

any wavelength between 0.2 nm to 0.47 nm could be selected for the hutch. To fill in the gap, two paraffin wax and steel-shot-filled steel “wings” were attached to sides of the drum and that translated with the drum as it moved for various wavelengths. With the addition of the NIOFa beamline the upstream most wing was removed.

Due to the large angles the exit hole on the downstream shield is 279 mm high by 1334 mm wide. A paraffin and steel insert with a 63.5 mm vertical gap was installed inside the 279 mm exit hole to reduce backgrounds at the facility. Since a large epithermal neutron background has been measured, a high-density polyethylene (HDPE) block was installed in the gap to downscatter neutrons so that they could be more efficiently captured on neutron shielding. A combination of 6.35 mm thick boron nitride (BN) and 76.2 mm thick lead sits beyond the downstream shield wall. To limit horizontal beam divergence a 0.2° Söller collimator [38] with neutron absorbing gadolinium-coated blades is inside the shielding upstream of the boron nitride and lead shielding.

To open and close the beam at the facility, a shutter is used containing 12.7 mm thick boron-nitride, 1.0 mm thick cadmium, and 101.6 mm of lead. The shutter is translated vertically in and out of the beam using air pistons⁶. A fission chamber⁷ with a detection efficiency of 10^{-5} is located after the shutter to monitor reactor fluctuations. Following the fission chamber there is an adjustable slit assembly labeled as Slit1 which is made of two orthogonal pairs of 3.2 mm-thick boron-nitride-layered cadmium mounted on translational stages. Because there is a substantial component of higher energy neutrons in the NIOFa beamline (see Sec. 3.3.2) a 177.8 mm diameter, 234.95 mm long cylindrical dewar with a beryllium filter inside was installed after Slit1. The beryllium filter scatters neutrons with $\lambda < 0.40$ nm out of the direct beam where they are absorbed in the surrounding boron shielding. To minimize the transmission loss of the desired 0.44 nm neutrons from inelastic phonon scattering, the beryllium

⁶Bimba model # T-316-EB2

⁷LND model # 3005

283 filter is continuously cooled using liquid nitrogen (LN).

284 Downstream of the filter is a supermirror polarizer. In a supermirror polar-
285 izer, the undesired neutron spin state is reflected out of the direct beam using
286 a a multilayered, CoFeV-coated mirror. At the NIOFa facility neutrons are po-
287 larized and analyzed using double ‘V’ cavity supermirrors made by SwissNeu-
288 tronics. They were designed to achieve a neutron polarization $P_n \geq 98\%$ with
289 minimal physical size for neutrons with wavelengths larger than 0.2 nm. Inter-
290 nally, these double cavity supermirrors are divided into three identical channels.
291 Each of these channels have two back-to-back, double-side coated supermirrors
292 in the shape of a ‘V’. This insures that neutrons passing through the channels
293 always pass through multiple coatings and thus maximize the final neutron po-
294 larization. The supermirror has an overall length of 260 mm with an interior
295 that is 10 mm wide by 50 mm tall. A second adjustable slit assembly labeled as
296 Slit2 and identical to Slit1 is used downstream of polarizer to limit the beam
297 divergence. Both Slit1 and Slit2 have a maximum height and width of 76.2 mm.
298 A precession coil spin flipper located after the polarizer can flip the polarity
299 ($P_n \rightarrow -P_n$) of the neutron beam when energized. The interferometer rests on
300 a custom 1.5 m by 1.8 m nonmagnetic optical table (see Fig. 10) with 25.4 mm
301 separated 1/4-20 threaded holes that allows easy sample mounting and detector
302 placement.

303 Since temperature fluctuations as little as 10 mK can produce phase drifts,
304 an aluminum box 76.2 cm by 76.2 cm by 76.2 cm that is lined with cadmium
305 provides isolation from the environment. This aluminum box is isolated from the
306 breadboard by a 3 mm thick fiberglass base. PID looped temperature controlled
307 heaters are placed along the walls of the aluminum box. A spin analyzer identical
308 the supermirror polarizer can analyze the outgoing polarization state of the
309 O- or H- beam. A beam block consisting of a combination of high-density
310 polyethylene, boron nitride, and lead is placed at the end of the optical table to
311 completely stop the direct neutron beam.

Figure 9: Schematic of the new facility. A PG(002) crystal (Mon2) reflects 0.44 nm neutrons into the facility. The neutron beam passes through a through collimator, fission chamber, beryllium filter, polarizer and spin flipper before entering a cadmium-lined, aluminum enclosure that houses the the interferometer. The crystal Mon1 reflects neutrons into the NIOF hutch.

312 The interferometer is supported by a rotation⁸, translation⁹ and height

⁸PI Micos model # PRS-200 180:1 with SiGNUM Encoder

⁹Huber model # 5101.20

Figure 10: The actual setup of the NIOFa beamline looking from the guide.

313 stage¹⁰. The rotation stage is used to find the Bragg angle of the interfer-
 314 omer which is typically 3.5×10^{-3} radians wide (full-width-half-max). The
 315 translation and the height stage are used to find the interferometer's "sweet"
 316 spot; an area typically no bigger than few square millimeters where the contrast
 317 is highest. The interferometer crystal rests on a common pool-table felt cloth
 318 which, from experience, provides enough friction to hold the interferometer in
 319 place without stressing the base of the interferometer. Both the H-beam and
 320 O-beam detectors are 10 bar ^3He filled proportional counters that are typically
 321 25.4 mm in diameter¹¹ although other size and pressure detectors are sometimes
 322 used depending on experimental conditions.

3.3. Beam Characteristics

3.3.1. Fluence

The neutron fluence rate was measured after the first slit (Slit1) at new facility using a calibrated fission chamber containing $32.6 \mu\text{g}$ of Uranium. Data was taken at the different positions relative to the center of the beam. The measured neutron fluence at the center was 3.56×10^6 neutrons/($\text{cm}^2 \cdot \text{s}$) Table 5 shows the measured fluence rates as a function of beam position relative to the center. This is higher than the measured NIOF neutron fluence rate of 1.32×10^5 neutrons/($\text{cm}^2 \cdot \text{s}$) at $\lambda = 0.235 \text{ nm}$ after its first monochromator. Systematic uncertainties of calibrated fission chamber owing to the deposit particulars are estimated to be $\approx 10\%$. Fluence rates for both NIOFa and NIOF included neutrons with wavelengths λ/n where $n = 2, 3, \dots$ present in the beam (Fig. 11a). In the case of the NIOFa the fractional component of λ/n compared to the peak λ was 25% . To eliminate the faster neutrons, a $76.2 \text{ mm} \times 76.2 \text{ mm} \times 152.4 \text{ mm}$ long beryllium filter was installed immediately after the upstream slit assembly. Beryllium scatters neutrons below the Bragg cut-off $\lambda \leq 0.396 \text{ nm}$ out of the direct beam. With the Be filter installed the intensity of the beam dropped 62.2% overall as measured using a fission chamber but no detectable λ/n could be seen (see Fig. 11b) using a disk chopper and measuring the time-of-flight. Cooling the Be filter to liquid nitrogen temperatures minimizes phonon scattering and thus increases transmission for 0.44 nm neutrons.

¹⁰Huber model # 5103.A20

¹¹For the 25.4 mm in diameter: GE Energy, model # RS-P4-0802-204

Calibrated detector position (relative to center)	Fluence rate (neutrons/($\text{cm}^2 \cdot \text{s}$))
0 cm	3.56×10^6
1 cm up	3.12×10^6
1 cm down	2.83×10^6
0.5 cm toward NIOF	2.63×10^6
0.5 cm toward reactor	2.17×10^6

Table 5: Neutron fluence measurement of NIOFa beamline using a calibrated fission chamber at different positions relative to the beam center.

When the filter was cold the overall drop of intensity was measured to be 15 % when using a fission chamber and corresponds to very little transmission loss — for 0.44 nm neutrons. The difference between the measured loss of 15 % and the expected 25 % loss is consistent with the efficiencies of the fission chamber at different neutron wavelengths.

3.3.2. Wavelength Measurement

The wavelength was analyzed using a nearly perfect (111) silicon crystal analyzer in Laue geometry. This particular crystal is called nearly perfect because it has a relatively small mosaic which allows a greater intensity to be reflected than in a perfect crystal. The analyzer crystal was rotated $\pm\theta_B$ (Fig. 12) using a stage with a highly accurate encoder¹². The analyzer crystal was also tilted so that the lattice planes could be optimally aligned. Two detectors were placed at angles $\pm 2\theta_B$ to measure the intensities of parallel and anti-parallel reflected beams and third detector was placed on the direct beam after the analyzer crystal to measure the intensity drop of the transmitted beam. Figure 13 shows the measured θ_B as a function of tilt angle where the minimum is the correct Bragg angle. By comparing the peak positions of the anti-parallel and parallel reflected beams (see Fig. 14a) in the two detectors and using Eqn. 7 one can determine λ . The wavelength of new facility was measured to be $\lambda = (0.4389 \pm 0.0009) \text{ nm}$ with $\Delta\lambda/\lambda \approx 0.8 \text{ \%}$ (see Fig. 14b).

3.3.3. Contrast

The parameter C in Eqn. 8 is known as the contrast or fringe visibility of the interferometer, it is the modulation depth in the intensity of the O-beam with the rotation of the phase flag. Contrast is a measure of interferometer quality and is calculated from the background adjusted ratio

$$C = \frac{I_{O,\max} - I_{O,\min}}{I_{O,\max} + I_{O,\min}} \quad (15)$$

¹²Heidenhain model # RON 287 18000 lines per revolution

369 where $I_{O,\max}$ and $I_{O,\min}$ are maximum and minimum intensities of the O-beam,
 370 respectively. Contrast of an ideal interferometer is 100 %, but in practice the
 371 maximum contrast for a neutron interferometer is always less than unity due to
 372 reasons such as imperfections in the interferometer, sample absorption, coher-
 373 ence effects, temperature gradients, and environment instabilities. The maxi-
 374 mum O-beam contrast of the interferometers at NIST is $\approx 90\%$. This is not
 375 true of the H-beam which, complicated by the exact reflection and transmission
 376 coefficients of the interferometer, has $I_{H,\min} \approx I_{O,\max}$. and therefore always has
 377 lower contrast than that of the O-beam. Higher contrast suggests higher qual-
 378 ity of the neutron interferometer and/or more stable operating environmental
 379 conditions. The nonmagnetic optical table at the NIOFa facility has vibration
 380 isolation supports to minimize vibrations of the interferometer crystal. Typi-
 381 cally neutron interferometers are concerned with vibrations greater than 1 Hz.
 382 This low frequency is outside of most standard vibration isolated optical tables.
 383 A table with active support structure ¹³ was purchased that suppresses vibra-
 384 tions at this level using PZT driven compensators. However well vibrationally
 385 damped this system was, under normal operation the absolute position of the
 386 table's surface can drift. This is a disadvantage for neutron interferometry since
 387 the neutron source (unlike that for light) can't be mounted on the table. For this
 388 reason several other support systems were tested. These included a pressure-
 389 driven control scheme from the manufacture ¹⁴, a modified feedback system, and
 390 supporting the table on simple rubber pads. Figure 15 shows the contrast of an
 391 interferometer for different vibration isolation configurations: the optical table
 392 is supported in Fig. 15a by air pads and in Fig. 15b by rubber pads. Currently
 393 the optical table is supported only by rubber pads. In this configurations an in-
 394 terferometer that in the hutch has $C = 90\%$ at 0.271 nm decreases to $C = 21\%$
 395 at 0.44 nm. Part of the decrease in contrast is most likely due to the lower
 396 neutron velocity as well as that with an increase in Bragg angle the neutron

¹³TMC model # STACIS iX

¹⁴model # PEPS II

beam interacts with a larger slice (and thus potentially more imperfections) of the interferometer blades.

3.3.4. Neutron polarization

NIOFa beamline is designed for spin based neutron experiments which require a high degree of neutron polarization. Neutrons are polarized and analyzed using double ‘V’ cavity supermirrors¹⁵. The neutron polarization P_n is determined by measuring the flipping ratio f defined as

$$f = \frac{I_{\text{off}}}{I_{\text{on}}} \quad (16)$$

where off(on) denotes the state of a precession spin flipper located in between the polarizer and analyzer. The quantity f is related to the polarization by

$$P_a P_n = \frac{f - 1}{f + 1} \quad (17)$$

where P_a is the analyzer efficiency. Since we used the same polarizer and analyzer models it is assumed that $P_a \approx P_n$. Initially neutron polarization measured at the NIOFa was $\leq 90\%$ because of the presence of $\sim 26\%$ λ/n which are left unpolarized. Neutron polarization increased to $\sim 99\%$ after the installation of beryllium filter. We have found that the exact P_n for these polarizers depends very strongly on the experimental conditions such a beam size, divergence and polarizer and analyzer positions.

3.4. DAQ

For motion control, the new facility uses two 3-axis controllers¹⁶ that can operate both 2-phase stepper motors and DC motors, incorporates hard limits, encoders, and drive motors in either closed or open loop operation. For 5-phase motors a 4-axis controller¹⁷ is keep in-reserved, but is rarely used. Temperature

¹⁵custom designed and made by SwissNeutronics

¹⁶Newport model # 301

¹⁷Kohzu model # 410

418 is PID controlled and monitored¹⁸ with either platinum resistors or thermistors.
419 All processes and control is administered through a single Windows-based com-
420 puter. Each communicates to the PC using RS232 communication standards or
421 through virtual COM ports when directly using USB connections .

422 The detector electronics are all standard NIM modules. Each ^3He detector
423 is supplied¹⁹ a bias voltage of 1200 V. The signal from the ^3He detectors is
424 transported via a 9.1 cm long MHV to SHV cable to a preamp²⁰ after which the
425 signal travels a few meters to an amplifier/SCA²¹ where the signal is converted
426 to a standard TTL pulse. This TTL pulse is registered by a DAQ control
427 board²² as a neutron count. Fission chamber neutron detectors use the same
428 electronics but operate at a lower bias voltage of 400 V. Four detectors can be
429 supported simultaneously with this setup. Electrical current for the precession
430 spin flipper is provided by high current supplies²³ and controlled using a low
431 voltage²⁴ DC signal.

432 Data is saved in either .txt, .csv, or excel-native .xls files. The DAQ is
433 controlled through Visual Basic for Applications (VBA) script and customized
434 excel templates. Excel is an atypical program to run experiments but was
435 chosen because of its universally familiar and expected continuous support from
436 Microsoft. Excel is more than adequate for our needs because data rates at
437 the instrument are modest; requiring no Herculean DAQ software. Remote
438 monitoring and control is accomplished with independent executable programs,
439 written in-house using Visual Basic (VB) or C# which can be communicated
440 with through VBA script.

¹⁸Lakeshore model # 331 or 336 and SRS model # CTC100

¹⁹Ortec model # 660

²⁰Ortec model # 142IH

²¹Ortec model # 590A

²²NI model # PCI-6602

²³Kepeco model # ATE 30-15

²⁴Labjack model # U12 DAQ

441 **4. Future work**

442 Improvements to the new facility are still ongoing. At this time, only the
443 prototype DFS interferometer exists. Unfortunately with a 220 lattice vector
444 this interferometer can't operate at the peak 0.44 nm wavelength. Neutron inter-
445 ferometer crystals are exceedingly hard to manufacture as high-quality, perfect
446 silicon ingots are expensive. More importantly expertise in machining silicon
447 for neutron interferometry purposes is being lost with time as the apex in sil-
448 icon manufacturing research was during the 1970's and 1980's. Despite this,
449 two new DFS-type interferometers designed for 0.44 nm have been procured by
450 the University of Waterloo. In support of this effort, the University of Water-
451 loo has installed a facility for researching and improving crystal manufacturing
452 techniques. These new vibrationally-insensitive, DFS-type interferometers will
453 greatly improve contrast at the facility.

454 A test of a cryostat in the neutron beam using a well characterized test
455 sample will soon be completed. Thermal neutron backgrounds at the facility
456 are still high and increased shielding for both the detectors and the facility
457 overall are being implemented. Temperature control has been demonstrated
458 at the beamline but is offline until the DFS-type interferometers are tested.
459 Continuous work on increasing the neutron polarization and spin control are
460 ongoing. We hope that with these improvements the new facility NIOFa can
461 transition from a developing test station to a User-Supported neutron facility.

462 **5. Conclusion**

463 The neutron interferometer facility at NIST is a functionally robust yet pre-
464 cise instrument capable of a wide array of both fundamental and applied neu-
465 tron experiments. The NCNR now supports a second beamline for neutron
466 interferometry applications that has increased flux and certain advantages over
467 the hutch facility. The new NIOFa has improved neutron polarimetry capa-
468 bilities, increased ease-of-access, a designated cryostat with vibration isolation,
469 and environmental temperature control. Currently low-contrast observed at the

470 beamline is being addressed with the construction of new interferometers better
 471 suited to work under these conditions. Our hope is that it will greatly expand
 472 the interferometry program at NIST in the field of spin-based neutron interfer-
 473 ometry, testing of quantum mechanics, spintronics, neutron spin manipulation,
 474 material research and demonstrations of quantum information science.

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(a)

(b)

Figure 11: (a) The neutron spectrum $\lambda = (0.44/n)$ nm where $n = 1, 2, 3, \dots$ measured using a disc chopper before installation of the beryllium filter. Detector efficiencies ϵ_{λ} are a function of neutron wavelength have not been accounted for here. (b) After the installation beryllium filter only the $\lambda = 0.44$ nm peak remains. Note, measurement time was not the same for (a) and (b).

Figure 12: Wavelength measurement setup for the NIOFa beamline. A nearly perfect (111) silicon crystal analyzer was rotated $\pm\theta_B$. Two detectors were placed at $\pm2\theta_B$ to measure the reflected intensities. A third detector was placed on the direct beam right after the crystal to measure the decrease in the intensity of transmitted beam.

Figure 13: Alignment of a nearly perfect (111) silicon crystal analyzer.

(a)

(b)

Figure 14: (a) The anti-parallel (red squares-scale on left) and parallel (green circles-scale on right) Bragg reflections. The average background rate has been subtracted from the points shown. For the parallel reflection the central location was found by taking a weighted average of peak locations of separate three Gaussian functions used to fit the data. (b) Data in (a) plotted versus wavelength.

(a)

(b)

Figure 15: O-beam intensities for $\lambda = 0.22$ nm (red squares) and $\lambda = 0.44$ nm (blue circles) neutrons. (a) Here the PZT-control of the STACIS system (which caused positional drift) was turned off, but the table still had some vibration isolation. The contrast was $C = 47\%$ for 0.22 nm and $C = 32\%$ for 0.44 nm. (b) Without any active vibration isolation. The optical table resting on rubber pads where the contrast decreased to 30% for 0.22 nm and 21% for 0.44 nm.