Search for effects on neutron transmission due to multiple reflection by glass capillary walls

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ABSTRACT

We have performed two separate experiments using glass capillary fibers to transport 1) polarized neutrons, and 2) cold neutrons with the fiber at high temperature. The same type of capillary fibers has been used to construct neutron and x-ray focusing lenses. The purpose was to observe whether multiple glancing angle collisions during transport could change either the polarizations or the transmission and exit divergence. In the first case, polarized 0.235 nm neutrons were transmitted through a bent glass capillary fiber, and the spin states of the emergent neutrons were measured. In the second experiment, 0.5 nm neutrons were passed through a glass capillary fiber heated to 200° C, and transmission and divergence were compared to the values at room temperature. The negative result for the first experiment indicates that capillary fibers can be used to transmit polarized neutrons. The heating experiment demonstrated that thermal vibrations of the capillary walls or collisions with heated air molecules did not significantly affect fiber properties; however, some mechanical shifting took place at high temperature.

Keywords: capillary fibers, cold neutrons, transmission, polarized neutrons, thermal effects

1. INTRODUCTION

The transmission of cold neutrons by glass capillary fibers is the result of many small-angle reflections from the glass walls. A typical fiber contains over a thousand capillaries of 10 μm. In the course of testing such fibers to assist in the design of focusing lenses and benders, we became interested in searching for measurable effects on the transmission of spin-polarized neutrons passing through a curved fiber and the consequences of heating a straight fiber.

If an observable neutron depolarization was measured, this could lead to further investigation of the physics of the interaction. On the other hand, if no effect were observed, polarized neutrons could be successfully transported through benders and lenses. Since the reflected neutrons slightly penetrate the capillary walls on each reflection, we considered the possibility that a fraction might undergo a spin-reorienting magnetic interaction with the nuclear magnetic moments of the glass molecules. In addition, as the neutrons pass through the capillary, their trajectories change direction many times in a complex way, particularly if the fiber is curved. The neutron spin would have to remain fully decoupled from its path for there to be no change in its polarization state. We had considered the Mott-Schwinger interaction as a possibility, but electron screening at cold neutron wavelengths makes it very unlikely.

In the heating experiment, we questioned whether cold neutrons would "warm up," thereby reducing the critical angle for reflection, leading to a reduced transmission. Energy transfer from thermal vibrations of the capillary walls or collisions with heated air molecules could, in principle, cause neutrons to exit prematurely. A very small addition to their transverse momentum could cause some trajectories to exceed the critical angle subsequently, leading to reduced transmission and an altered divergence of exiting neutrons. The behavior of the fibers in a high temperature environment would also determine whether thermal stresses caor a permanent deformation after cooling. In some other instances the capillaries might need to be heated, for example, to desorb hydrogen from capillary walls prior to using prompt gamma-ray activation analysis (PGAA) to determine small amounts of hydrogen in samples. In untreated glass, the bulk value[1] of hydrogen concentration is

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approximately 3.8 x 10^{20} H-atoms/cm^3. A subsequent measurement of hydrogen on the surface of the capillary walls using nuclear reaction analysis[2] came up with an approximate figure of 4 X 10^{21} H-atoms/cm^2 to a depth of roughly 20 nm.

The heating experiment was limited to 200° C in order to avoid melting a cadmium lining which was part of the existing apparatus.

2. THE EXPERIMENT WITH POLARIZED NEUTRONS

The neutron polarization experiment was carried out on the NIST reactor beam line BT-2 using 0.235 nm neutrons. The apparatus to create and measure polarization is based on a design by Rekveldt[3]. A 457-mm long lead-glass capillary fiber was placed at the sample position of the triple axis diffraction assembly used with the polarized neutrons. Both the deflected beam and the direct beam which bypassed the capillary fiber could be detected during an angular scan of the analyzer assembly. The latter gives a measure of the incident beam polarization. The glass composition was nominally: SiO_2-55%; PbO-30%; Al_2O_3 - 2%; Na_2O-3.8%; K_2O-9.2%. The fiber had an initial straight section followed by a bent one, and the neutrons were deflected by 8.5°, an angle limited by the geometry of the analyzer assembly. A simulation showed that the neutrons should undergo approximately 200 reflections in passing through the fiber.

A schematic diagram of the arrangement used to measure the effect of the capillary on the incident spin orientation is shown in Fig. 1. Initially unpolarized neutrons are incident on a Heusler alloy crystal, which causes them to become nearly completely polarized, typically with spin up ($m_s = +1/2$). They then enter a vertical guide magnetic field B_o, which maintains the spin orientation along the path. However, an initial horizontal spin orientation and guide field. After the polarized neutrons interact with the sample, here the glass capillary, they pass into a spin flipper. The guide field extends to the flipper. Next, the neutrons are diffracted from a second Heusler alloy crystal oriented so that it would only reflect neutrons with spin up When the spin flipper is off, only neutrons with spins up reach the detector. When the flipper is on, it generates a magnetic field B_l perpendicular to B_o. During the time of their passage through the activated flipper, the neutrons precess for one half a Larmor period around B_l which rotates the spin orientation by 180° ($m_s = +1/2 \Rightarrow -1/2$, or $m_s = -1/2 \Rightarrow +1/2$)). If passage through the capillary has rotated a fraction of the neutron spins to $m_s = -1/2$, with flipper on the detector records these formerly $m_s = -1/2$ neutrons, since they strike the analyzer crystal with $m_s = +1/2$.

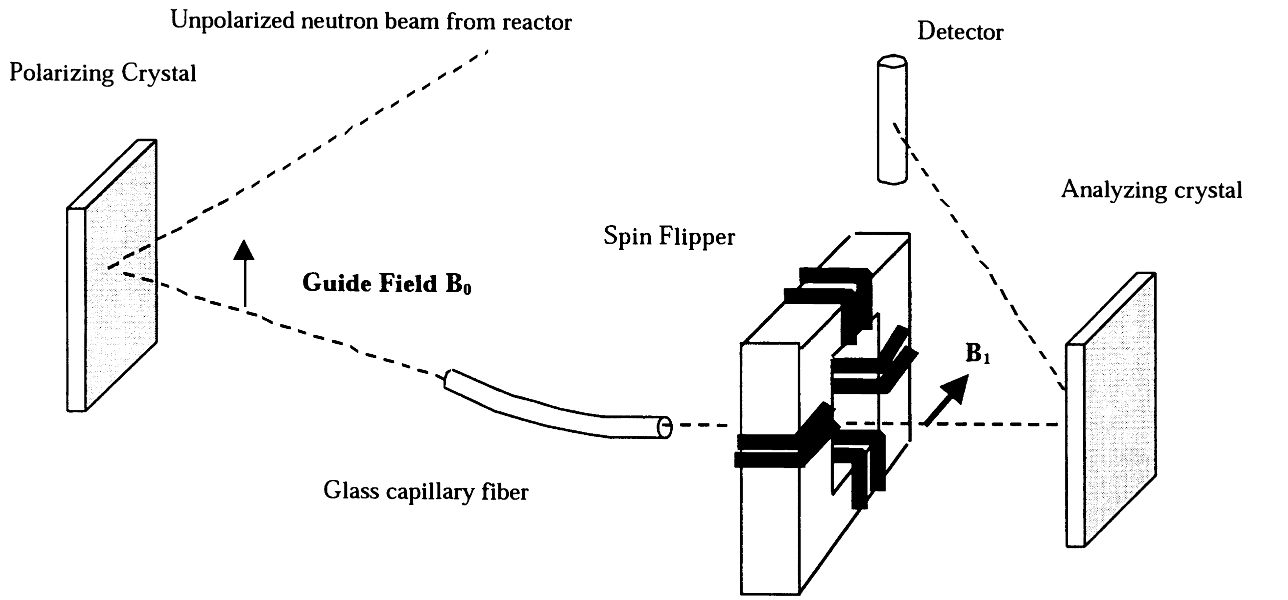


Fig. 1 Schematic diagram of the polarization experiment. The dashed line is the neutron path. Unpolarized neutrons from the reactor beam port are incident on a Heusler alloy single crystal which reflects only those neutrons with spin up, which is then maintained by the guide field B_o which extends to the spin flipper. The analyzer assembly consists of a second Heusler alloy analyzer crystal and a detector. The spin flipper here is shown in the on condition to produce the field B_1, which will cause neutrons w have been reversed by the fiber to enter the detector. When the flipper is off, the initial guide field B_o prevails throughout.

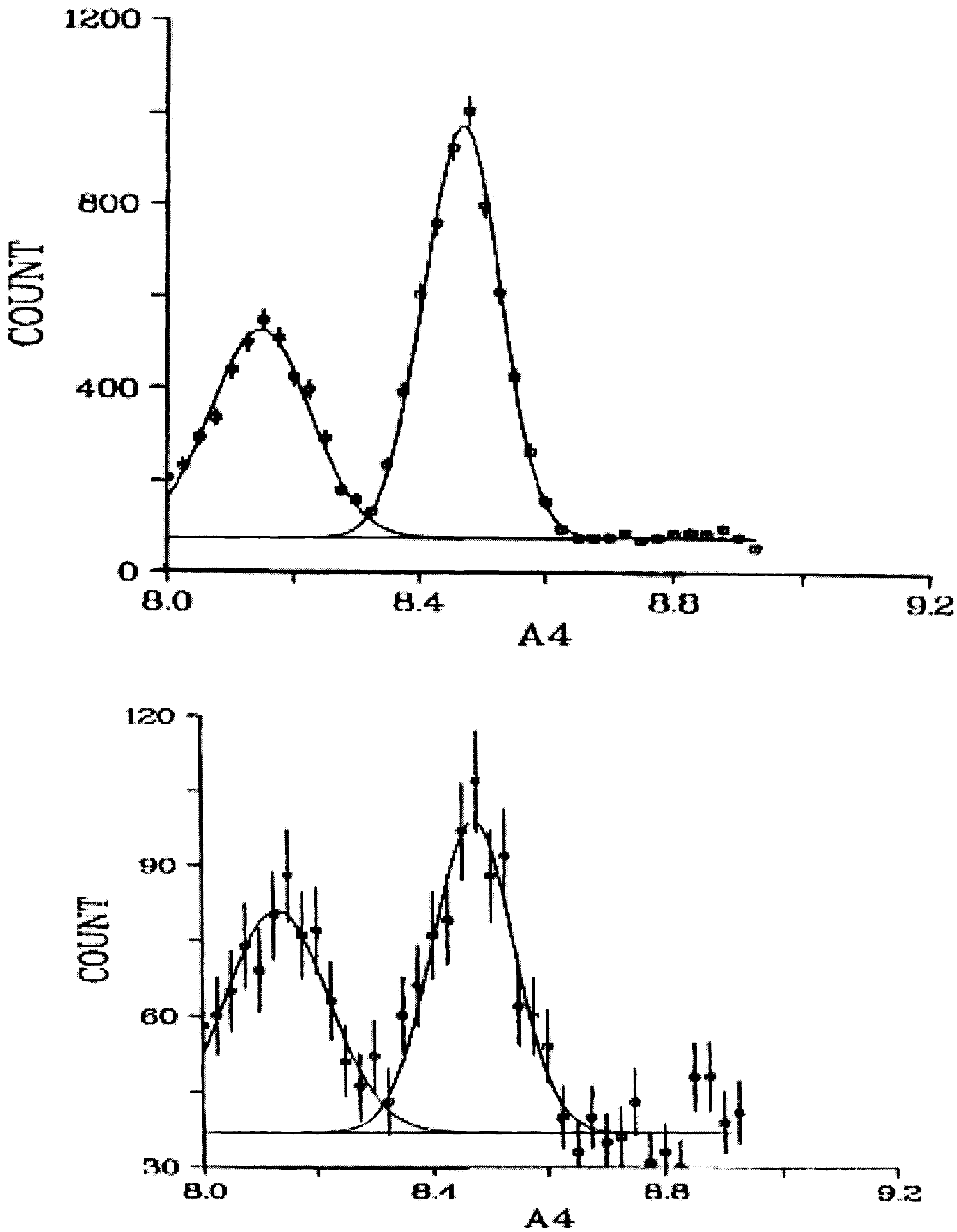


Fig. 2 Raw data from polarized beam experiment for the incident neutron spin in the plane of the bent fiber. Upper diagram: flipper off. Lower diagram: flipper on. The left peak in each diagram is detector counts as a function of the angle (A4) in degrees that the analyzer assembly makes with the center of the sample table. The right peak is the direct beam which bypasses the fiber.

Neutron polarization experimental results are here expressed through the inverse flipper ratio[4] f:

$$f = \frac{I\,(m_s = -1/2)}{I\,(m_s = +1/2)} = \frac{\text{detector counts with flipper on}}{\text{detector counts with flipper off}}. \qquad (1)$$

If the flipper is 100 per cent efficient as expected, then the neutron polarization P emerging from the capillary is:

$$P = \frac{1 - f}{1 + f}. \qquad (2)$$

For each flipper setting, the computer records the number of neutrons entering the detector for a preselected number of monitor counts at each angular increment of the analyzer assembly, which rotates around the center of the sample table as axis. As shown in Fig. 2, the data are represented as detector counts vs. angle (A4).

In these experiments, two different incident spin orientations were used. For the first, as illustrated in the left part of Fig. 1, the vertical incident spin orientation and guide field B_o are perpendicular to the plane formed by the beams incident on, and emergent from the fiber (i.e., perpendicular to the plane of the bent fiber). In the second orientation, the incident spins and guide field B_o were rotated to lie in the plane of the bent fiber. In this case, $m_s = +1/2$ would be horizontal, and the guide fields preceding the analyzer crystal rotated accordingly. The data for this latter case are shown in Fig. 2, the upper graph for flipper off, the lower for flipper on. The left peak in each plot is the number of detector counts as a function of the angle of the analyzer assembly for the beam transmitted through the fiber, and the right peak for the beam which bypasses the fiber.

The raw data for the first case, spins perpendicular, look very similar to those shown in Fig. 2, except that the error bars are larger because of a shorter run time. Table I is based on the integrated counts under each peak, with precisions largely determined by the counting statistics of the flipper-on peak.

Table I. Summary of the results of the polarization parameters shown in Fig. 2.

Incident neutron spins	**vertical**		**horizontal**	
direct beam	f = 0.064 ± 0.14	P = 0.88 ± 0.04	f = 0.081 ± 0.008	P = 0.85 ± 0.02
transmitted through fiber	f = 0.105 ± 0.02	P = 0.82 ± 0.04	f = 0.11 ± 0.01	P = 0.80 ±.0.02

From these preliminary experiments, there is no measurable evidence for any depolarization introduced by the capillary fiber.

3. THE HEATING EXPERIMENT

At the NIST small-angle neutron scattering (SANS) beamline NG-7, which is equipped with a mechanical chopper, $\lambda = 0.5$ nm neutrons ($\Delta\lambda/\lambda = 30\%$) entered a borosilicate glass fiber mounted inside a heating apparatus which was placed on top of a computer-controlled alignment table. The fibers rested in a straight V-shaped trough, but were otherwise unconstrained. A pinhole in a cadmium sheet in front of the fiber eliminated neutrons outside the fiber cross-sectional area. The pinhole was aligned with a laser. The critical angle for the capillary is 5.9 mrad. For the first of the two experiments, a small ^{6}Li-coated CID-based position-sensitive detector[5] was placed at the fiber exit for alignment, then the large NG-7 SANS two-dimensional wire detector captured the fiber output for quantitative measurements. In the second experiment, the SANS detector was used for both alignment and measurement. The SANS detector is located 7.5 m from the sample position, has a pixel size of 5.5 mm, and has a sensitive area of 100 X 100 square pixels. The nominal composition of the glass fiber was: SiO_2 68.2%, B_2O_3-19%, Al_2O_3.-3.5%, Na_2O-4.8%, K_2O-4.5%, and the individual capillary diameter was 16 μm. A simulation indicated that on average approximately 90 wall collisions would occur as a neutron travels through the capillary.

In the first experiment, the averaged neutron intensity (counts per pixel) was measured using the SANS detector for neutrons passing through a 300 mm long fiber at either room temperature (about 22 °C, labeled as RT) or high temperature (200°C, labeled as HT). The duration of the measurement at each temperature setting was 150 minutes. The sequence of measurements was RT, HT, and RT. However, we were concerned that thermal expansion of some part of the apparatus could have affected the initial alignment. Therefore, the experiment was repeated with a 315 mm long fiber aligned at 200° C. The second sequence was HT, RT, HT, and again RT. The data collections were 200 min, except for the last RT run for which, accidentally, only 15 min of data were saved, but the statistical accuracy was still satisfactory. The column-averaged intensities normalized to the intensity recorded on the beam monitor are shown in Figs. 3 and 4.

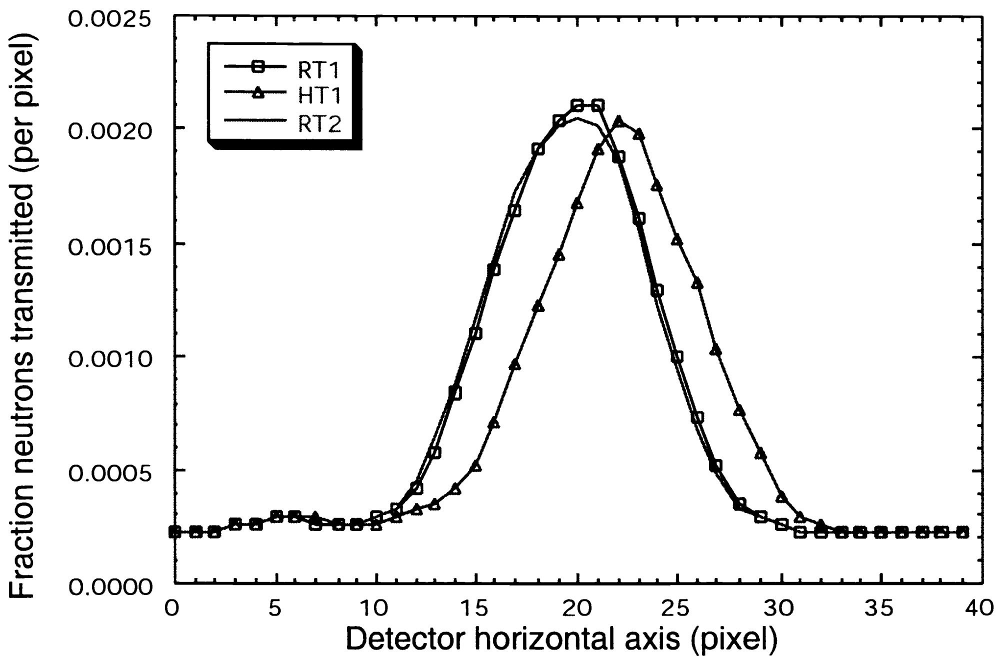
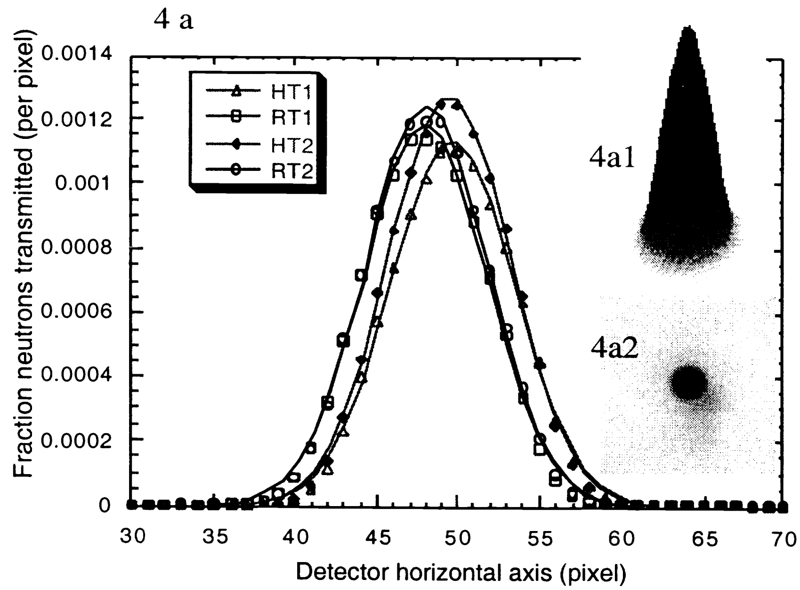


Fig. 3 First heating experiment column averages for the fraction of neutrons transmitted by a capillary fiber at room temperature (RT) and high temperature (HT). The neutrons were measured by a position-sensitive detector in an array of approximately 100 pixels by 100 pixels. The relative transmissions at the two temperatures can be evaluated by integrating the area under the curves.

The results of the first experiment are presented in Fig. 3, where the average neutron transmission as a function of the detector horizontal coordinates is shown over a range of 40 pixels, which completely encompass the horizontal distribution of the neutrons that have emerged from the fiber. The average transmission is obtained by integrating in the vertical direction over an 8 pixels width region at the center of the neutron beam spot. Similarly, the results of the second experiment are shown in Fig. 4a. Fig. 4b is a summary of the results from both experiments, including the transmission and the full-width-at-half-maximum of each peak. The latter was calculated by fitting a Gaussian curve to each peak.

As shown in Fig. 4b, the first three data points from the left, all from the first experiment, show no significant difference. For the next four points obtained from the second experiment, the transmission values show a rising trend from the first pair (HT1, RT1) to the second (HT2, RT2), but no difference between the heat-cool conditions within each pair. The origin of the rising trend is uncertain. However, both Figs. 3 and 4 demonstrate a real shift of just under 1.5 mrad in the map centroids, according to whether the fiber is at high or low temperature. This suggests a warping of the fiber at 200° C that relaxes at room temperature. The FWHM data remain constant within errors for all seven measurements.



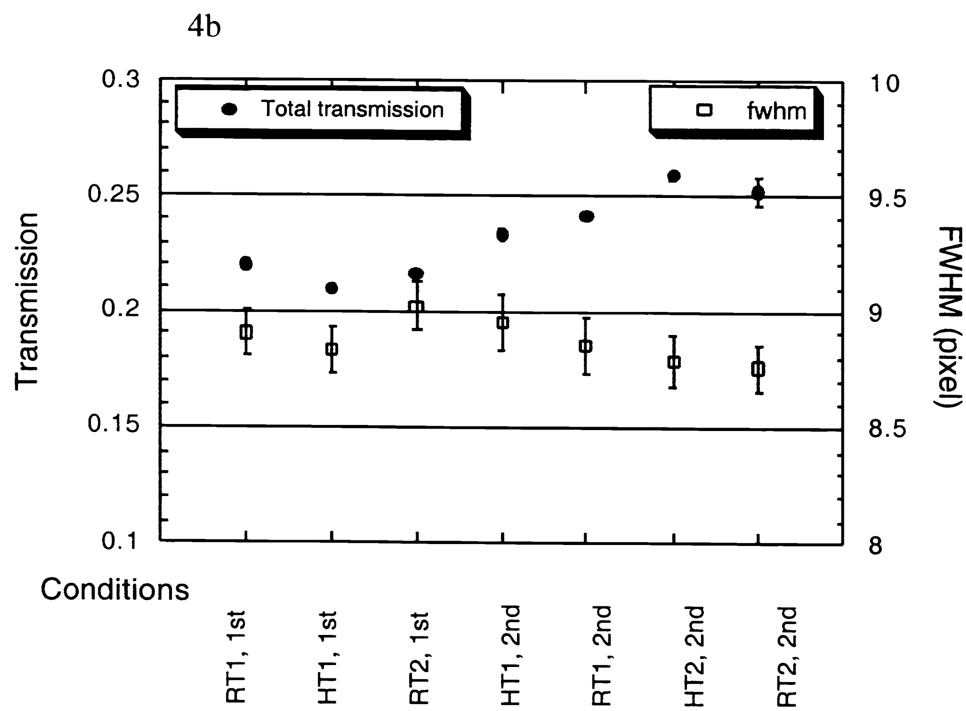


Fig. 4a. Average neutron transmision for the second experiment. Insert: 4a1 – intensity (3D) and 4a2 – foot print (2D) map obtained from the SANS detector. The off-center shadow on the 2D map represents neutrons that have leaked through the fiber. 4b: Summary of transmitted intensity (solid circles) and the FWHM (squares) for both experiments.

To verify the results of the heating experiments which indicate no measurable effects on the transmission and beam divergence from multiple collisions of the cold neutrons with the glass wall, we need to assess contributions of an increment in wall thermal vibrations. We first follow the introductory portion of a treatment in Golub et al.[6] on the transfer of momentum from the walls of a containment bottle to ultracold neutrons. The wall was assumed to be vibrating with simple harmonic motion of amplitude A and angular frequency ω. A velocity diagram and momentum vector addition are given in Fig.5. For glancing-angle collisions, the angles shown are greatly exaggerated, and the momentum imparted by the wall to the neutron is essentially perpendicular to the velocities before and after the collision; in other words, the triangle formed by P_i, P_f, and Δp_f is a narrow right triangle. Cumulative small transfers of momentum perpendicular to the nearly forward path of the neutron could alter the recoil angle by a fraction of the critical angle. After many integrations over angles and coordinates, Golub et al. obtain the average energy gain per bounce, for neutron mass m_n, as $2m_n(A\omega)^2$ used here to extract the product $A\omega$, (maximum v_w), from some given numerical values.

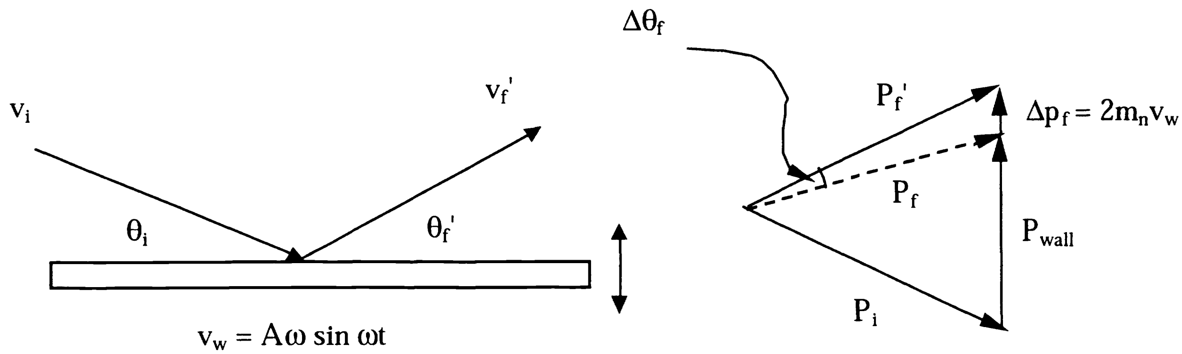


Fig. 5 A neutron making a glancing angle collision with an oscillating wall experiences an incremental change of momentum given by $2m_n v_w$. Affected vectors are shown primed. The wall is assumed to oscillate with amplitude A at angular frequency ω, causing a small change in the angle of the recoiling neutron. The right diagram represents conservation of momentum. The dashed arrow is the momentum after recoil, as if the wall were not moving.

Taking $2m_n(A\omega)^2 = 10^{-13}$ eV from data on 1) an oil, and 2) a grease, we obtain $A\omega = 2.19 \times 10^{-3}$ m/s, which we interpret as the velocity amplitude for an incremental change in the collective oscillations of the wall molecules: $\Delta p_f = 2\, m_n v_w = 7.3 \times 10^{-30}$ kg-m/s. For 0.5 nm neutrons, and p_i from the de Broglie relationship:

$$\Delta\theta_f = \Delta p_f / p_i = 7.3 \times 10^{-30} / 1.33 \times 10^{-24} = 5.5 \times 10^{-3} \text{ mrad}, \qquad (3)$$

too small to have an observable effect, even if the average energy gain were an order of magnitude larger.

In conclusion, the results of the polarization experiment show that capillary fibers can transport polarized neutrons. This may be of advantage in benders or focusing lenses, for example, in proton crystallography. Heating the fibers showed no significant changes in transmission or divergence, but caused the neutrons to be redirected. The initial direction was restored after cooling. We believe the shift more likely to be the result of fiber warping, rather than distortion of the surrounding metal.

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