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Polarized ^3He cell development and application at NIST

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Abstract. Over a period of well over a decade, a large number and variety of polarized ^3He cells for neutron applications have been developed and tested at the U.S. National Institute of Standards and Technology (NIST). These cells have primarily been employed for spin-exchange optical pumping (SEOP), and applied to neutron scattering and fundamental neutron physics. We describe the procedures we have employed for producing these cells, as well as their characteristics and applications. Whereas our best results are for cells blown from boron-free aluminosilicate glass, we summarize results with a range of other methods. We discuss our recent work on SEOP cells for wide angle neutron polarization analysis.

Key words: polarized

1. Introduction

Production and application of polarized ^3He by spin-exchange optical pumping (SEOP)[1, 2] depends critically on the characteristics of the cells in which the optical pumping occurs. A relaxation time long compared to the slow pumping time constants typical for SEOP is a key requirement. Application to neutron spin filters (NSFs) put additional demands on cell fabrication. Although there is currently a thrust towards continuous optical pumping for neutron spin filters, remote optical pumping is often employed. In this case there is an additional, often stronger need for long relaxation time beyond that which is required for the SEOP process itself. To avoid the need for gas transfer and recycling, as well as to allow for future continuous operation, it is often desirable to directly polarize ^3He cells for use on the neutron beam line. In this case, the need to heat cells to typical temperatures of 170 °C for pure rubidium or 220 °C for Rb/K hybrid SEOP[3] presents additional issues for SEOP cells, in particular for relaxation phenomena[4, 5]. Neutron spin filter cells cannot contain any ^{10}B , further constraining the choice of acceptable glasses. These requirements have led to the use of boron-free aluminosilicate glass, which has low He permeability, high neutron transmission, and good alkali resistance. For well over a decade, a large number and variety of cells have been made at the National Institute of Standards and Technology (NIST) for the development and application of polarized ^3He . These

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cells have primarily been for studies of SEOP and SEOP-based neutron spin filters, but have also included cells for metastability-exchange optical pumping (MEOP[6]). In Sec. 2 we present a detailed discussion of our procedures and experience in preparing these cells and in Sec. 3 we discuss apparatus and results for characterization of cells. In Sec. 4 we survey the wide range of behavior of relaxation times and discuss some special cell constructions. The status of our most recent goal of fabricating cells for wide-angle polarization analysis[7] is presented in Sec. 5 and we summarize the paper in Sec. 6. The Appendix contains detailed lists of a large range of cells and the applications they have made possible.

2. Cell Fabrication

In this section we provide the detailed procedure we have employed to produce ^3He cells for a wide variety of applications. The majority of the cells have been fabricated from the boron-free aluminosilicate glass GE180[8]. Other constructional materials have included the aluminosilicate glass Corning 1720[9], ^{10}B -depleted Corning 1720, Corning 7056, fused quartz, pyrex, and silicon.

2.1. Preparation at glass shop

Most of our cells are blown by the NIST glassblower on a lathe, beginning from either 16 mm or 25 mm diameter GE180 tubing and then reshaping to a desired geometry, typically a cylinder with a volume up to 1 liter. The completed cells are immediately placed into an annealing furnace at 785 °C (GE180) for about 10 min to remove residual stress in the glass. The glassblower attaches one or two cells to a glass manifold referred to as the “string” (see Fig. 1), which also has one or two vertical tubes (“pull-offs”) for alkali-metal ampoules at the end of the string. Between the cell and the pull-offs is a small dip in the string, referred to as the “retort”, into which alkali-metal will be distilled before being distilled into the cell. The string and attached cell(s) are first checked with a polariscope to ensure sufficiently low residual stress. To minimize the possibility that the cell will rupture in the SEOP oven, the cells are then tested at room temperature to a pressure 25 % higher than the pressure expected under SEOP operating conditions.

2.2. Cleaning and first distillation

To make practically useful cells with long relaxation time (T_1) and desired performance, we have followed an extensive cleaning and baking procedure to ensure a cell has a minimal amount of impurities adsorbed to the surface of the glass, potentially yielding a long ^3He polarization relaxation time. Nevertheless, cell to cell variations and the exact significance (or lack thereof) of aspects of the procedure are not well understood. The principles are to clean the cells with simple soap and water, bake out impurities from the cell and string, and then do a double distillation of the alkali-metal. A clean location is prepared for the alkali by baking, the alkali is distilled into this location, then the cell and string are baked again before the alkali is distilled from this location into the cell.

All cells are thoroughly cleaned before they are attached to the vacuum system. The general cleaning procedure involves, in the following order: one rinse with soapy water (laboratory glassware detergent powder and water), several rinses with distilled water, one with acetone, several more rinses with distilled water, and then a final rinse with methanol (primarily to remove the water). More recently we have eliminated the acetone step, with no obvious ill effects. After the string is completely dry it is attached to an oil-free, high vacuum system (referred to as the cell filling station, see Fig. 2) consisting of a turbomolecular pump backed by a diaphragm pump. After leak-testing the string (often done quickly with alcohol), the pre-scored alkali metal ampoule(s) (Rb and/or K) are opened in a weak, outgoing flow of N_2 , and dropped with

open-end down into the pull-offs. The N_2 flow is then stopped and the top of the pull-offs are sealed off using a natural gas torch. At this point the cell(s) and string (except for the pull-offs that contain alkali-metal) are baked at 400°C for a total of four days to minimize impurities on the surface of the glass. When beginning baking, it is better to heat the cell and string gently to 400°C and ensure the temperature gradient near the cell is small. The pressure in the vacuum system will initially increase with the increasing temperature, then decrease slowly until approaching a vacuum of 10^{-7} mbar or better. After baking the string a day or so, the Rb or K is slowly melted out of each ampoule by gently heating the lower sides of the pull-offs. The pull-offs, which are not in the baking oven, are also gently heated with the torch until the pressure rise is minimal. After the alkali metals are melted out of the ampoules, the vacuum will reach about 6×10^{-8} mbar in another day of pumping.

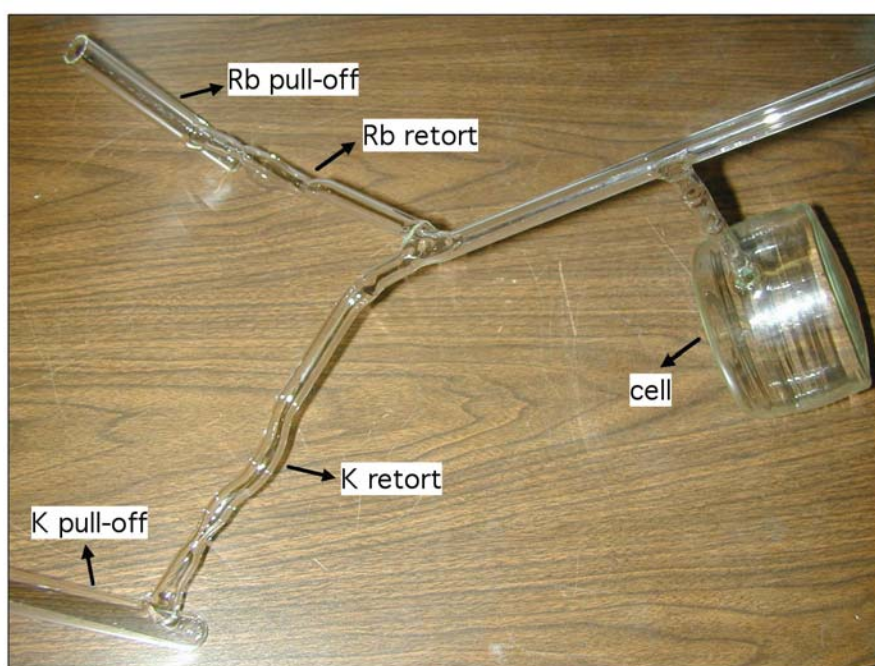


Figure 1. A glass manifold (“string”) with cell attached. One or two (one for pure Rb cells two for Rb/K mixtures) vertical tubes (“pull-offs”) for alkali-metal ampoules are located at the end of the string (left). On each arm of the string (two arms shown for this mixture string) there is a small dip, referred to as the “retort”, into which alkali-metal will be distilled before being distilled into the cell. The string is attached to the vacuum system by a glass to metal seal followed by a metal-sealed flange (right, not shown).

On the third day the baking is stopped so that portions of the Rb and/or K can be “chased” (evaporated and re-condensed several times to move the metal along the string) from the pull-offs and into the retort. The pull-offs are then removed by sealing the string under vacuum, and baking is continued. For a pure alkali-metal (Rb or K) cell, we typically chase about $1/8$ to $1/6$ of the alkali-metal from the 1 g ampoule into the retort. For a Rb/K hybrid cell, we typically chase much more (about $1/2$) of the K from its ampoule into the K retort. During chasing, it is better to distill the alkali metals in the vapor form many times. The cells are baked for two more days.

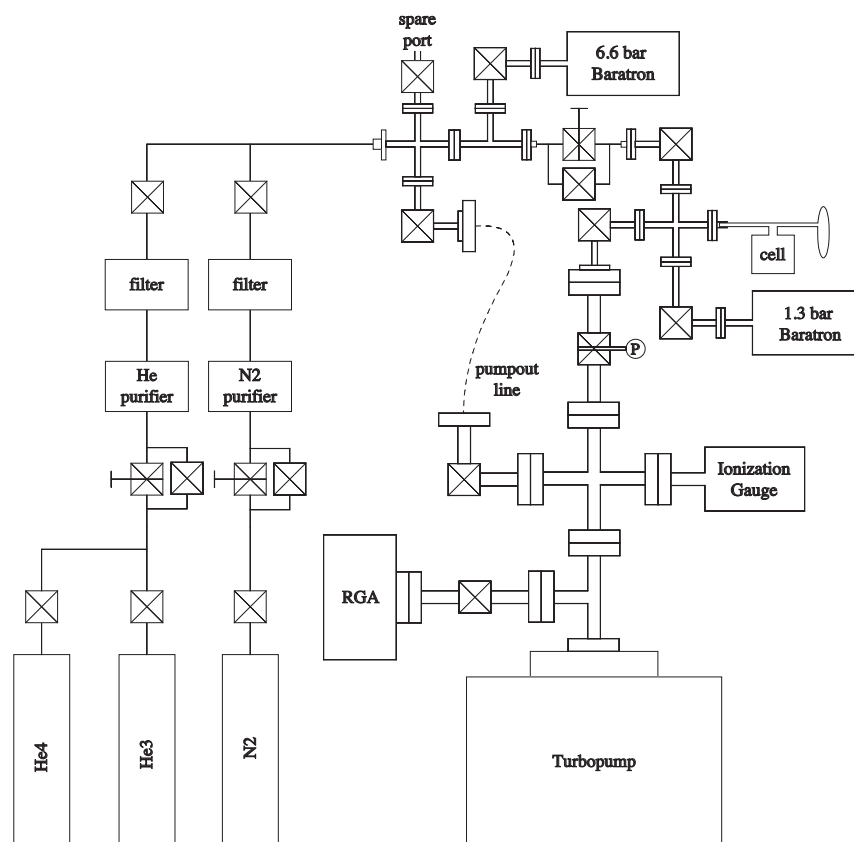


Figure 2. A schematic diagram for the cell filling system. It consists of three main sections, the oil-free high-vacuum system, the gas-handling system, and the cell-baking unit. The outside dimensions of the tubing in the diagram are 7 cm diameter (large), 3.4 cm diameter (small), and 6 mm (gas lines, shown as single lines); all connections are metal-sealed. The gas-handling system provides ^3He , ^4He , and N_2 ; each gas line has a getter and a particle filter for purifying the gas, and a needle valve (with bypass for pumpout) for flow control. It can be isolated from the other systems. The lower-conductance pump-out line is used for initial pump-out of a string and for pumping gases from the gas lines without affecting the string vacuum. The cell-baking unit (not shown) has two types of furnaces for different baking stages, a larger one for initial baking and a smaller one for final baking. It can accommodate three cells simultaneously, and can also accommodate valved cells.

2.3. Distilling Alkali metal into the cell

For a pure Rb or K cell, distilling either Rb or K into the cell is simple and straightforward as described previously[10]. As reported previously[11], K/Rb vapor density ratios (D) between 2 and 6 have yielded the best results for high polarizing rate without losing the maximum achievable polarization. Cells with vapor density ratios below this range yield lower gain in SEOP efficiency although are still usable. However, in a cell with too high a vapor density ratio the alkali-metal polarization does not reach 100 %, with the limit decreasing with increasing vapor density ratio [3, 11]. Hence it is essential to control the vapor density ratio to the desired range although it requires more complicated distillation of alkali metals into the cell. For D

between 2 and 6, about 12 to 36 times more K than Rb must be distilled into the cell. We have developed a convenient way to achieve the desired vapor density ratio and check it before the cell is filled with ^3He and N_2 gas and completely sealed off from the vacuum system. It was determined through trial and error that chasing Rb about six times in films fairly thick and about 5 cm long, then chasing about 1/5 of the K from the ampoule into the cell typically yields a vapor density ratio in the desired range between 2 and 6. After chasing, the Rb in the cell should have a slight translucent tint to it. It is better that after the Rb is distilled in the cell, the string for the K path to the cell is cleaned free of Rb, as the final vapor density ratio is sensitive to Rb that may be carried into the cell with the K.

It is crucial to measure and check the vapor density ratio on the vacuum system before the hybrid cells are removed from the string. We illuminate the cell with a 50 W halogen spot light and use an optical spectrometer with a wavelength range from 755 nm to 830 nm and a resolution of 0.07 nm[12] to measure the ratio of the absorption of K and Rb for each fine-structure transition (see Fig. 3). The cell is cycled to typical SEOP temperatures to establish the Rb/K alloy. In vacuum, the absorption will saturate in a bandwidth that is much smaller than either the resolution or 0.03 nm pixel separation of the spectrometer, hence the absorption is difficult to observe. Introducing gas broadens the response, yielding more easily visible absorption. We typically fill the cell with N_2 gas to a pressure of between 200 mbar and 260 mbar, then heat the cell to about 85 °C in the baking oven with a clear path for light absorption spectroscopy. There are four related fine-structure transitions in the spectrometer wavelength range, Rb $5s_{1/2}-5p_{1/2}$ (denoted as Rb D_1) and $5s_{1/2}-5p_{3/2}$ (denoted as Rb D_2), and K $4s_{1/2}-4p_{1/2}$ (denoted as K D_1) and $4s_{1/2}-4p_{3/2}$ (denoted as K D_2). Recently we have used a dual channel optical spectrometer[13] that allows us to observe both the $5s-5p$ and $5s-6p$ (D_2 at 420.18 nm and D_1 at 421.55 nm) transitions for Rb and $4s-4p$ and $4s-5p$ (D_2 at 404.41 nm and D_1 at 404.72 nm) for K. The temperature of the cell is adjusted so as to obtain absorption dips for these four transition of 10 % to 40 % (typically 85 °C for the infrared transitions or 170 °C for the blue transitions). Because mixture ratio determinations from the blue transitions are performed closer to actual optical pumping conditions, they require less correction for the different slopes of the vapor pressure curves. If the vapor density ratio is lower than 3 and higher than 6 after initial distillation of both Rb and K into the cell, it is necessary to either chase extra Rb into the cell for a vapor density ratio higher than 6 or bake the cell at some modest temperature for a vapor density ratio less than 3. The idea of baking is to remove more Rb out of the cell than K by fractional distillation, hence improving the vapor density ratio. The baking time should strongly depend on the temperature, varying from half an hour at 150 °C to overnight at 80 °C. We have successfully employed this approach, but have not experimented with the required baking time much yet. The vapor density ratio is re-checked until it falls within the desired range.

2.4. Filling the Cell with Gas

Before the cell is filled with gas, the gas lines are evacuated, and the ^3He and N_2 getters are heated to about 350°C. After about a hour, the vacuum is typically below 10^{-7} mbar. Both the nitrogen and ^3He gas lines have needle valves that are used to control the flow rate through the getters and a third needle valve controls the flow rate into the cell. Each needle valve has a bypass line which is closed except during pumping of the gas lines. We first add between 65 mbar and 130 mbar of nitrogen into the cell, and then close the valve between the cell and the gas lines, and pump out the nitrogen. To avoid a return flow of nitrogen into the ^3He lines, we admit ^3He gas until the pressure read on the 6.6 bar gauge is higher than the nitrogen pressure, and then open the valve to the cell to fill the appropriate amount of the ^3He gas into the cell. The

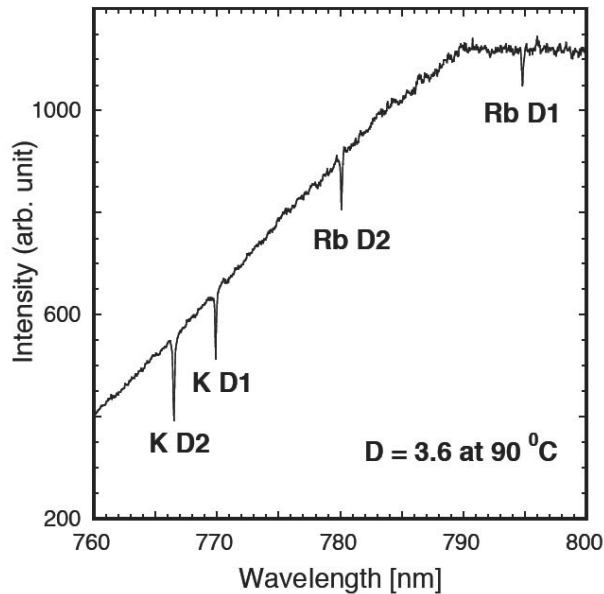


Figure 3. Light absorption spectroscopy for measurements of the vapor density ratio of K to Rb. The four absorption dips correspond to the four atomic transitions (Rb D_2 and D_1 and K D_2 and D_1) as discussed in the text. The K/Rb vapor density ratio D is determined from these four absorption dips. Shown here is the vapor density ratio measurement for the cell Syrah at 90 °C. The variation with wavelength of the transmitted light is primarily due to the spectrometer response.

amount of ^3He gas depends on the neutron wavelength, the length of the cell and the practical pressure limit for the cell. There are two approaches to filling the cell with ^3He , depending on how much gas in total (^3He , N_2 , possibly ^4He) is required. If the desired total pressure is less than 1 bar, the gas filling procedure is straightforward; we simply admit nitrogen gas first and then ^3He gas into the cell. For cells with an overall pressure greater than 1 bar, it is required to completely or partially submerge the cell into liquid N_2 (hence a maximum pressure achievable in the cell of ≈ 3.7 bar) to allow the cell to be sealed off from the string under 1 bar. However, we have found that using complete immersion is not reliable for large cells because of the buoyant force and close proximity of the hot torch and liquid N_2 . To make the seal more reliable for the typical final pressure range of 1 bar to 2 bar for neutron spin filters, we submerge only a small portion of the cell in the liquid nitrogen. We fill an appropriate total pressure, p_i , of nitrogen and ^3He gas (N_2 first, then ^3He) into the cell at room temperature. With the cell and string isolated from the vacuum system, we gradually submerge the cell into the liquid nitrogen until a final pressure, p_f , of about 0.9 bar is obtained. Typically, the cell is submerged no more than a couple of centimeters into the liquid nitrogen and thus the final seal from the string can be easily done. The total pressure of N_2 and ^3He gas in the cell, p_c , after the cell is removed from the string and equilibrated to room temperature is given by

$$p_c = p_i + \frac{V_s}{V_c}(p_i - p_f) \quad (1)$$

where V_c and V_s are the volumes of the cell and the string, respectively. For a large number of cells, we have found that the values of p_c determined with this method agreed with those

determined from neutron transmission[14] within 5 % (see Fig. 4). Data points in Fig. 4 are scattered around the line that represents the same pressure from both methods and has a slope of unity.

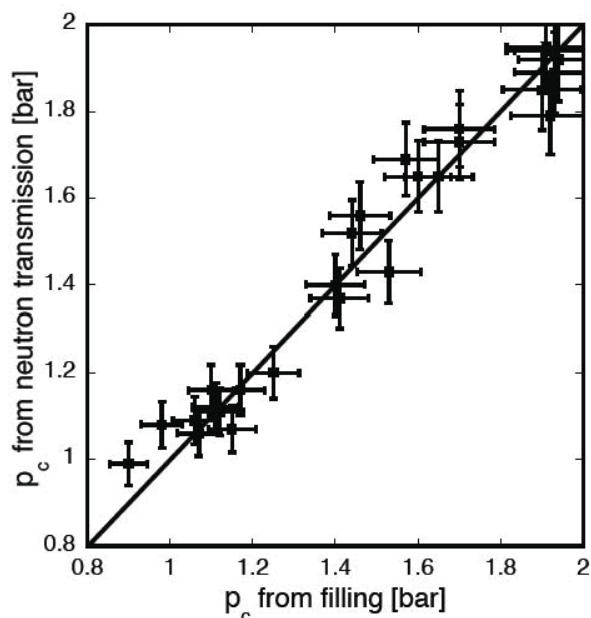


Figure 4. ^3He partial pressure in the cell obtained from both filling and neutron transmission measurements. The solid line represents an equal ^3He pressure from filling and neutron measurements. We estimate the relative standard uncertainty for both ^3He pressure determinations from cell filling and neutron transmission measurements to be 5 %. For transmission-based values the uncertainty is dominated by the cell length determination.

3. ^3He cell performance tests and diagnostics

After the cell is removed from the string, there are extensive tests and measurements to perform, including the pressure test at high temperature; the vapor density ratio check; ^3He polarization relaxation time, T_1 , and its orientation dependence [4] if applicable; and maximum achievable ^3He polarization and related value of X . (X is a parameter that describes the recently observed linear increase in relaxation with alkali density, which limits the maximum ^3He polarization[15].) This section simply describes how these tests were done. The pressure test at high temperature is an additional safety check to minimize the possibility of cell rupture in the SEOP system. The hot pressure test is carried out in a well-controlled environment at a temperature 20 °C higher than the maximum temperature expected for optical pumping. After the cell passes the hot pressure test, we check the vapor density ratio on one of the SEOP systems using the protocol mentioned earlier. We found the initial vapor density ratio measurement for the sealed cells agreed with the measurement done on the cell filling system within 15 %. However, the vapor density ratio can change (typically an increase) during the first few cycles of cell heating to optical pumping temperatures presumably because the Rb-K alloy is not fully mixed.

3.1. SEOP systems

We currently have four SEOP systems at NIST used for neutron science applications. The first one[16, 11] has been used for over a decade for research and development. During this time period we have transitioned from using a single, 30 W, fiber-coupled, broadband laser to using two or three spectrally narrowed lasers, each based on a 50 W or 100 W diode array bar. It is currently employed primarily for the development of wide-angle analysis[7], but is also being used for other activities such as tests of large double-chambered cells. Two newer systems, based on the first system, are dedicated to providing polarized ^3He gas for polarized neutron experiments at the NIST Center for Neutron Research (NCNR)[17]. Finally we have a fourth compact system on the NG6M beam line[14] that was recently employed for polarizing small cells for neutron interferometry[18, 19]. The first three systems employ 795 nm spectrally narrowed diode lasers to illuminate cells from opposite sides. Use of a polarizing beam splitter just before the quarter-wave plate cleans up any loss of ideal linear polarization due to optical elements and also rejects light originating from the laser on the other side of the cell. In the first system we currently have three lasers in use. Two employ water-cooled single bar diode arrays, each narrowed with an external cavity. The first is based on a 50 W bar[20] that operates at minimum feedback, whereas the second is based on a 100 W bar[20] and employs a polarized beam splitter cube in the external cavity[21]. In the 100 W system we employ a half-wave plate between the two telescope lenses to control the feedback to the laser. The optic axis of the half-wave plate is typically adjusted to rotate the linear polarization of the laser light by 25° - 30° relative to the zero-feedback condition. The third is a commercial fiber-coupled laser narrowed by a volume Bragg grating (VBG) and temperature-controlled with a thermoelectric cooler[22]. This system is convenient and compact, but for our particular unit we have had trouble obtaining ideal overlap with the proper wavelength. In each of the two NCNR systems, we employ two 100 W bars, each with an external cavity with an internal polarizing beamsplitter. Both bars are water-cooled by a single chiller[23], with flow control to allow operation at different temperatures. The lasers are interlocked such that loss of water flow will shut down the lasers. All the key components in these systems including Helmholtz coils; laser, optics and chiller; heating unit; and polarization monitoring apparatus (see below) are integrated into a portable aluminum[24] cart. The laser shaping optics in these SEOP systems[16] can be conveniently adjusted to fully illuminate cells with cross sections up to 12 cm by 12 cm. We have recently replaced the external cavity in one laser system with a chirped VBG[25]. A chirped grating can be tuned about 1.5 nm, which avoids the wavelength matching issue sometimes encountered with a fixed VBG. We have obtained a linewidth of 0.25 nm full width at half maximum (FWHM) with excellent suppression of broadband background and only $\approx 10\%$ loss of the free-running power output[26]. Due to heating of the grating, the central wavelength should be specified below the desired transition. For 50 W and 100 W bars we have employed a grating with a central wavelength of 794.7 nm (vacuum wavelength; Rb transition at 795.0 nm). Although this specification was close to ideal for the 50 W bar, the laser beam is near the grating edge for the 100 W bar. We have recently tested gratings with central wavelengths of 794.1 nm (vacuum), and found that this wavelength specification is preferable for 100 W bars. We expect to convert more of our off-line lasers to operation with chirped gratings and modify the beam shaping optics to optimize the performance in this configuration. Fiber-coupled, VBG-narrowed lasers with thermoelectric cooling promise convenience for on-line operation.

3.2. Polarization measurement and monitoring

The ^3He polarization during optical pumping or relaxation is monitored by either the adiabatic fast passage (AFP) or the free induction decay (FID) nuclear magnetic resonance (NMR)

methods [27, 28]. The AFP NMR data is obtained by sweeping the magnetic field that maintains the ^3He polarization through the ^3He resonance frequency (typically 70 kHz to 90 kHz) and sweeping back to restore the original ^3He polarization state. The AFP data is fit to the square root of a Lorentzian, with a background term that includes a possible linear drift. This yields an NMR amplitude proportional to the ^3He magnetization. To obtain the absolute ^3He polarization, the AFP NMR is calibrated for each cell against neutron transmission measurements[14]. We have also compared the neutron-based calibration to that obtained from an absolute calculation of the AFP signal based on the known geometry and measurements of the pick-up coil quality factor. For small cells we find that the AFP signal is typically 20 % lower than one would expect from the absolute calculation, whereas for large cells this difference can be between 20 % and 50 %. We often employ FID NMR during optical pumping or relaxation because it does not require nulling of the signal induced in the pick-up coil and thus is more easily automated. Fig. 5 shows typical NMR signals and pumping and relaxation curves. Both AFP and FID for both SEOP systems are controlled by a single NMR unit, which may be expanded in the future.

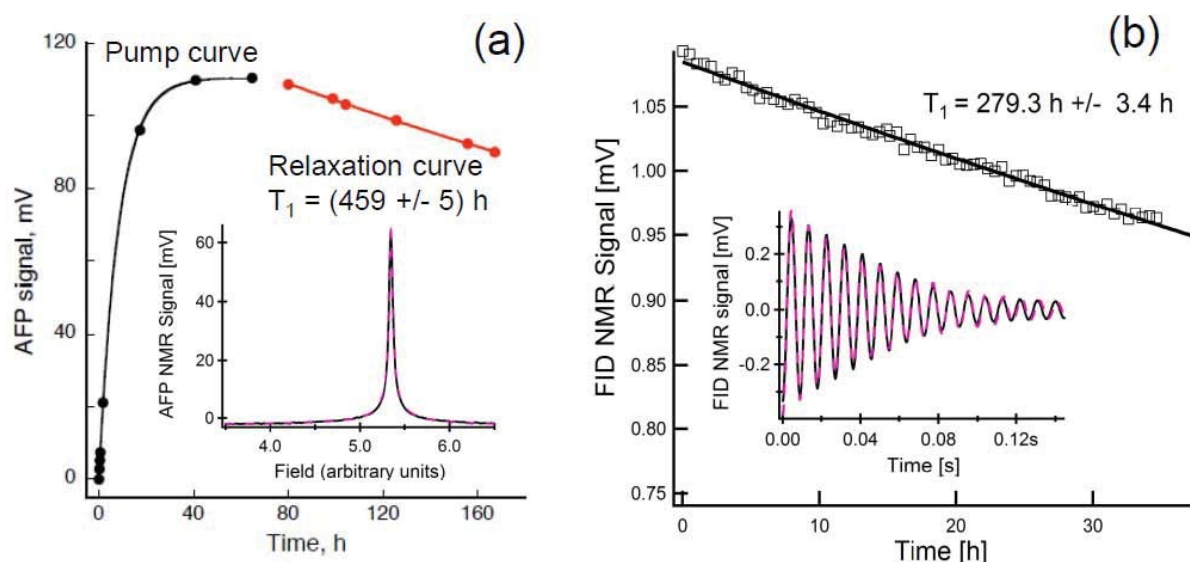


Figure 5. Typical NMR signals and pumping and relaxation curves. (a) Pumping and relaxation curves determined from AFP NMR; inset shows an AFP signal. AFP signals are calibrated against neutron transmission measurements to yield absolute ^3He polarization values with typical relative standard uncertainties of 4 %. (b) Relaxation curve from FID signals shown in the inset.

4. Discussion of cells

4.1. Survey of relaxation characteristics

In the appendix we provide a detailed listing of NIST cells and applications. Here we survey the wide range of behavior we have observed for relaxation times. Fig. 6 shows the room temperature T_1 of the blown GE180 cells for the ^3He partial pressure range between 0.13 bar to ≈ 2 bar. Several cells have relaxation times approaching the dipole-dipole limit[29], with the longest T_1 of 3000 h obtained in the cell Diamond[30]. For the ^3He partial pressure of 0.13 bar for this cell, this result indicates the wall relaxation contribution to the total relaxation

is ≈ 6000 h. The cells Diamond and Emerald had ^4He added to reduce relaxation from magnetic field gradients[31].

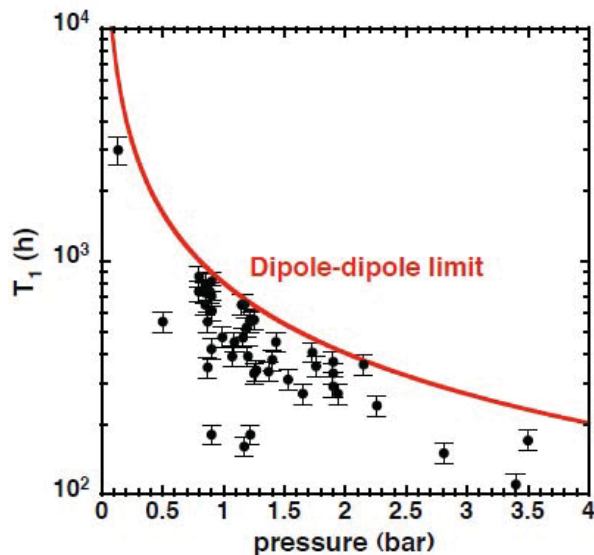


Figure 6. The room temperature relaxation time vs the partial ^3He pressure for the blown GE180 cells made at NIST. The solid line shows the limit from dipole-dipole relaxation. The longest relaxation time was 3000 h for the cell Diamond with a partial ^3He pressure of 0.13 bar. The error bars show the typical relative standard uncertainty of 10 % or less in fitted values of T_1 .

Many cells, in particular those for which the relaxation is dominated by dipole-dipole relaxation, exhibit a stable relaxation time. However, many cells often show low field orientation dependence[4], which may or may not converge to a single, stable value after repeated cycles of optical pumping. More generally, a cell that exhibits a dependence of its relaxation time on its orientation with respect to a magnetic field may also show a dependence of its relaxation time on the magnitude of the magnetic field, even for fairly weak magnetic fields. Jacob[32] observed minima in the relaxation time of a GE180 SEOP cell at coercive fields of $\approx \pm 200$ G. In Fig. 7 we show magnetic field effects on relaxation for two cells. In Fig. 7(a) the wall relaxation rate for the cell Spock shows a variation between 0.004 h^{-1} and 0.01 h^{-1} for fields between -2.6 mT and 2.6 mT , with the longest relaxation time recorded at 1.15 mT . For these studies an FID signal was measured at 2.6 mT with the bipolar power supply for the Helmholtz coils operating in current control mode, then the supply was switched to voltage control mode (set to maintain nearly the same current) and the voltage was varied to produce fields between -2.6 mT and 2.6 mT for some period of time. Finally the voltage was returned to produce 2.6 mT and the supply was switched back to current control mode for another FID measurement. We tested that quickly passing through zero field and switching modes of the power supply did not affect the ^3He polarization.

To investigate the effect of stronger fields we used a makeshift set of four small coils to produce the results in Fig. 7(b) for the cell Skylight. This cell had a reasonably long relaxation time of $T_1=156 \text{ h}$, as measured in the Helmholtz coils of our SEOP apparatus operating at $\approx 2.5 \text{ mT}$. Exposing the cell to a field of 43 mT and returning to check the T_1 at 2.5 mT decreased

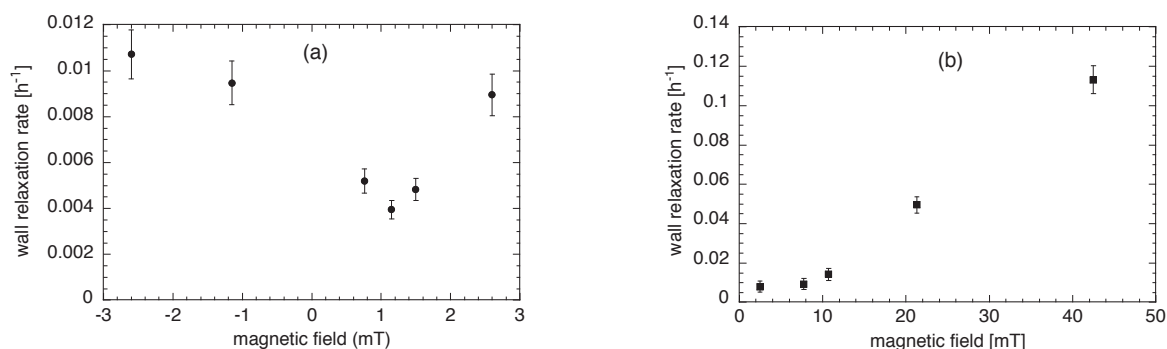


Figure 7. Dependence of the relaxation rate on magnetic field for two cells. (a) Wall relaxation rate for the cell Spock for fields between -2.6 mT and 2.6 mT. The data shown were corrected from the measurements by the dipole-dipole relaxation rate of 0.0011 h^{-1} for ^3He partial pressure of 0.9 bar in this cell. (b) Wall relaxation rate for the cell Skylight for magnetic fields between 2.5 mT and 43 mT. The data shown were corrected for dipole-dipole relaxation (0.0037 h^{-1} at 3.0 bar) and gradient-induced relaxation (0.013 h^{-1} for the relatively large value of $2 \times 10^{-3} \text{ cm}^{-1}$ in the makeshift four-coil apparatus employed). For both plots the error bars indicate the estimated uncertainty in the measurements due to stability of the NMR signals, and for (b) also include uncertainty in the correction for gradient-induced relaxation.

the T_1 to 100 h, and the subsequent series of measurements obtained at fields from 2.5 mT up to 43 mT showed over an order of magnitude decrease in relaxation time with increasing field. For these tests the AFP signal from the cell was measured in our Helmholtz coils, then the cell was transferred directly to the nearby four coil system operating at values between 2.5 mT and 43 mT and maintained for some period of time, and finally the cell was transferred back to the Helmholtz coils for another NMR measurement. While the cell was in the four coil system the Helmholtz coils were turned off to avoid affecting the measured T_1 , and while the cell was in the Helmholtz coils the four-coil system was turned off to avoid affecting the AFP signal. Whereas such effects will surely be cell-dependent, these effects must be considered for any application in which one expects cells to experience magnetic fields greater than ≈ 10 mT.

Long relaxation times are most reliably obtained for fully blown cells, but can be obtained in flat-windowed cells. Cells with short relaxation times can often be improved by opening the cell, reacting away the alkali metal, and completely repeating the cell filling process. For some of the cells listed below, this procedure was performed one or more times. In some cases the cell is rinsed or soaked in nitric acid after the alkali-metal is removed. For one cell (Pike) our glassblower “flame-polished” the inside of the windows, and then an optical seal in the middle of the cylindrical section was used to seal the cell. The goal of this construction was to see if flame-polishing improved the relaxation time; the results were inconclusive and due to the complex constructional procedure we did not pursue this further.

In the case of the small flat-windowed cells Cashew, Peanut, Almond and Pistachio that were fabricated for neutron interferometry experiments, the least understood behavior was observed, in particular for the cell Cashew. For Cashew and Peanut we observed relaxation times of 350 h and 53 h, respectively, whereas the relaxation times for Almond and Pistachio were very short (≈ 1 h). These cells were not used for two years until the interferometer experiment was

ready for them. Upon testing them, we found that the relaxation times for Cashew and Peanut had decreased to between 1 h and 5 h. We attempted to demagnetize the cells using a small demagnetizing unit typically employed for demagnetizing tools. In addition, in desperation, we made various attempts to redistribute the rubidium, and repeatedly optically pumped the cell. We were able to increase the relaxation times of these two cells to about 8 h. Finally Cashew was optically pumped “upside-down”, in an attempt to cause greater flow of rubidium over the cell walls. The relaxation time of the cell increased dramatically to the listed value of 330 h, similar to its original value, and remained at this value during the course of use for the experiment. We cannot say what caused the change, but speculate that there is a highly relaxing spot on the cell that was eventually covered with alkali-metal. In the case of Peanut we were not able to exceed 8 h. Due to this strange behavior, we demagnetized and tested the originally bad cells Almond and Pistachio, and obtained relaxation times of about 35 h for both. The cells Cashew and Pistachio were employed for the interferometer experiment, with most of the data obtained using Cashew.

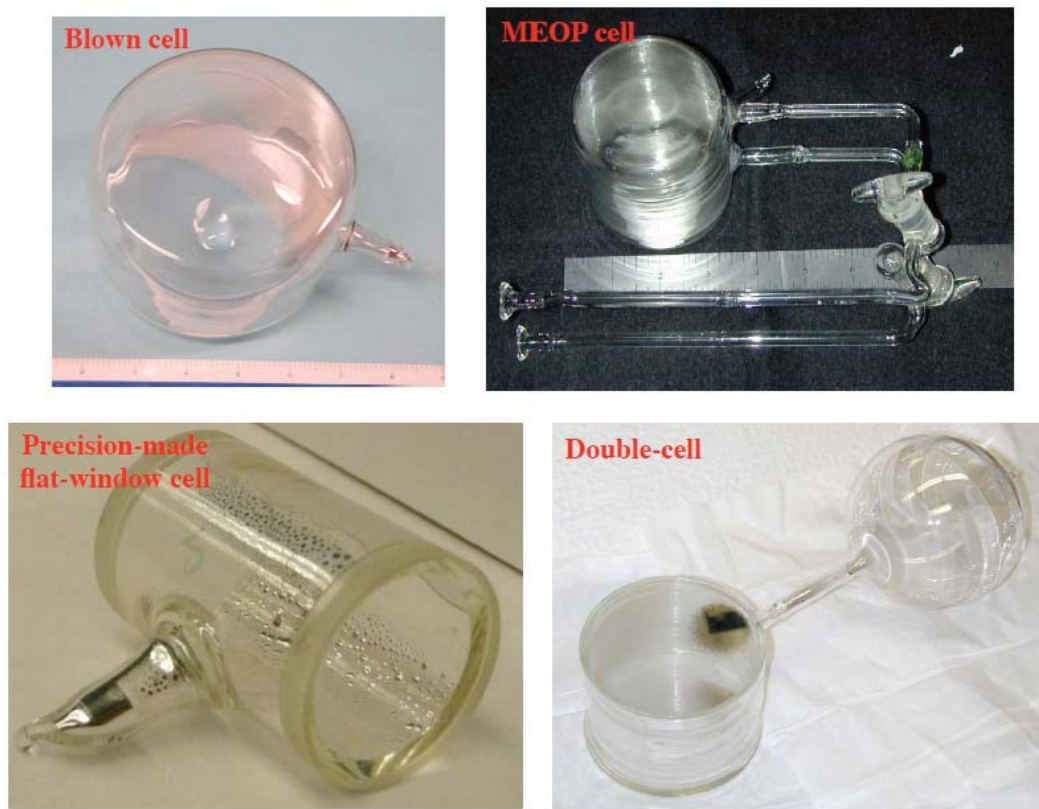


Figure 8. Photographs of a typical large blown cell (Barbera, 12 cm diameter), a valved MEOP cell (Orion, 7.5 cm diameter by 10 cm long), flat-windowed interferometer cell (Cashew, 2.3 cm diameter by 3.4 cm long) , and a large double cell (Sarek, 11 cm diameter spherical optical pumping chamber and 10 cm diameter flat-windowed spin filter cell). See the text and appendix for additional information on these cells.

MEOP cells provided additional information on cell relaxation times. For example, the Rb in the cell Arcturus became substantially oxidized due to slow leakage of air when on the

shelf for a long time without exercise of the stopcock valves. Nevertheless, the relaxation time was measured to be 130 h, similar to the value of 170 h measured when the cell was first constructed. This result, along with other similar experiences we had with SEOP cells that developed accidental leakage, indicate that Rb oxides provide a low relaxation surface. This is expected as studies have shown excellent relaxation properties for cesium oxides[33]. In Ref. [10] we reported a relaxation time of 74 h for the cell Spica, whereas a relaxation time of 240 h was reported in later work[4]. This may have been due to slight oxidation that occurred while the cell was on the shelf for a year or more. As described in Ref. [4], the cell Spica was then employed to establish the role of heating in low field orientation dependence. Before heating this cell showed an average relaxation time of 240 h with little orientation dependence, whereas after heating the relaxation time varied with orientation between 119 h and 258 h.

4.2. Special cell constructions

Fig. 8 shows photographs of a few cells: a typical, blown cell for neutron spin filter applications (Barbera); a flat-windowed cell for interferometry (Cashew), a valved, alkali-coated, MEOP cell (Orion), and a large double cell (Sarek).

A few other special types of cells are worth noting. In principle, Rb/Na hybrid cells should yield even greater efficiency than Rb/K cells[34]. However, due to the low vapor pressure of Na, extremely low mole fractions of Rb and operation at temperatures over 300 °C is required. We filled three Rb/Na cells, two from GE180 (denoted Margarita and Merlot) and one from Corning 1720 (denoted Shiraz). Our first cell, Margarita, contained too much Rb and thus was essentially a pure Rb cell with a Na coating. The value of 76 % polarization obtained in Margarita indicates that X is comparable to that obtained in the absence of the Na coating. The cells Merlot and Shiraz (not listed in the appendix) had more appropriate mixture ratios, allowing some studies before these cells developed an opaque, brown film. Sapphire can accommodate these temperatures, and a 24 h relaxation time has been reported for a pure Rb cell made completely from sapphire[35]. We filled two Rb/Na cells that employed sapphire end windows bonded to glass[36], but these yielded unacceptably short relaxation times of less than 10 min[37]. We have not yet attempted to refill these cells or construct others.

Silicon is an ideal material for neutron spin filter windows because of its high neutron transmission. For MEOP, relaxation times ≥ 240 h have been obtained in cesium coated cells constructed from silicon windows bonded to Pyrex[38]. We have tested two SEOP cells (denoted by Horta and Lazarus), that were constructed by the NIST Optical Shop from silicon windows and blown Pyrex. The relaxation times of these cells are in the 50 h range, but in some cases have shown substantial orientation dependence. We have not listed polarization values because of limited studies of these cells. However, the maximum values of ≈ 50 % polarization that we have observed to date suggests that they may show higher than average relaxation at high temperatures. Recent studies for SEOP Pyrex cells[39] indicate that they may exhibit higher than average X values, in particular for pure Rb cells. Further studies of the temperature dependence for Pyrex cells are needed. However, for larger silicon-windowed cells X may be sufficiently low so that polarization values comparable to those obtained in GE180 cells can be achieved. The cell Lazarus was reconstructed as a double cell so that the silicon-windowed part would not have to be heated. Nevertheless, this cell still showed orientation dependence, which we plan to study further in the future.

The recent discovery of neutron beam induced alkali spin relaxation[40, 41, 42, 43] presents a new issue for the use of spin filters in high flux beamss. Whereas not a major concern for most neutron scattering applications, this phenomenon must be considered for many fundamental neutron physics experiments. Double cells present a method for decoupling the optical pumping

from the neutron beam, as has been done for targets for electron beams[44, 45]. Successful results were obtained in neutron tests at the Institut Laue Langevin using the double cell Roadrunner[42]. For further work in this area we have constructed a large double cell, denoted by the name of the original single cell that is used for the spin filter section, Sarek. This cell has a $\approx 700\text{ cm}^3$ spherical optical pumping chamber that is connected to a 530 cm^3 flat-windowed filter cell through a tube that provides a 0.7 h transfer time for diffusion of the gas between the cells. Due to the 30 cm overall length of this extended cell, we employed an electrically heated oven located within a 40 cm diameter, 70 cm solenoid (prototype for the MACS apparatus) for tests. Despite a relaxation time of 150 h in the optically pumped orientation, we have observed only 46 % polarization in this cell. This result is lower than expectations, and is being studied further.

5. Cells for wide-angle polarization analysis

Wide-angle neutron polarization analysis presents new challenges for cell fabrication. Substantial progress has already been made for MEOP-based wide-angle spin filters[46], but directly optically pumped SEOP wide-angle cells present additional issues due to the need for operation at elevated temperatures. Although ideally we would fabricate such cells from GE180 glass, to date this has not been possible due to the difficulty in working this glass and the limited forms in which it is available. Before reporting our results for fused quartz wide-angle cells, we review some basic information about glasses for polarized ^3He .

In early cell development, aluminosilicate glasses were found to be preferred for storage of polarized gas in bare glass cells because of the low ^3He permeability for such glass. Fused quartz and borosilicate glasses were found to exhibit relaxation related to their higher permeability[47]. For fused quartz the permeability is sufficiently high such that ^3He loss for extended operation at SEOP temperatures is an issue. For these reasons and also because of good alkali resistance, aluminosilicate glass has also been used for SEOP. It has been shown that the alkali metal in SEOP cells improves relaxation time[48], which has led to the routine use of cesium as a coating for MEOP spin filter cells. Once alkali is introduced, high permeability glasses can be tolerated, indeed very long relaxation times have been obtained in cesium coated cells fabricated from fused quartz[49]. For magnetic resonance imaging applications, long relaxation times have also been obtained in valved Pyrex cells[50]. Nevertheless, the longest relaxation times are still most reliably obtained in aluminosilicate glass cells[10]. To explain this observation, it has been speculated that the wall relaxation observed in alkali-coated cells is due to imperfections in the coating. Such imperfections would be expected to have a more detrimental effect on the relaxation time for a high-permeability glass[33]. Such considerations become particularly critical for SEOP, as permeability increases exponentially with temperature. Indeed it has recently been shown that fused quartz cells show significant temperature-dependent ^3He relaxation that varies from cell to cell[5].

We have constructed two types of fused quartz cells to yield 120° of angular coverage[7]: three commercially made[51], welded cells (7 cm \times 7 cm inside dimensions for cross section), and two cells made at the NIST shop from slightly resized, 7 cm or 8 cm inner diameter GE124 quartz tubing[52]. One of each type, denoted by the names Rainbow (welded) and Jersey is shown in Fig. 9. We employed pure Rb for the fused quartz analyzer cells due to browning of the glass in the presence of Rb-K vapor at temperatures above 200° C . (The brown coating rinsed off when the cell was opened and cleaned.)

For all three welded cells (denoted by Rainbow, Crescent and California), we observed significant, persistent orientation dependence in the relaxation time[4]. For example, for the wide angle cell Rainbow, we repeatedly obtained a relaxation time of 20 h when it was cooled to



Figure 9. One of each type of fused quartz cells for wide-angle analysis cells: welded cell Rainbow (left) and cell Jersey (right) made from three connected sections of slightly resized tubing.

room temperature after optical pumping, and 90 h when the cell was then rotated 180° . When this cell was optically pumped at 170°C , we obtained an optical pumping time constant of (8.4 ± 0.1) h. Assuming a typical value of $X = 0.3$ [15] for this size cell, a maximum polarization of 0.45 was expected, in reasonable agreement with the measured polarization of 0.42. The polarization values were determined with a typical relative standard uncertainty of 5 % from neutron transmission measurements and/or electron paramagnetic resonance [53, 14].

It has generally been found that fully blown GE180 glass cells typically have smaller wall relaxation rates than non-blown cells[29, 10]. Hence to improve the relaxation times in our wide-angle cells we made three additional cells, denoted by Jekyll, Peru and Jersey, by fusing together 2 to 4 sections of fused quartz tubing. Each section was slightly resized so as to yield blown surfaces. This fabrication approach yielded a cylindrical test cell Jekyll (7 cm inner diameter (ID) by 13 cm long) and a wide-angle cell Jersey (8 cm ID cross section) with relaxation times of 210 h and 180 h, respectively. Whereas we would normally obtain over 70% polarization for such long relaxation times, we obtained an unexpectedly low polarizations of 0.47 and 0.42 for Jekyll and Jersey, respectively. In addition, the pumping time constant was shorter than expected. For example, for Jersey, only (7.1 ± 0.2) h was measured, compared with an expected value of 11.5 h (assuming $X \approx 0.3$) for the optical pumping temperature of 170 C. We believe this result is due to the same decrease in relaxation time with temperature as was recently reported for fused quartz cells[5]. In SEOP cells, the relaxation rate has been found to increase linearly with alkali-metal density[15]. However, the data in Ref. [5] indicates that for fused quartz the measured relaxation rates increase substantially in the absence of any significant Rb density as the temperature is increased. We plan further T_1 tests in this temperature regime to test our hypothesis. This temperature dependent phenomenon is not presently understood. It may be related to the high permeability of the fused quartz. Although it appears that this temperature dependence may not exist in our welded cells, this is difficult to ascertain because of the short relaxation times observed in the optically pumped orientation.

To temporarily bypass this fused quartz issue we have constructed two blown, cylindrical, GE180 analyzer cells (Barolo and Barbaresco), which we are currently employing for the first experiments on MACS, albeit with reduced (30°) angular coverage. As discussed in Ref. [7] the cells Monastrell, Gamay and Grenache will be used to polarize the MACS beam. On the longer

term, we will make further attempts to fabricate wide-angle cells from GE180 and investigate coatings such as sol-gel to address the high temperature relaxation issue in fused quartz. Other alternatives include valved cells or double cells made from fused quartz, to avoid heating of the spin filter cells.

6. Conclusions

We have described our procedures for fabricating and testing SEOP cells, and reviewed and documented results for over a decade of development and application of polarized ^3He cells. The relaxation times for such cells show remarkably complex behavior that is not well understood. Each new goal in cell development or more careful study of existing cells reveals new phenomenon. While interesting, these phenomena can often be an impediment to applications, but somehow we always muddle through the maze. We presented the current state of the most recent challenge of wide-angle neutron polarization analysis.

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Appendix

In this section we present a series of tables of NIST cells, divided into four categories: SEOP cells for tests and studies, MEOP cells, cells for neutron scattering applications at the NCNR, and cells for neutron scattering applications at other laboratories and fundamental neutron physics. Although this list is close to complete for cells made in the last decade, it does not include many older cells. There is of course overlap in these categories, as many cells have had multiple uses. For each cell, we provide references for where further information on the cells and/or applications can be found. Whereas NIST was involved in most of these applications, we also include applications of loaned cells.

Table 1 lists cells used for tests and studies, including development of long relaxation time neutron spin filters[10], SEOP with spectrally narrowed diode lasers[16], low-field orientation dependence of ^3He relaxation time in SEOP cells[4], limits to the polarization for SEOP[54, 15], hybrid SEOP[11], neutron beam effects on SEOP[40, 41, 42, 43], and evaluation of magnetic field gradients[55, 56].

Table 2 list storage cells used for metastability-exchange optical pumping, including development of compression systems[57, 58]; application to small angle neutron scattering (SANS)[59], reflectometry[60], and magnetic resonance imaging[61]; and studies of low field orientation dependence of ^3He relaxation time[4].

Table 3 lists cells employed for neutron scattering applications at the NIST Center for Neutron Research (NCNR)[14, 17], divided into three categories: 1) small angle neutron scattering

(SANS)[59, 62, 63, 64, 65, 66] and the NCNR reflectometers (REFL)[67, 68, 69], 2) triple-axis spectrometry (TAS)[70, 71, 72, 73, 74] and 3) the NCNR Multi-Axis Crystal Spectrometer (MACS)[7].

Table 4 lists cells used for neutron scattering applications on the Single Crystal Diffractometer (SCD) at the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory (ANL)[75, 76], the magnetism reflectometer at the Spallation Neutron Source (SNS-MR)[77, 78], and the CRISP instrument at ISIS[21], followed by fundamental neutron physics applications[30]. The latter are divided into three categories: neutron interferometry at the NCNR[18, 19], the NPDGamma experiment at the Los Alamos Neutron Scattering Center (LANSCE)[79, 80, 81, 82, 83], and limits on short range spin-dependent forces from spin relaxation of polarized ^3He [84]. A detailed paper on the neutron interferometry experiment, including the precision polarimetry for this work[85], will appear in a future publication.

For all four tables the following information applies: D is the vapor density ratio for Rb/K cells ($D=0$ indicates pure Rb and $D=\infty$ indicates pure K), d is the inside diameter in cm, and l is the average inside length in cm. Most cells are cylindrical, but the absence of a value for l indicates that the cell is spherical. An additional value in parentheses indicates the diameter of the spherical optical pumping chamber for double cells. V is the volume in cm^3 , p is the ^3He partial pressure in bar, T_1 is the ^3He relaxation time in hours, and P_{He} is the maximum ^3He polarization observed for 795 nm optical pumping. For T_1 , two values are listed where orientation dependence was measured at least once or a range of values is listed for more extensive studies of orientation dependence. For P_{He} , a number in parentheses for mixture or pure K cells indicates results for optical pumping with a 770 nm laser[11] based on either a 20 W or 40 W diode bar. The last column includes notes and references for further information and/or applications for each cell. If the P_{He} was never measured accurately (or if old records are inconclusive), there is no entry in this column. In addition, we note that not all cells were optically pumped under ideal circumstances. Relative standard uncertainties for data in these tables varied with the amount of studies of a given cell, but are typically equal to that indicated by the last significant figures or 5 %, whichever is greater.

In many cases where details on how the cells were pumped is available in the listed references. Except where noted all cells were constructed from GE180 glass; in the last column FQ indicates fused quartz, 1720 indicates Corning 1720[9], D1720 refers to a special batch of glass that was made with ^{10}B -depleted Corning 1720 glass, and 7056 indicates Corning 7056[9]. In several cases, the material for the body and windows for a cell may differ. Cells may be listed twice if they have been reconstructed at some point. The cells Lazarus and Sarek were originally fabricated as single cells, but later became part of a double cell with the name unchanged. The cell Mars was first fabricated as an valved, uncoated cell for MEOP and then later became a sealed, pure Rb SEOP cell.

Table 1. ^3He cells used for tests and development. The cells are divided into two categories, those that were fabricated from blown glass and those that have flat, optically sealed windows[86].

Cell name	D	d	l	V	p	T_1	P_{He}	References, notes
<u>BLOWN</u>								
Bonnie	0	2.8	-	12	3.4	110		[15]
Ringo	0	2.5	-	8	3.4	64	0.48	[15]
Fred	0	4	4	50	0.8	≈ 170	35	[87]
Mrs. Peel	0	6	7	200	1.60	180	23	[87]
Barney	0	8.5	4	230	1.1	380		[10, 15]
Natasha	0	4.5	4.5	72	0.7	440		[10, 15], FQ
Red Baron	0	5.8	1.5	40	0.9	82/270	0.53	[4, 15]
Riesling	4.8	9.8	9.0	680	3.5	170	0.77 (0.68)	[11]
Cabernet	46	11.8	7.6	830	1.94	270	0.58 (0.71)	[11]
Gigantor	96	9.1	9.4	611	0.85	800	0.56 (0.73)	[11]
Quasimoto	155	6.7	5.8	205	1.12	550	0.48 (0.76)	[15, 11]
Sonora	∞	4.5	4.3	68	0.81	500	(0.77)	[11]
Otto	0	1.4	9	14.7	0.9	420	0.45	[15]
Uhura	0	5.0	5.4	104	1.22	180	0.64	[15]
Wilma	0	4.9	4.9	91	0.8	830	0.76	[10, 16, 15, 11]
Scotty	0	5.1	5.3	108	0.90	610		
Tin Man	0	4.9	4.9	91	0.58	70	0.77	[43]
Lion	0	4.7	5.0	86	0.57	510	0.77	[43, 88]
Scarecrow	0	5	5	90	0.5	25	0.22	[43], low N_2 pressure
Diamond	0	3	-	≈ 14	0.13	3000		[30], 0.77 bar ^4He
Emerald	0	2.5		≈ 7	0.13	≈ 2000		[56], 0.70 bar ^4He
Sunshine	0	11.2	-	740	0.5	550		[15]
Washington	0	2.2	4.8	27	0.87	550	0.65	
Margarita	≈ 0	6.4		140	0.9	820	0.76	[15], Na coating
Merlot	-	6.4		140	0.9	250		Rb/Na
<u>FLAT</u>								
Betty	0	4.7	4.9	81	0.87	240	0.72	[10, 54, 16, 4, 15], 1720 body
Sulu	0	4.8	6.2	110	0.9	115	0.63	[16, 15]
Pike	0	5.3	6.1	135	0.77	40/310	0.67	see text
Boris	0	4.7	4.9	84	0.85	85		[10, 15], 1720
Mars	0	6.0	8.0	230	0.9	270	0.73	[16, 4, 15], 1720 body
Spock	0	10.3	7.4	620	0.92	35-229	0.65	[4, 30]
Sarek	0	10	6.7	530	1.06	39-135		
BamBam	0	9.4	4.7	330	0.85	95	0.51	[16, 4, 15]
Algonquin	0	3.7	7.4	80	1.58	13-70	0.24	[15]
Horta	0	4.2	5.6	81	1.3	75		Si windows
Lazarus	0	4.7	5.1	88	0.8	21-124	0.49	Si windows
Sarek	1	10 (11)	6.7	1200	0.85	150-320	0.46	double
Lazarus	0	4.7 (6)	5.1	200	0.9	42/76		double, Si windows

Table 2. ^3He cells used for MEOP. All cells are valved, hence there is no column for pressure. Achievable polarization depended on operating conditions and can be found in the references provided. All cells were fabricated from blown GE180, with transitions to Pyrex stopcock valves, except where noted.

Cell name	d	l	V	T_1	References, notes
<u>UNCOATED</u>					
Mercury	4.4	10	155	37	[14, 59, 57], 1720 body, D1720 flat windows
Saturn	9.5	150	1060	50	[57], 1720 body, D1720 flat windows
Neptune	7.2	10.0	410	72	[57], 1720 body, D1720 flat windows
Venus	5.9	10	270	27	[60], 1720 body, GE180 ends
Earth	6.2	9	270	15	[61], 7056, O-ring valves
Earth-II	5.9	8.5	230	33	1720, O-ring valves
Mars	5.9	8.0	220	25	1720 body, GE180 windows
<u>Rb-COATED</u>					
Orion	7.5	10	440	240	[10, 30, 58]
Betelgeuse	7.5	10	440	230	[10]
Spica	7.0	10	390	74-258	[10, 4], see text
Antares	7.5	10	440	110	[4]
Arcturus	7.5	10	440	170	see text
Europa	5	5	100	30	[4]

Table 3. ^3He cells used for neutron scattering applications (SANS - small angle neutron scattering; REFL - reflectometry; TAS - triple-axis spectrometry; MACS - Multi-Axis Crystal Spectrometer). The MACS cells are discussed in Sec. 5.

Cell name	D	d	l	V	p	T_1	P_{He}	References, notes
<u>SANS/REFL</u>								
Snoopy	0	5.6	1.5	34	3.4	180	0.75	[59, 15]
Joe Cool	0	6.9	1.2	45	3.1	120	0.63	[10, 16, 15]
Bullwinkle	0	6.9	7.1	268	1.3	550	0.72	[16, 67, 68, 69, 15, 11, 66]
Chekhov	0	8.1	6.0	310	1.3	340	0.79	[4, 30, 11, 55]
Chardonnay	1.6	8.4	7.3	400	1.07	390	0.77	[15, 11, 55]
Orvieto	2.2	8.7	7.2	430	1.1	80	0.70	[15, 11, 40, 41, 42]
Olaf	4.4	10.8	6.0	545	0.96	348/472	0.72	[65]
Burgundy	2.2	12.0	8.0	895	1.09	450	0.80	[55, 63, 64]
Frascati	4.2	12.0	7.0	795	1.19	160	0.76	
Maverick	4	11.2	6.2	615	1.4	370		[63, 64]
Icemann	3.4	11.8	6.8	745	0.75	122	0.76	
Peabody	0	7.0	7.8	300	1.17	650	0.62	[69],sol-gel coating
(Yeoman) Rand	0	6.0	6.0	175	1.15	650		[69, 15]
(Nurse) Chapel	0	7.2	6.5	260	1.25	330	0.75	[30, 15]
<u>TAS</u>								
Zinfandel	1.0	11.6	8.9	940	1.86	330	0.78	[70, 11]
Syrah	6.2	10.2	9.7	790	1.43	450	0.76	[70, 11, 55]
Beaujolais	3.2	10.5	11.7	1010	1.37	336	0.69	
Sangiovese	3.4	11.0	10.0	950	1.76	354	0.79	
Chablis	7	11.3	9.4	945	1.65	187-270	0.75	
Mercurey	3.0	11.7	7.8	840	1.76	357	0.69	
<u>MACS[7]</u>								
Monastrell	≈ 5	8	6	300	2.2	160/190	0.70	polarizer
Gamay	≈ 2	7	5.5	170	2.1	90/120		polarizer
Grenache	5	7	5.5	170	2.35	140/220	0.63	polarizer
Barolo	11	8	11.5	580	1.3	170/190	0.7	30 ° analyzer
Barbaresco	11	8	11.5	580	1.3	250/320	0.7	30 ° analyzer
California	1	7	7	1100	1.35	17/32	0.4	120 ° analyzer (FQ plate)
Crescent	0	7	7	1100	1.32	30/50	0.4	120 ° analyzer (FQ plate)
Rainbow	0	7	7	1100	1.24	20/90	0.42	120 ° analyzer (FQ plate)
Jekyll	0	7	13	500	0.83	200	0.47	FQ analyzer (blown, test)
Peru	0	6.8	-	840	1.25	55/65		120 ° FQ analyzer (blown)
Jersey	0	7.8	-	1100	1.17	190	0.42	120 ° FQ analyzer (blown)

Table 4. ^3He cells used or fabricated for neutron scattering applications at the Single Crystal Diffractometer (SCD) at Argonne National Laboratory or the magnetism reflectometer (MR) at the Spallation Neutron Source and for fundamental neutron physics applications (NPDGamma and interferometry experiments).

Cell name	D	d	l	V	p	T_1	P_{He}	References, notes
<u>SCD/MR</u>								
Felix	0	1.6	5.1	11	2.8	120	0.62	[15]
Oscar	0	1.7	5.1	12	3.1	20	0.51	[75, 15]
Marcy	0	3.5	5.3	51	2.2	360	0.67	[15, 76]
Colden	0	4.4	4.6	70	2.53	140/300	0.69	
Phelps	0	4.7	5.0	79	2.26	240	0.72	
Chianti	2.0	11.8	8.1	875	1.82	290	0.75	[70, 11]
Barbera	4.4	11.8	7.5	820	1.52	310	0.76	[70, 11, 77, 78]
Malbec	3.8	10.9	8.9	820	1.69	114/186	0.69	[21]
Bordeaux	3	11.4	8.2	840	1.09	80/310	0.67	
<u>NPDGamma</u>								
BooBoo	0	12.6	4.8	590	1.19	520		[10, 81]
Dino	0	10.6	5.1	450	0.9	530	0.75	[10, 16, 30, 15, 11, 81]
Pebbles	0	11.2	5.2	508	0.87	350	0.76	[10, 30, 15, 81, 40]
Kirk	0	10.5	7.2	620	0.80	740	0.77	[11, 81]
McCoy	0	9.7	6.1	450	1.16	470	0.66	
Yogi	0	10.6	4.9	432	0.9	180		[10]
Elroy	0	11	4.5	430	0.85	98		[10, 81]
Rocky	0	13.4	5.5	770	0.85	150		[81]
Astro	0	11.3	6.4	640	0.89	740	0.72	[10, 16, 30, 81]
Elmer	0	7 (5)	1.6	120	3	51	0.27	[79], double, meniscus NSF
Roadrunner	0	5 (4.5)	1.5	95	3	220		[42]
<u>Interferometry</u>								
Cashew	0	2.3	3.4	14	1.9	330	0.65	[15, 18, 19], flat windows
Peanut	0	2.3	3.4	14	1.7	8		[15, 18, 19], flat windows
Almond	0	2.3	3.4	14	1.8	35		[18, 19], flat windows
Pistachio	0	2.3	3.4	14	1.7	35		[18, 19], flat windows
Haystack	0	4	5.8	70	2.94	140	0.72	[18, 19], polarimetry
Skylight	0	4	5.8	70	3.1	156	0.69	[18, 19], polarimetry
Whiteface	1	4.5	5.9	94	3.50	28/143	0.74	[18, 19], polarimetry

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