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Towards Wide-Angle Neutron Polarization Analysis with a $^3$He Spin Filter for TOPAS and NEAT: Testing Magic PASTIS on V20 at HZB

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Abstract. An XYZ polarization analysis solution has been developed for the new thermal time-of-flight spectrometer TOPAS [1], to be operated in the coming east neutron guide hall at the MLZ. This prototype is currently being prepared to use on NEAT at HZB [2]. Polarization Analysis Studies on a Thermal Inelastic Spectrometer, commonly called PASTIS [3], is based on polarized $^3$He neutron spin filters and an XYZ field configuration for the sample environment and a polarization-preserving neutron guide field. The complete system was designed to provide adiabatic transport of the neutron polarization to the sample position on TOPAS while maintaining the homogeneity of the XYZ field. This complete system has now been tested on the polarized time-of-flight ESS test beam line V20 at HZB [4]. We present results of this test and the next steps forward.

Introduction

Since the early applications of polarized $^3$He for neutron polarization and analysis there have been proposals for its use in wide-angle neutron polarization analysis, especially for neutron spectrometry with large-area detector arrays and instruments using thermal energy neutrons [5]. This may be achieved by using an uniform magnetic field insert to house a large-angle $^3$He cell that can be placed around the sample environment of a typical wide-angle neutron spectrometer. This would allow polarization analysis over the full detector angle using a moderately-sized $^3$He cell while needing minimal instrument modifications. One such application has been shown at NIST on the MACS spectrometer, however here only for “Z” polarization analysis, i.e. for the magnetic field perpendicular to the scattering vector[6]. The full polarization analysis version, which permits to measure magnetic scattering both perpendicular and parallel to the scattering vector of such a polarized $^3$He analyzer system, has become known in the community by its acronym PASTIS, for Polarization Analysis on a Thermal Inelastic Spectrometer [3]. Several projects towards such systems are in development at the ILL [7, 8], ISIS [9], SNS [10] plus upcoming spectrometer projects at the ESS, TREX and DREAM [11] as well as the system described in this proceeding for eventual use on TOPAS at MLZ [1] and on NEAT at HZB in the meantime [2].
FIGURE 1. Photo of the magic PASTIS system and neutron X Y Z guide fields on V20. The detector is to the left, PASTIS with a 3He cell installed is in the center, followed by the X Y Z guide fields and the incoming beam flight path to the right edge.

The use of a 3He spin filter in these applications will have the benefits of the “idealized” characteristics of not having alignment or sample size dependencies while giving a deterministic neutron energy/wavelength dependence which can be used for analysis of neutrons of arbitrarily high energy and high inelastic neutron energy transfer. Other neutron polarization analysis methods such as wide-angle neutron super mirrors have been applied for wide-angle diffraction and spectroscopy, but normally for cold-spectrum neutron instruments (i.e. approximately wavelengths greater than 2.4 Å or less than 15 meV energy) due to the limitations of the high-energy neutron efficiencies of such devices [13, 14, 10]. For a thermal neutron spectrometer such as TOPAS [1] which will use incident-neutron energies of up to 165 meV or 0.7 Å such devices would not provide the required performance leading us to further develop the magic PASTIS concept taking advantage of the before mentioned characteristics of 3He spin filter cells like the other groups cited above [6, 9, 10, 11].

This proceeding will summarize recent on-beam testing of the JCNS Magic PASTIS system from an experiment on the V20 ESS test beamline at Helmholtz-Zentrum Berlin.

**Magic PASTIS Prototype**

The PASTIS system plus neutron guide fields have been reported previously [15, 1]. In some ways this concept bears resemblance to the PASTIS 2.0 implemented at the Institut Laue Langevin [8], however the details of the magnetic systems are different, and while our system has small dead angles of around 3 degrees every 90 degrees in the horizontal plane, the vertical opening is higher than the ILL PASTIS 2.0, on the order of 40 degrees, and matched to the out-of-plane vertical acceptance of the TOPAS or NEAT detector systems. The values of the 3He $T_1$, or polarization decay time, of this system measured after optimization and in laboratory conditions in [15] implies a maximum normalized magnetic field gradient over the 3He cell volume of less than $1 \times 10^{-3}$ cm$^{-1}$ which translates into a magnetic plus dipole-dipole limited 3He lifetime in excess of 100 hours for cells of over 1 bar pressure [15]. The magic PASTIS was also designed to ensure fully adiabatic transport of the neutron polarization to the sample position for the specific mechanical geometry of TOPAS. This guide field system has been reported in [1] and it has been assembled and tested in laboratory conditions. The test results in Jülich using a Hall probe magnetometer met the expectations from the calculations and also permitted us to test the newly developed control software for automation of the PASTIS power supplies. This construction was then bench tested with the magic PASTIS system, also in Jülich, with a polarized 3He cell. In this test we did not observe adverse effects on the 3He lifetime via an NMR measurement of the cell lifetime due to the guide fields operating near magic PASTIS. The full prototype, consisting of the magic PASTIS coil system, guide field system, and control electronics was then shipped to HZB for testing.
FIGURE 2. Total neutron flipping ratio $F_n$, which is related to the total neutron polarization $P_n$ by $F = (1 + P_n)/(1 - P_n)$ for each of the three orthogonal field orientations after optimization of the RF gradient flipper using the “Mary” cell which had 17.5 bar cm of $^3$He and a polarization of 39% at the time of this measurement. Red is the vertical direction “Y”, blue is the transverse direction “X” and green in the longitudinal direction “Z”. This cell had a higher opacity (product of $^3$He pressure and length) than the cell used for the overnight measurements, thus it had very low transmission above 4.5 Å for the dark state, i.e. incident beam polarization antiparallel to the $^3$He analyzer polarization, so the flipping ratios above this wavelength are noise/background limited. The dotted black line is a fit assuming a $P_n = P_p \tanh(P_{He} \Theta \lambda)$ dependence of the neutron polarization, where $P_p$ is the polarizer efficiency, and the tanh term is $P_n$, the polarization efficiency provided by the $^3$He spin filter cell as described in the text. This data allows us to conclude the incident beam polarization can be considered uniform with adiabatic transport in the X, Y and Z field directions over the range of neutron wavelengths we used.

Magic PASTIS Installed on V20

Testing the magic PASTIS components in realistic conditions was performed on the V20 instrument [4]. The particular goals where to utilize the interface and test the practical handling of the system while obtaining the performance with polarized incident neutrons. Earlier tests of PASTIS systems, such as the tests on IN3 [3] showed that care must be taken with the guide fields to insure neutron polarization transport. Therefore this test was important to fully ensure and experimentally verify the neutron polarization transport beyond the expectations from calculations or field mapping.

The V20 instrument is a “test” beam line and is therefore very adaptable and has a very open geometry for installation of equipment [4]. The instrument essentially consists of a chopper system which can replicate the European Spallation Source (ESS) -proposed pulse structure [11, 12], an incident beam super-mirror bender polarizer, and a 6 m (can be extended to more than 10 m) open neutron flight path with adaptable detector options. Using a polarized $^3$He cell, we optimised an RF gradient (neutron AFP) flipper by simply maximizing the obtained neutron flipping ratio, i.e. the ratio of the flipper-on transmission to the flipper-off transmission as a function of neutron wavelength. The RF neutron flipper was constructed and optimized for this particular experiment and is described in [16]. The results of the experimental optimization showed us the instrument’s bender polarizer provided a good polarization over the range of our measurement. From fits of the unpolarized neutron transmission of the polarized and unpolarized $^3$He cell, we determined the $^3$He cell parameters. Then by flipping the incident polarization, and assuming that our RF gradient flipper had a negligible inefficiency, fits to the total neutron polarization gave an incident beam polarization $P_p = 97.7\% \pm 0.2$ for neutron wavelengths from 1.6 Å to 7 Å[16] for the configuration of the instrument during the overnight measurement. While this fit value of $P_n$ is an average value that is largely determined from the asymptotic value of the tanh dependence of the polarizing power of the $^3$He spin filter, non-statistical deviations from the fit lines can not be observed for the shortest wavelengths, so assuming $P_p$ is constant is a reasonable assumption for these tests.

Race-track neutron guide fields, seen in the right hand side of figure 1 maintain the neutron polarization after the incident beam polarizer, past the neutron flipper and up to the beginning of the magic PASTIS installation which was placed directly after. The photo in fig. 1 show the TOPAS X-Y-Z guide fields on the right, the magic PASTIS system in the middle, and the neutron detector to the left. The guide fields plus PASTIS require a total of 11 independently set power supplies, and a 45° rotation of one of the permanent-magnet Halbach rings (used in the MANDELA config-
FIGURE 3. (Neutron transmission) Graph of the neutron transmission vs wavelength at different times during our sample measurement. A global analysis of this data gives a $^3$He $T_1 = 109$ hours and an initial polarization of $P_{He} = 50\%$.

Flipping ratio data from optimization of the neutron flipper shown in figure 2 shows that the observed flipping ratios vs. neutron wavelength follow the expected dependence over wavelength giving result for each of the 3 field directions. The data in figure 2 was fit assuming a uniform incident neutron beam polarization and an analyzer efficiency of $P_a = \tanh(P_{He} \Theta \lambda)$ where the $^3$He polarization, $P_{He}$, and the cell pressure, length, cross-section product, $\Theta$, are also determined independently from unpolarized neutron transmittance of the polarized and unpolarized $^3$He cell. The results of this measurement lead us to conclude the neutron polarization remains constant in all three field configurations, and thus infer that the neutron polarization transport through the fields is adiabatic from the fits.

For this test the Halbach ring rotation was not automated, but simply rotated by hand between the two configurations required. The large number of power supplies did however require automation, to prevent errors as well as to minimise the time required to switch between field directions and thus minimise possible losses in $^3$He polarization due to higher field gradients while switching. For this purpose we set the Delta-Elektronica power supplies via a profi-bus interface that was addressed over an ethernet port by a control computer running a PYTHON application and GUI. The application allows us to select the desired field direction and also insures that there is always one field ON in the PASTIS system, enabling the new set direction for the holding field before shutting off the prior field with a small time delay. After configuring the currents to the previously determined optimal values in the programs GUI, one enters the operation mode and can simply give a command (mouse click) to choose the X, Y or Z field direction. This command can also be sent from any eventual instrument control computer and be integrated into measurement scripts.

Over-night Test Measurement

For the sample measurement a fresh $^3$He cell was installed in the magic PASTIS system. The cell was removed from the polarizer at the MLZ in Garching at around 9 am and was eventually installed in PASTIS on V20 at around 7 pm. By performing a global analysis of transmission data taken from 7:30 pm until approximately noon the next day, shown in figure 3, we were able to determine the initial $^3$He polarization of 50 % and on-beam lifetime of 109 hours. A suitable c-shaped cell was not available for this measurement so we used a D=4.3 cm by L=15 cm cylindrical cell which has a 230 hour $^3$He $T_1$ in laboratory conditions and 3.29 bar of $^3$He. The cell cylindrical axis was placed perpendicular to the neutron beam off-center in the PASTIS coils behind a sample holder in the middle (see fig. 1). This cell is of comparable size and pressure to an eventual c-shaped cell optimized for a cold neutron spectrum, which would provide a neutron polarization of 94% at 2.4 Å with an initial $^3$He polarization of 70% for example. This cell’s 14.2 bar cm neutron path length in this configuration clearly doesn’t compare to the approximately 30+ bar cm that will be required for the thermal neutron spectrum of TOPAS, production of suitable high performance cells for both the cold-neutron spectrum on NEAT and the thermal-neutron spectrum of TOPAS is the topic of continuing work [20].
FIGURE 4. Graph of the fraction of coherent ($f_{coh}$, closed squares) and incoherent ($f_{incoh}$, open squares) scattering for the hydrated graphite (blue) and the dried graphite (red). The lines (solid for coherent scattering and dashed for incoherent) are to guide the eye.

During this overnight measurement, the field direction was switched a total of 10 times, with measurements of the transmitted and scattered beam acquired for the two neutron polarizations (flipper On and flipper Off) for each field setting. The starting polarization of 50% is certainly not optimal but was sufficient for this test. Considering the transport via car and the 10 hour delay after polarization this value was a very positive first result that we believe can be improved upon with further experience for use on NEAT. The eventual permanent use of this device on TOPAS will be in Garching nearby the polarization laboratory further helping to minimize any polarization losses during cell transportation.

For the data acquisition, the position-sensitive-detector was not yet available on V20, thus we used an array of 4, 40 cm long $^3$He detector tubes placed horizontally in order to achieve a wide effective Q-range. A beam stop was made of cadmium and was attached to the detector housing such that the transmitted beam could be blocked for the scattering measurements, and conversely extra cadmium masks where also attached to the detectors to block the scattered neutron beam while performing transmission measurements. For the analysis of the scattering data, we simply used the distance from the mid-point of the detector to the left or right of the transmitted neutron beam to define $Q = 4\pi\sin(\theta)/\lambda$. This was calculated by measuring the sample to detector distance and the distance from the beamstop in the center of the detector to the midpoint of the scattered beam on the detectors active length to give us the value of $2\theta$ and the neutron wavelength was determined from the time-of-flight.

The sample used was a hydrated graphite powder in an aluminum holder. The expected signal was thus a combination of the diffuse non-spin flip, coherent scattering of the graphite powder plus a diffuse incoherent scattering from the hydrogen, with the usual 2/3 spin-flip scattering characteristic [17]. While the beam intensity was sufficient for statistics on the transmitted beam, the scattered beam however, even after one hour of integration, provided only on the order of 10,000 counts for the entire spectrum from 1.6 Å to 6.5 Å. Even after binning the data in 0.25 Å steps, the relative errors remain on the order of 5-10% for the raw data, and since the transmission of the empty cell measurement was anomalously low with respect to the sample measurements (a different but “identical” aluminum cell was used for the empty cell attempt) conclusions from the scattered-beam measurements are not readily obtainable. The data was however processed to separate the fraction of incoherent scattering from the coherent scattering as in [18, 19] and we did not see statistically significant differences in the scattered beam for the 3 different directions of the hydrated sample. The analyzed data of the fraction of coherent and incoherent scattering for the hydrated sample and the sample after drying it in a 100°C oven for 2 hours is shown in figure 4. The scattering of such systems is complex to explain [21] but we did not measure a statistically significant difference between the hydrated and dried powder. However, the sample served the purpose of this test which was simply to attempt to observe a combination of coherent and incoherent scattering while monitoring the $^3$He cell performance and verifying the neutron polarization transport under the conditions of possible experiments.
Conclusion and next steps

In realistic experimental conditions we have verified that the magic PASTIS field system and guide field configuration can perform to desired specifications. The $^3$He lifetime met the desired benchmark of over 100 hours on beam while performing an amount of X-Y-Z field direction changes that one would employ during a measurement. The neutron polarization transport was also verified to be fully adiabatic, again in agreement with the magnetic field calculations, up to the shortest available neutron wavelength of this instrument which was 1.6 Å. The control of the 11 power supplies used to control both the magic PASTIS system and the guide fields functioned as required to enable us to switch between field directions simply and quickly without a loss of $^3$He polarization.

Consequently further practical testing and proof-of-principle work is justified with actual TOF spectroscopy measurements, also with samples of scientific interests. During these tests the magic PASTIS system was craned into the NEAT detector tank (see photo in fig. 5) and subsequently preparations have been underway at HZB to prepare the mechanical systems for installation. Once these systems and the NEAT polarization is installed and tested, further testing and experiments will be conducted using magic-PASTIS on NEAT at HZB.

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REFERENCES


