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Neutron spin manipulation devices using YBCO films

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Abstract. The Meissner effect in a thin-film superconductor can be used to create a sharp boundary between regions of different magnetic field and hence can be used as a component of neutron spin manipulation devices. We have developed two cryogenic neutron spin manipulation devices using single-crystal, high- T_c , YBCO films, which can be cooled without using liquid cryogens and eliminate small angle scattering associated with polycrystalline films.

The devices are a spin flipper and a spin precession device both of which use 350-nm-thick YBCO films covered with gold on a 0.5 mm thick sapphire substrate. The spin flipper consists of one such film mounted on an oxygen-free copper frame and connected to a closed-cycle He refrigerator. The flipper is capable of working with a maximum neutron beam size of 42×42 mm^2 and can be used with both vertical and horizontal guide fields.

The spin precession device was constructed by mounting two of the YBCO films parallel to one another with an H-magnet between them. By changing the current through the H - magnet, the precession of the neutron polarisation between the films can be controlled. Tests at the Low Energy Neutron Source (LENS) show that this device is capable of generating controlled spin precession for a neutron beam up to $20 \times 20 \text{ mm}^2$ in cross section.

1. Introduction

Precise manipulation of the neutron spin is vital in a number of types of neutron scattering experiments [1]. These can be broadly arranged into three categories: (1) magnetic structure investigation either in elastic (for example [2, 3]) or inelastic scattering (for example [4]), (2) incoherent background subtraction for hydrogenous materials [5] and (3) Larmor labelling techniques involving either scattering angle [6, 7] or energy encoding [8]. For all of these applications highly efficient devices are required to manipulate the neutron spin. These rely upon a combination of non-adiabatic transitions and/or precession of the neutron spin in a magnetic field.

The Meissner effect in a superconducting film can be used to provide sharp well defined field boundaries and the use of superconducting tape allows high currents and hence high magnetic fields to be achieved. The Meissner effect in low-temperature niobium foil has been used in a number of devices pioneered by the ILL in France; a white beam spin flipper (Cryoflipper) [9, 10] and a vector polarimeter (Cryopad) [11]. In the former (Cryoflipper) the superconductor is used to provide an abrupt non-adiabatic transition between two separated anti-parallel fields. In Cryopad, the orientation of the neutron polarisation can be placed in any direction parallel to a Nb Meissner screen by the use of rotatable guide fields. This polarisation may be further rotated by a precise magnetic field that is contained between two Nb Meissner screens. Precise control of the precession is only possible by the use of abrupt transitions in the magnetic field provided by

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the superconductor which separates the guide and precession magnetic fields. Using Cryopad, information not accessible by other means can be obtained about the spatial arrangement of the magnetisation vector within a sample. As described by Brown [2], the control of incident beam polarisation and the directional analysis of the scattered neutron polarisation allows the full polarisation tensor to be determined.

In Cryopad the use of superconducting screens effectively creates defined regions for spin precession. In another device called MuPAD [12], designed to achieve the same goals, superconducting screens are not used. Rather the penetration of external fields is prevented by mu-metal shields and a combination of two precession fields orthogonal to each other is used to control the neutron polarisation vector.

While Cryopad performs very well, it requires considerable operational infrastructure and it is not designed for use at pulsed neutron sources. Furthermore, it is more complex than is needed for applications with small neutron scattering angles, such as small angle neutron scattering (SANS) and reflectometry. To address these concerns, we decided to design a simple, compact device that uses high temperature superconductors as Meissner screens. A key component of such a device is the precession region. This paper describes the current status of our design of this component.

2. YBCO material details and small angle scattering

Single crystals of Yttrium Barium Copper Oxide (YBCO) grown on sapphire are now commercially available (Ceraco GmbH, Germany) and can be cooled below their superconducting transition using a closed cycle refrigerator (CCR) with a base temperature of ≈ 10 K. This simplifies the device, lowers the maintenance requirements and cost of operation. As we have previously shown [13] these films are highly transparent to neutrons and are not expected to produce significant small angle neutron scattering (SANS), in contrast to the case of polycrystalline Nb where SANS can occur from grain boundaries.

The penetration of magnetic flux quanta into the superconducting sheet is a significant concern for the operation of a cryoflipper. The critical field of high-T_c materials is anisotropic and various values have been reported in the literature [14, 15, 16], all in the range of $\approx 100-200$ G for films and single crystals of YBCO. The strength of magnetic guide fields is much less than the magnitude of the critical magnetic field, so we do not expect flux penetration problems.

The films used have a high critical temperature (87 K). Each one consists of a $78 \times 100 \times 0.5$ mm³ sapphire substrate with a 40 nm CeO₂ buffer layer onto which is grown a 350 nm thick single-crystal YBCO film, capped with 100 nm of gold.

In order to check the assertion that the films produce negligible SANS, a series of tests were performed using unpolarised neutrons at the LENS [17, 18] SANS instrument. In all cases, no change in scattering was observed from the instrumental background [13]. From these measurements a wavelength independent transmission of 98.4 \pm 0.1 % was calculated over a neutron wavelength region of 4 Å to 14 Å. The cutoff at 4 Å is due to the Be filter on the LENS SANS instrument.

3. Cryogenic system

Both devices presented in this proceedings use the same cryogenic device and electromagnetic guide fields. The later are mounted on either side of a short, rectangular cryostat tail, which contains the YBCO film. The cryostat tail and electromagnets are 200 mm long along the neutron beam. The guide fields can be used in either a horizontal or vertical configuration, both of which produce magnetic fields that are approximately parallel to the YBCO film in the absence of the film. The soft iron pole pieces of each guide field are 52 mm apart. Sapphire windows on either side of the cryostat tail allow for high neutron transmission whilst minimising parasitic scattering and background effects. The housing incorporates a standard commercial



Figure 1. (a) Exploded view schematic of the cryoflipper components showing the electromagnets in the horizontal orientation. (b) Picture detail of the CCR with the YBCO film in an oxygen free copper mount. (c) Schematic of the cryostat tail, showing YBCO film placement and arrangement of the aluminium radiation shields.

closed cycle refrigerator (CCR) (Sumitomo CH-204, USA). The vacuum vessel is fabricated from aluminium to eliminate potential distortions of the magnetic field. Figure 1 shows a schematic and a photograph of the device.

4. Cryogenic spin flipper

The design of the cryoflipper and electromagnets is presented in [13] whilst the efficiency for both pulsed and continuous sources is presented in [19]. The efficiency of the device was determined using a two flipper measurement which allows for decoupling of the individual flipper efficiencies (for example [20]). In all cases the beam size was defined by Cd slits placed close to the cryoflipper.

Flipping efficiencies measured at LENS are shown in Figure 2 for an electromagnet current of 3A with a $42 \times 42 \text{ mm}^2$ beam. This shows a uniform efficiency over a broad neutron wavelength range demonstrating that the device is suitable for white neutron beams. Furthermore the average efficiency is $99.33 \pm 0.25\%$. With optimisation of the electromagnet current the flipper efficiency increases to a maximum of $99.5 \pm 0.3\%$ for a current of 5A. A number of different beam sizes were tested from $10 \times 10 \text{ mm}^2$ to $42 \times 42 \text{ mm}^2$ and no statistically relevant difference

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Figure 2. Wavelength dependence of the extracted cryoflipper efficiency for a $42 \times 42mm^2$ neutron beam obtained on the SESAME instrument at LENS. The dashed line is the average over the wavelength range shown (99.3±0.3%).

was observed.

Measurements were performed with the magnetic field from electromagnets in both the horizontal and vertical directions. As the film is rectangular this places the field along the long or short axis of the film respectively. Mounting the electromagnets such that the field is pointing along the short axis of the film (78 mm) produces a slightly lower efficiency ($\approx 1\%$ lower for a 41 × 41 mm² beamsize) than when the field is along the long (100 mm) axis, indicating that the film size is the principal limiting effect on the device efficiency. It appears likely that larger guide fields and a larger YBCO film could be used to flip the polarisation of even larger cross-section neutron beams if required. The results are reproducible within error from cycle to cycle, including dismantling and reassembly of the device [19].

5. Cryogenic spin precession device

Using the same vacuum vessel and electromagnets a spin precession device was also constructed. This consists of two YBCO films, as discussed in section 2. The YBCO films are parallel to one another, separated by 15mm with an H-magnet between them (Shown in Figure 4(a)). Thin cryogenic mu-metal is used as a magnetic flux return path and ensures that the region between the two YBCO films is magnetically isolated. The pole pieces are wound using YBCO superconducting tape (Superpower, USA). By changing the current through the tape, the precession of neutron polarisation between the parallel YBCO films can be controlled.

In order to optimise the dimensions of the device and gain a better understanding, the whole assembly of YBCO, cryogenic mu-metal and superconducting tape (Superpower, USA) was modelled using commercial finite-element software (Magnet[©], Infolytica, Canada). Shown in figure 3 (a) is the field profile in the y-z plane (the same plane as the YBCO films) midway between the two films. The contours show a highly uniform region between the pole pieces, however the uniformity decreases with increasing beam size. This is more apparent in 3 (b) which shows the modulus of the magnetic field integrated through the device. The simulation shows that the field is well contained by the YBCO and mu-metal pieces. As the field integral along the x-axis varies slightly with position across the area probed by the neutron beam, the total precession angle of the polarisation will depend on position within the beam. The simulation indicates that for an average precession angle of π the precession angle will have a standard deviation of 2.7 ° for a 20×20 mm² beam size and a 4A current at a neutron wavelength of 3.90 Å. For 15×15 mm² and 10×10 mm² beam size the precession angle deviates by 1.6 ° and 0.7 ° respectively.



Figure 3. Simulation result using MagNet[©] software. (a) is a contour and vector plot of the field in the mid-plane (x=0) of the device. (b) shows a magnetic field integral map of the device at 4 A. The field integral within the central region defined by the red box is 17.4 ± 0.28 G.cm. Note z is the vertical direction, x the direction of the neutron beam with y orthogonal to the other two axes.

Simulations were also performed for a rectangular solenoid wound from one layer of the superconducting tape. This option was not chosen for two reasons: the field integral is lower compared to that achieved using the separated pole pieces in the H-magnet configuration and, secondly, most of the superconducting tapes available commercially now contain a certain amount of gadolinium, which greatly reduces the transmission. Neutron transmission measurements were performed on a number of different superconducting tapes, but only one of them was found to have high transmission. However this tape was on a steel backing which cannot be bent with a small radius of curvature.

An exploded view of the final device design is shown in Figure 4 (a) along with the coordinate axes used in this contribution. The whole device is only 15 mm in length along the beam and the separation between the pole pieces, shown in figure 4 (b) is 41 mm. The solenoid has two layers of 5 mm wide superconducting tape with four turns on one layer and five on the other.

The prototype device was measured on the SESAME beam line at LENS. We employed a continuously pumped nuclear spin polarised ³He analyser [21], instead of the supermirror device used to test the flipper. The device was cooled to below T_c of the YBCO films inside a mu-metal box to prevent flux trapping. The procedure for the experiment was to measure the zero-current polarisation ($P_{I=0}$) first and to use this to normalise the polarisation measured with current on (P_I). This omits the polarisation losses from other sources but measures only the dephasing loss from the precession. Flipping was performed by reversing the incident electromagnet, using the first YBCO film as a cryoflipper, as described earlier.

The measurement of $P_I/P_{I=0}$ is shown in Figure 5 for a 20×20 mm² beam for both positive and negative precession fields. Results for positive and negative field agree, indicating that there was very little magnetic flux trapped between the YBCO films. With a 4A current, the



Figure 4. (a) shows an exploded view of the precession device. Also indicated is the coordinate frame used in this communication, where x is the direction of the incident neutron beam. The bottom picture (b) shows the physical precession device with the front YBCO film removed. Note the mu-metal ring and superconducting tape. (Colour version available online)

polarisation returns almost to its full magnitude after a π rotation from which we conclude that the field integral does not vary significantly over the area of the neutron beam. The experiment shows that the mu-metal and YBCO combination provides a good zero field chamber (with current in the device off) implying that these materials may be utilised to provide a zero field region, similar to that of Cryopad and MuPAD. Measurements were performed with a range of beam sizes and the behaviour of the ratio of the polarisation with current on/current off $(P_I/P_{I=0})$ is well described by;

$$P_I/P_{I=0} = (1 - a\lambda)Cos(\sigma\lambda) \tag{1}$$

where the constant *a* is the depolarisation per Å caused by the variation of the field integral over the neutron beam and σ is a constant of proportionality between precession angle and the current in the precession coils. Fitting the data to this function gives good agreement as shown in Figure 5. At 4A the π flip occurs at 3.87 \pm 0.01 Å which is close to the value obtained from simulation (3.90 Å). The measured depolarisation was 1.6%, 0.4% and 0.1% for beam sizes of $20 \times 20 \text{ mm}^2$, $15 \times 15 \text{ mm}^2$ and $10 \times 10 \text{ mm}^2$ respectively. Simulation results gave 0.37%, 0.10% and 0.02% for these beam sizes, somewhat less than we measure. However, because our neutron source produces a pulse width of 600 μ s there is also a spread in values of neutron wavelength for any given time of flight. Correcting for this leads to a predicted depolarisation of 0.65 %, Journal of Physics: Conference Series 528 (2014) 012024





Measured polarisation with different currents (P_I) through coils divided by Figure 5. polarisation with no current (P_{I=0}) for a 20 \times 20 mm² beam size. Points are experimental data and solid lines are fitted curves. Current used is labelled on the top with each current having both positive and negative values as shown by the same colour. Note data is shown from 2.2-12Å, whilst the fits were performed over the regions indicated by the solid lines. These lines when dotted are extrapolated from the fitted region.

0.29 % and 0.19 % for beam sizes of 20×20 mm², 15×15 mm² and 10×10 mm² respectively. This is in good agreement for the 10×10 and 15×15 mm² beam sizes although we measure a significantly higher depolarisation for the $20 \times 20 \text{ mm}^2$ than is predicted. This may be a result of slight offsets in the positioning of the device at the larger beam size, although we have not investigated this point in detail.

The limiting of this device to 4A was due to heating at the superconductor/copper contacts interface. Changing these contacts allows for significantly higher currents to be achieved and will be reported in a later publication. Also, changing the current as a function of time will allow us to achieve the same precession angle for a range of neutron wavelengths.

6. Conclusion

The simple devices shown in this proceedings demonstrate the applicability of high T_c YBCO superconductors to polarised neutron instrumentation. The cryoflipper has a high efficiency and and easy to setup for a white beam. The device is robust, compact and requires very limited operational overhead. The precession device shown here could be mounted close to the sample. Combining two of these precession regions, one before a sample and the other after it would allow a compact vector polarimeter to be constructed. Combined with rotatable guide fields and a zero field sample chamber, a full spherical neutron polarimeter can be constructed. The

total length of the device would be ≈ 0.4 m including the external guide fields.

Further uses of this technology include Wollaston prisms for spin echo scattering angle encoding applications [6, 22, 7] and work is underway to develop such a device.

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