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In situ SEOP polarised ^{3}He neutron spin filter for incident beam polarisation and polarisation analysis on neutron scattering instruments

S. Boag [a,*], E. Babcock [b,c], K.H. Andersen [b], M. Becker [b], T.R. Charlton [a], W.C. Chen [d], R.M. Dalgliesh [a], S.D. Elmore [a], C.D. Frost [a], T.R. Gentile [d], R. Lopez Anton [a,e], S.R. Parnell [f], A.K. Petoukhov [b], M.W.A. Skoda [a], T. Soldner [b]

[a] ISIS, Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, UK
[b] Institut Laue-langevin, 6 rue J. horowitz, BP 156, 38042, Grenoble Cedex 9, France
[c] Jülich Centre for Neutron Science at FRM II, Lichtenbergstrae 1, 85747 Garching, Germany
[d] National Institute of Standards and Technology (NIST), Gaithersburg, MD 20899, USA
[e] ICMA, CSIC-Universidad de Zaragoza, Zaragoza 50009, Spain
[f] Academic Unit of Radiology, University of Sheffield, S10 2JF, UK

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ABSTRACT

We discuss the development and characterisation of a new in situ spin exchange optical pumping (SEOP) based ^{3}He neutron spin filter polarisation device. We present results from a recent test of the prototype system developed with the Institut Laue-Langevin. The polariser was installed on the polarised reflectometer CRISP at ISIS in the analyser position. The ^{3}He was pumped continuously in situ on the beamline. The system also integrated a ^{3}He adiabatic fast passage spin flipper that allowed reversal of the ^{3}He and therefore neutron polarisation state, allowing for measurement of all four polarisation cross-sections. The system was run for a number of days reaching a ^{3}He polarisation of 63%.

1. Introduction

Spin polarised ^{3}He has growing applications in a wide area of neutron science as a neutron polariser or analyser [1–3]. The highly spin dependent absorption cross-section of polarised ^{3}He allows the polarisation of neutrons over a broad wavelength range and although the resultant neutron polarisation is wavelength dependent it can be determined easily through neutron transmission measurements [4]. ^{3}He neutron spin filters currently have a similar performance to supermirror polarisers, they are both broadband and have similar transmissions, but spin filters do not increase beam divergence or gamma background and have a large area/angular acceptance. Furthermore it is possible to reverse the ^{3}He polarisation and therefore resulting neutron polarisation through the use of a swept RF field using adiabatic fast passage (AFP) [5–7], resulting in a combined flipper and polariser in one device.

In most current applications the ^{3}He cell is polarised off line and transferred to an instrument. The ^{3}He polarisation will decay over time and the resulting neutron transmission and polarisation will also decrease, which needs to be corrected for in the data. Previous tests [7] have shown that a continuously polarising spin exchange optical pumping (SEOP) system can maintain a constant polarisation for the duration of an experiment, thereby removing the need for corrections and limiting the need to regularly change the spin filter cell or polarised gas and also improving the time averaged figure of merit. However, recent experiments [2,8] have shown a potential depolarisation during in situ SEOP in the case where a high neutron flux ($>1\times10^8$ cm^{-2} s^{-1}) is incident on the spin filter cell.

Here we report on the development and characterisation of an in situ SEOP polariser that will maintain high ^{3}He polarisation levels in large diameter ($D>8$ cm) neutron spin filter cells throughout the duration of an experiment. We also report briefly on the use of the polariser in the investigation of the high neutron flux effect on the SEOP process and describe an experiment where the polariser was installed in the analyser position of a polarised neutron reflectometer.

2. ^{3}He in situ polariser design

2.1. SEOP magic box

The main magnetic holding field was produced from a new magneto-static cavity based on the 'magic box' design from the ILL [9]. This new design 'magic box,' as pictured in Fig. 1, has

* Corresponding author. Tel.: +44 123 544 5206; fax: +44 123 544 5720.
E-mail address: s.boag@rl.ac.uk (S. Boag).

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dimensions of 200 mm width, 600 mm height and 700 mm length and features the magnetic holding field B_0 along the long (600 mm) axis. It is constructed from five 600 mm yokes of μ-metal, with uniform windings of copper wire on each side and μ-metal caps on the top and bottom. The large size allows space for gold mirrors that can be used to propagate the light along the field axis for the optical pumping of the cell, thereby removing unnecessary material from the path of the neutron beam. The magnetic field is of high homogeneity and determined through observation of the relaxation rate (T_1) of a ^{3}He cell to have a gradient of $\sim 4 \times 10^{-4}\,\mathrm{cm}^{-1}$ over the volume of the cell [10]. The box also contains a volume RF coil with field (B_1) orthogonal to B_0 (Fig. 1) which is used for AFP reversal of the ^{3}He spin state [5].

The cell was heated to suitable temperatures of 170−220 °C using a forced air oven. The main body of the oven was constructed from calcium silicate insulation with double silicon windows 0.7 mm thick, located at the front and rear, reducing neutron scattering or absorption. Similarly the top and bottom of the oven contained Borofloat glass windows, allowing high transmission of the optical pumping light into the oven. The oven was heated using on-site compressed air flowing through a 1.2 kW air process heater and controlled and monitored using a resistance temperature device connected to a solid state temperature controller.

2.2. Optical pumping lasers

The optical pumping setup used was based on two high power frequency narrowed diode array bars (FNDAB) spectrally narrowed using a system previously employed in the laboratory [11]. Two 100 W actively cooled diodes were narrowed in an external cavity, each providing approximately 50 W of light with a bandwidth of <80 GHz in a collimated beam of up to 80 mm × 100 mm incident on the cell.

Fig. 2 shows a single modified FNDAB used for optical pumping. The primary difference between this design and that of Babcock et al. [11] is the inclusion of a polarised beam splitter cube within the external cavity [12]. The principle of operation is similar, the individual emitters from the diode array bar are imaged onto the grating and the first order diffraction is then fed back to the diode, allowing the output wavelength to be adjusted and narrowed. However, the polarising beam splitter allows the majority of the power to be output from the cube itself, rather than relying on the zero order diffraction from the grating. This approach limits the amount of optical power that is incident on the grating (thus reducing thermal distortion and stress) as only a small amount of light, with the proper polarisation for efficient first order diffraction, is incident on the grating. This has the advantage of decreasing the overall footprint of the laser, whilst allowing the wavelength to be adjusted without affecting the output position.

Further modifications to this design were in the output section of the laser. Due to space constraints and the large size of the cells used, standard large diameter focusing mirrors were used to expand the beam. These could not only accommodate a large collimated beam, but also allowed the beam to be steered onto the final mirror. The final mirrors for each laser were located within the magic box either side of the oven (Fig. 1). Each mirror was fixed at 45°, meaning that the light could travel through the cell parallel to the field axis and avoid effects of skew optical pumping [13].

2.3. Diagnostic equipment

In order to fully assess the performance of the polariser a number of diagnostic tools were installed. The first of these was a simple low field NMR spectrometer [14] that could be used to monitor the relative ^{3}He polarisation over time. Other diagnostic measurements were based on the polarisation Faraday rotation of a longitudinal probe beam through the optical pumping cell and were used to determine the alkali metal number density, polarisation and relaxation rate [15]. Knowledge of these values is essential when assessing the performance of the polariser, particularly during the high neutron flux experiment.

For these measurements the relative alkali metal polarisation was monitored through the Faraday rotation of a probe laser tuned near the Rb D2 resonance at 780 nm. From this it was possible to determine the alkali metal density through calibration of the received detector signal to the known rotation of a $\lambda/2$ waveplate. The alkali metal polarisation was determined through EPR measurements [16], where an RF source (B_{RF}), located along side the cell, was swept over the $I = \frac{3}{2}$ electron paramagnetic resonances at 7 MHz/mT. The resulting dips in the Faraday rotation signal as the RF became resonant with a particular m_f sublevel are recorded and the areas of a particular sublevel are then proportional to its population, so the absolute polarisation is then related to the ratio of these sublevels.

The alkali metal relaxation was measured using the 'relaxation in the dark' method [15]. By chopping the pump laser when running at low power (i.e. <10 W) and thus low alkali metal polarisation the resulting signal gives an exponential decay which is the alkali metal electron relaxation rate multiplied by a factor, known as the slowing down factor. This factor is from the coupling of the nuclear polarisation to the electronic polarisation, resulting in an effective slowing of the observed electron relaxation rates, it can be calculated for the various compositions of alkali metals including mixtures used for hybrid SEOP [17].

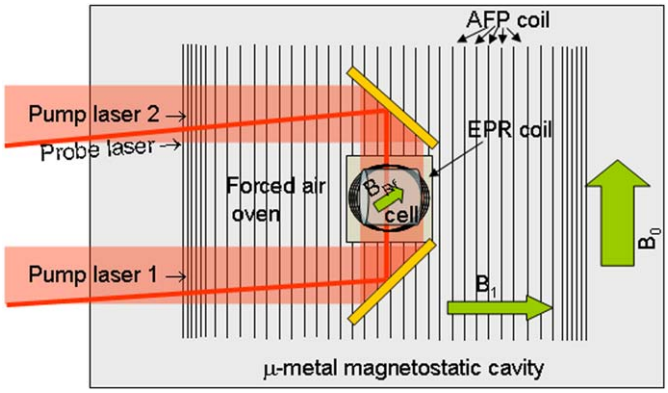

Fig. 1. Diagram of the in situ SEOP apparatus, in contrast to other in situ polarisers with μ-metal shielding, this configuration allows the laser access to be perpendicular to the neutrons, minimising the equipment such as laser mirrors in the neutron beam.

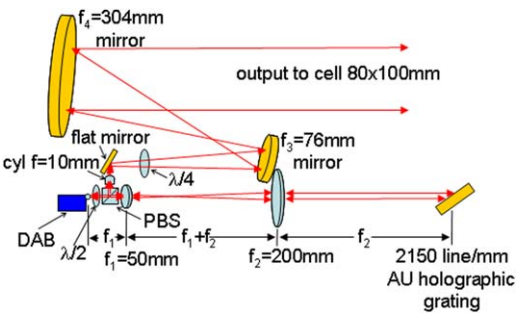

Fig. 2. Schematic of lasers used for this experiment.