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Polarized ^{3}He neutron spin filter program at the JCNS

E. Babcock *, A. Ioffe

Jülich Centre for Neutron Science, Institut für Festkörperforshung, Forschungszentrum Jülich GmbH, Lichtenberg Str. 1, Garching 85747, Germany

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ABSTRACT

Polarized neutron instruments will occupy about 80% of the Jülich Centre for Neutron Science (JCNS) instrument park. A successful polarized ^{3}He program will be integral to many of these instruments. We have been focusing the developments on spin-exchange optical pumping (SEOP) to polarize the ^{3}He gas in situ. Where possible, in situ polarization using the SEOP method will provide higher time averaged performance of the instruments. Further this allows a custom-built and independent source of polarized ^{3}He to be developed optimized for each instruments demands. In this paper we will: present an argument for the advantages of in situ polarization; describe an in situ polarizer we have constructed, and initial tests of its performance; describe testing of polarization analysis for small angle neutron scattering on biological samples, and our plans for an in situ polarizer for this application.

1. Introduction

Much work has been done to optimize polarized ^{3}He for use as a neutron spin filter (NSF). Routine experiments using ^{3}He NSF are conducted at many neutron research centers worldwide. These experiments include polarized neutron diffraction, polarized neutron reflectometry, polarized small angle neutron scattering (SANS), and fundamental particle physics [1–5]. Further, many additional neutron research centers have programs for developing the methods for ^{3}He NSF to be used at their facilities. The polarized ^{3}He program at the JCNS, started at the Forschungszentrum Jülich in 2002 [6,7], is focused on creating individual solutions optimized for each instrument application using the SEOP method [8]. In situ polarization is chosen because of the potential to improve time averaged performance via continuous polarization of the gas in the neutron beam on the instrument [9]. Continuous polarization can also help counteract short ^{3}He polarization lifetimes often experienced in neutron experiments because of non-ideal magnetic field conditions caused by the magnetic equipment used for such experiments.

Initial applications of ^{3}He NSF at the JCNS will include large area polarization analysis for reflectometry and SANS because ^{3}He NSFs do not cause angular distortion of small angle scattered beams, an important feature for MARIA (magnetism reflectometer) and KWS (SANS) ([10,11]. The prototype for the reflectometry application has been assembled and tested [9]. Initial testing using offline SEOP polarized ^{3}He gas has also been conducted on KWS-2 as a feasibility test for using polarization analysis to separate contributions from incoherent scattering. An in situ polarizer concept for the SANS application, which will have a very different geometry than that of the reflectometry polarizer, has also been developed and prototyping is underway. Knowledge developed from these devices will then be applied for incident beam polarization on TOPAS [12]. Subsequent plans will develop ^{3}He NSF for analysis over large solid angle detector banks on instruments such as TOPAS, where solid state analyzers become economically unfeasible, especially for neutrons of high incident energies. For this case, however, in situ polarization may not be feasible and we are considering options that will allow us to polarize large volumes of ^{3}He gas, around 50 bar liters per day, which will be required for full angular coverage of this instrument.

2. Advantages of in situ polarization

The polarization of ^{3}He gas is normally performed in the highly controlled conditions of a specialized laboratory since high power class IV lasers, highly uniform magnetic fields, and isolation from electronic and magnetic interference are required. But ^{3}He polarization is a dynamic process involving polarization and T_1 decay of nuclear spin. Thus once the ^{3}He is polarized and in an appropriate container without continual polarization from optical pumping, it begins to undergo T_1 relaxation to zero polarization. This relaxation time is limited by three terms and can be written as

$$\frac{1}{T_1} = \frac{p_{He}}{800} + \frac{1}{T_{wall}} + \frac{7000}{p_{He}} \frac{(\Delta B_x^2 + \Delta B_y^2)}{B_0^2} \quad (1)$$

The first term is from the dipole–dipole interactions of the ^{3}He spins with each other and is a function of the gas pressure [13], p_{He}, in bar at 25 °C, the second term is the relaxation in h^{-1} caused by

* Corresponding author.
E-mail address: e.babcock@fz-juelich.de (E. Babcock).

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interaction with the container walls. The last term is relaxation due to gas motion through magnetic field gradients where 7000 is the diffusion constant in units of $\mathrm{bar}^{-1}\,\mathrm{h}^{-1}$ and ΔB_x and ΔB_y are the orthogonal magnetic field gradients of B_0, the magnetic holding field [14]. Since the first term is proportional to pressure and last term is inversely proportional to pressure p_{He} can be seen as an optimization parameter in special instances, where magnetic field gradients limit the relaxation times.

Much work has been done to understand and minimize the relaxation in the middle term, relaxation to collisions with cell walls. This work has explored the influence of cell materials, wall coatings, magnetic impurities in the container material, and orientational dependance of the measured relaxation rates of the cells with respect to the applied magnetic field [15–17]. Further, most labs using ^{3}He NSF have done significant development on magnet systems to minimize the effects of the last term. In practice, on-instrument T_1 lifetimes of 100–300 h are the achievable goal in neutron experiments using ^{3}He NSF.

Because of these relaxation processes we must consider how to best utilize the ^{3}He polarization over time. For qualitative arguments will assume a time-integrated quality factor Q

$$Q = \int_{t=0}^{t} P_a^2 T_a \, dt \tag{2}$$

Here P_a is the neutron polarization for an unpolarized beam or the analyzing efficiency of an NSF, and T_a is the neutron transmission of the unpolarized neutron beam. These are both functions of the number density of the ^{3}He in the cell, the cell length, the neutron wavelength, and P_{He}, the ^{3}He polarization. The quantity $P_a^2T_a$ is an often cited quality factor for optimization of polarized ^{3}He NSF, while $P_a^2T_a$ may not be the optimal quality factor for all cases [18,5], for high degrees of neutron polarization assuming counting statistics, the obtainable quality factor will be largely dependent on T_a because P_a is a hyperbolic tangent of P_{He}, whereas T_a has an exponential dependence on P_{He} and one normally operates in the regime where P_a is not varying as rapidly with time as T_a. Thus our time-integrated quality factor arguments presented will qualitatively have very similar trends as a function of P_{He} regardless of the quality factor chosen, especially for the limit of $P_a \to 1$.

To take advantage of the full potential of a ^{3}He NSF one must actively counteract the ^{3}He T_1 decay trough periodic refreshing of the polarized gas or in situ polarization. Commonly when the ^{3}He is polarized either with SEOP or metastability exchange optical pumping method (MEOP) [19] offline and then transported to the location of use, depending on the in situ ^{3}He relaxation time, the cells are exchanged every one to two days, with calibration measurements of the instrument necessary for each cell, or cell filling, to correctly normalize to the time dependence of P_{He} [20,21]. Also refreshing of the polarized gas periodically in a pulsed mode has been proposed to maintain polarizations closer to those achieved in laboratory conditions in a pseudo-steady state. However, the only way to obtain the maximum performance is to develop systems capable of polarizing the ^{3}He continuously on the instrument and maintain it at levels as close as possible to the maximum.

As stated earlier, we simply assume that $P_a^2T_a$ should be optimized to obtain good performance with a ^{3}He spin filter cell as an analyzer. Conceptually this quantity is related to the fraction of neutrons used to obtain counting statistics in the limit of high P_a. For the typical values of P_{He} obtainable of 70–80%, the cell opacity, Θ, or the product of the cell length in cm, p_{He} in bar at 25 °C, and λ the neutron wavelength in Å,is about 28 for maximum $P_a^2T_a$. The cell transmission, $T_a^{\pm}$, for a $\pm$ polarized incident beam is

$$T_a^{\pm} = T_e e^{-(1 \mp P_{He})\Theta\lambda\sigma} \tag{3}$$

where T_e is the empty cell transmission and σ is neutron absorption cross-section of 0.0732 $\mathrm{bar}^{-1}\mathrm{Å}^{-1}\,\mathrm{cm}^{-1}$ (at 25 °C). For this opacity with P_{He}=80%, and a typical value of empty cell transmission of 88%, the flux is reduced to 58% of a fully polarized beam or about 29% of an unpolarized beam after transmission through the cell at the optimal neutron wavelengths. P_a is

$$P_a = \tanh(P_{He}\Theta\lambda\sigma) \tag{4}$$

where P_a=0.93 for the conditions stated above. If one were to chose a higher $\Theta\lambda$ product one would have a higher P_a and lower T_a but the following graphs would look qualitatively nearly identical in the relations between the curves for a given λ in the $P_a \to 1$ limit, however, the absolute values for quality would be different. Also note that our estimates do not account for non-ideal transmission and polarization of the incident beam polarizer which would lower the time integrated Q depending on its parameters.

Fig. 1 shows how a ^{3}He spin filter polarized continuously would perform with respect to the same cell and same maximum P_{He} but with time decay. Q normalized to the incident unpolarized flux n_0 as defined in Eq. (2) is plotted on the left axis, where Q/n_0=1 would be the time-integrated quality of the instrument recorded in 1 h without incident beam polarization and polarization analysis. One can see that to obtain a quality factor of $10n_0$, one must count for about 38 h with a constant P_{He} of 80% and 50 h for time decaying P_{He} starting at 80% with a 100 h T_1 that is refreshed daily. This is about the same time required for a cell polarized constantly at 70%. A cell that is not changed would require nearly double the counting time, about 70 h, to obtain the same quality as the cell continuously polarized to 80%.

Also shown in Fig. 1 is a cell with a 400 h T_1, a value similar to what we have obtained in tests on a SANS instrument presented in Section 4. Here the difference in time integrated quality becomes less over time scales short compared to T_1. As a rule of thumb, one can use a ^{3}He NSF cell for approximately one day per 100 h of on-beam T_1. In this case one obtains $Q/n_0 \simeq 3/4$ of that obtained with constant polarization. Further one could chose to refresh the polarization more often to approach the levels obtained with constant polarization if the resources are available. However,

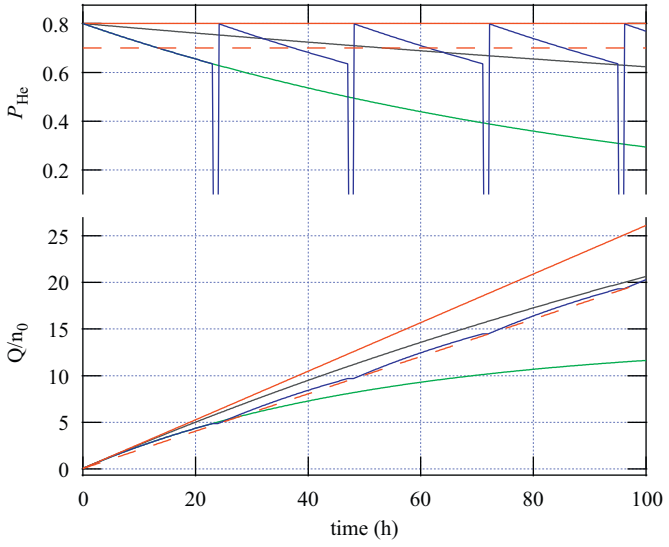

Fig. 1. Graph of quality vs time with corresponding ^{3}He polarization above for several cases. The solid lines assume a maximum (initial) achievable ^{3}He polarization of 80%, the value we have obtained in our tests. The red line is constant polarization, the blue line is time decaying polarization with a 100 h time constant that is refreshed every 24 h assuming a 1 h pause in data taking to perform calibrations and change the cell or polarized gas, and the green/grey lines are a cell decaying with a 100/400 h time constant but not changed. The dashed red line is for constant ^{3}He polarization of 70%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)