Nuclear Inst. and Methods in Physics Research, A 895 (2018) 19–28

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Measurement of the absolute neutron beam polarization from a supermirror polarizer and the absolute efficiency of a neutron spin rotator for the NPDGamma experiment using a polarized ^{3}He neutron spin-filter

M.M. Musgrave [a,b,*], S. Baeßler [c,d], S. Balascuta [e], L. Barrón-Palos [f], D. Blyth [e], J.D. Bowman [d], T.E. Chupp [g], V. Cianciolo [d], C. Crawford [h], K. Craycraft [a,h], N. Fomin [a], J. Fry [i,c], M. Gericke [j], R.C. Gillis [d,i], K. Grammer [a,d], G.L. Greene [a,d], J. Hamblen [k], C. Hayes [a], P. Huffman [l], C. Jiang [d], S. Kucuker [a], M. McCrea [j], P.E. Mueller [d], S.I. Penttilä [d], W.M. Snow [i], E. Tang [h], Z. Tang [i,m], X. Tong [a,d], W.S. Wilburn [m]

[a] *University of Tennessee, Knoxville, TN 37996, USA*
[b] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[c] *University of Virginia, Charlottesville, VA 22904, USA*
[d] *Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[e] *Arizona State University, Tempe, AZ 85287, USA*
[f] *Instituto de Física, Universidad Nacional Autónomaónoma de México, Apartado Postal 20-364 01000, Mexico*
[g] *University of Michigan, Ann Arbor, MI 48104, USA*
[h] *University of Kentucky, Lexington, Kentucky 40506, USA*
[i] *Indiana University, Bloomington, IN 47405, USA*
[j] *University of Manitoba, Winnipeg, MB, Canada R3T 2N2*
[k] *University of Tennessee, Chattanooga, TN 37403, USA*
[l] *North Carolina State University, Raleigh, NC 27695,*
[m] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

ARTICLE INFO

Keywords:
Polarized neutrons
Polarized ^{3}He
Polarimetry
Spin-exchange optical pumping
NPDGamma

ABSTRACT

Accurately measuring the neutron beam polarization of a high flux, large area neutron beam is necessary for many neutron physics experiments. The Fundamental Neutron Physics Beamline (FnPB) at the Spallation Neutron Source (SNS) is a pulsed neutron beam that was polarized with a supermirror polarizer for the NPDGamma experiment. The polarized neutron beam had a flux of $\sim 10^9$ neutrons per second per cm^2 and a cross sectional area of 10×12 cm^2. The polarization of this neutron beam and the efficiency of a RF neutron spin rotator installed downstream on this beam were measured by neutron transmission through a polarized ^{3}He neutron spin-filter. The pulsed nature of the SNS enabled us to employ an absolute measurement technique for both quantities which does not depend on accurate knowledge of the phase space of the neutron beam or the ^{3}He polarization in the spin filter and is therefore of interest for any experiments on slow neutron beams from pulsed neutron sources which require knowledge of the absolute value of the neutron polarization. The polarization and spin-reversal efficiency measured in this work were done for the NPDGamma experiment, which measures the parity violating γ-ray angular distribution asymmetry with respect to the neutron spin direction in the capture of polarized neutrons on protons. The experimental technique, results, systematic effects, and applications to neutron capture targets are discussed.

1. Introduction

Experiments in fundamental neutron physics often search for physical effects which are so small that one must use intense neutron beams with the largest cross sectional area allowed by the facility to see them in a reasonable running time. Many of these experiments also require the use of polarized neutrons to search for spin-dependent effects. The measurement of both the absolute neutron polarization

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[*] Corresponding author at: Massachusetts Institute of Technology, Cambridge, MA 02139, USA.
E-mail addresses: musgrave@mit.edu, mmusgrav@vols.utk.edu (M.M. Musgrave).

https://doi.org/10.1016/j.nima.2018.03.055
Received 9 January 2018; Received in revised form 15 March 2018; Accepted 16 March 2018

and the efficiency of spin reversal for such large cross sectional area polarized slow neutron beams therefore must be conducted with sufficient accuracy to isolate the physical effects of interest. The subclass of experiments which motivated our work are searches for the very small spin-dependent asymmetries in hadronic parity violation. For most current parity violation experiments in this field the uncertainty is strongly limited by neutron counting statistics: in fact many of the effects predicted by theory have not yet been resolved experimentally. It is therefore essential that the polarizer used in these experiments possess a high efficiency, can accommodate a large neutron beam cross sectional area, and operate continuously over long time periods of several months. At the moment there are two practical choices for neutron polarizer technology for this work: supermirror neutron polarizers and neutron spin filters based on either polarized ^{3}He or polarized protons [1].

The differences of certain properties of these polarizers such as the radiation backgrounds, time stability, ability to reverse the beam polarization, and phase space uniformity of the beam polarization are obviously very important considerations for experiments. An example of this is the NPDGamma experiment, which aims to measure the parity-violating γ-ray angular distribution asymmetry from polarized neutron capture on protons to an uncertainty of 1×10^{-8}. The γ-ray asymmetry is estimated to be $\sim 5 \times 10^{-8}$ or less [2,3], so the main challenge of the polarizer is to enable the high statistical precision since neutron polarization measurements better than 20% are readily achievable. A polarized ^{3}He spin filter was successfully used as a neutron polarizer for the initial phase of the NPDGamma experiment at LANSCE [4–7]. The spatial uniformity of the polarized neutron beam phase space produced by such a spin filter, the ability to easily flip the polarization of the ^{3}He in the spin filter by NMR, and the absence of γ-rays from neutron capture in ^{3}He all contributed to this choice. However, it was discovered that the high instantaneous neutron flux in the polarizer interfered with the long-term stability of the ^{3}He polarization produced in the spin-exchange optical pumping process, which occurred inside the neutron beam region [8]. In addition, it was observed that potential sources of systematic errors in the experimental apparatus were very well suppressed by downstream spin reversal. For the installation of the NPDGamma experiment at the FnPB at the SNS, whose much larger flux would have made this stability problem worse, a multichannel supermirror polarizer was used instead. This polarizer operates with a higher efficiency than present ^{3}He neutron spin filters and has a polarized neutron flux of $\sim 10^9$ neutrons per second per cm^2 [9,10]. It is the measurement of the polarization from this device that is described in this paper.

The neutron polarization was determined from transmission measurements through a polarized ^{3}He neutron spin filter. A comprehensive review of the science behind optically pumped ^{3}He including its previous uses as a neutron spin filter can be found in [11]. This method takes advantage of the spin dependence in the capture cross section of neutrons on polarized ^{3}He and of the pulsed nature of the neutron beam at the SNS, which allows the neutron wavelength to be determined from time-of-flight analysis. The pulsed neutron beam is also essential to our method of reversing the neutron polarization with high efficiency, and it allows the neutron polarization and spin-reversal efficiency to be determined independent of knowledge of the ^{3}He polarization [12]. To explain this, we review the physics of the operation of ^{3}He neutron spin filters below.

2. ^{3}He polarimetry principles

Neutrons readily capture on ^{3}He via the reaction $^3He + n \rightarrow p + ^3H$. The capture cross section is proportional to the neutron wavelength λ such that the transmission of N$_0$ neutrons through an unpolarized sample of ^{3}He is

$$T_0 = N_0 e^{-nl\sigma_0 \frac{\lambda}{\lambda_0}}, \tag{1}$$

where n is the atom density of ^{3}He, l is the length of the ^{3}He spin filter, and $\sigma_0 = 5316$ b is the capture cross-section of $\lambda_0 = 1.798$ Å neutrons [13]. The capture cross section is spin dependent such that capture only occurs in the singlet state, i.e. neutron and ^{3}He spins are anti-aligned, and experimental measurements of capture into the triplet state are consistent with zero [14]. The transmission of spin up (↑) and spin down (↓) neutrons through a polarized ^{3}He spin filter with polarization P_{He} is

$$T_\uparrow = N_{\uparrow,0} e^{-nl\sigma_0 \frac{\lambda}{\lambda_0}(1-P_{He})} \tag{2}$$

$$T_\downarrow = N_{\downarrow,0} e^{-nl\sigma_0 \frac{\lambda}{\lambda_0}(1+P_{He})}. \tag{3}$$

For an unpolarized neutron beam, $N_{\uparrow,0} = N_{\downarrow,0} = \frac{1}{2}N_0$, and the total transmission of an unpolarized neutron beam through polarized ^{3}He is the sum over both neutron spin states

$$T = T_\uparrow + T_\downarrow = N_0 e^{-nl\sigma_0 \frac{\lambda}{\lambda_0}} \cosh(nl\sigma_0 \frac{\lambda}{\lambda_0} P_{He}). \tag{4}$$

The transmission of a polarized neutron beam with a polarization of $P_n(\lambda)$ through polarized ^{3}He can be calculated for each neutron spin state from Eqs. (2) & (3) by making the neutron polarization implicit in the initial transmission coefficients, so that

$$T_\uparrow = N_0 \frac{1+P_n}{2} e^{-nl\sigma_0 \frac{\lambda}{\lambda_0}(1-P_{He})}$$
$$T_\downarrow = N_0 \frac{1-P_n}{2} e^{-nl\sigma_0 \frac{\lambda}{\lambda_0}(1+P_{He})}.$$

The total transmission of a polarized neutron beam through polarized ^{3}He is the sum of the transmission of these two spin states:

$$T = N_0 e^{-nl\sigma_0 \frac{\lambda}{\lambda_0}} \cosh(nl\sigma_0 \frac{\lambda}{\lambda_0} P_{He}) \left[1 + P_n \tanh(nl\sigma_0 \frac{\lambda}{\lambda_0} P_{He})\right]. \tag{5}$$

If $P_{He} = 0$, the transmission through unpolarized ^{3}He is found to be independent of the neutron polarization and Eq. (5) reduces to Eq. (1).

2.1. Spin-rotator efficiency

On the FnPB the neutron spins are rotated by π radians (spin-rotated) with an efficiency $0 \leq \epsilon_{sr} \leq 1$ on a pulse-by-pulse basis. We use the phrase "spin-rotated" rather than "spin-flipped" to distinguish between two different modes of spin reversal: one in which the kinetic energy of the polarized neutron beam is unchanged (spin-rotated) and the other to denote the case when the kinetic energy of the neutron beam is changed (spin-flipped). It was important for us to employ the former type of spin reversal in NPDGamma to avoid potential sources of systematic error. When the neutron spins are reversed, the magnitude of the neutron polarization becomes $(1 - 2\epsilon_{sr})P_n$. The transmission through polarized ^{3}He with the spin-reversed neutrons can be determined similar to Eq. (5) by using the reversed polarization value $(1 - 2\epsilon_{sr})P_n$ such that

$$T_{sr} = N_0 e^{-nl\sigma_0 \frac{\lambda}{\lambda_0}} \cosh(nl\sigma_0 \frac{\lambda}{\lambda_0} P_{He}) \left[1 + (1 - 2\epsilon_{sr})P_n \tanh(nl\sigma_0 \frac{\lambda}{\lambda_0} P_{He})\right]. \tag{6}$$

The spin-reversal efficiency can be calculated from four transmission measurements: two measured with the initial neutron spin state for both ^{3}He polarization states, T and T^{afp}, and another two measured with the neutrons spin-reversed, T_{sr} and T_{sr}^{afp}. T^{afp} and T_{sr}^{afp} are transmission measurements where the ^{3}He polarization was reversed by adiabatic fast passage (AFP). How AFP spin reversal is implemented and the AFP efficiency is accounted for are discussed in Section 4. Two ratios are determined from these transmission measurements:

$$\frac{T^{afp} - T}{T^{afp} + T} = P_n \tanh\left(nl\sigma_0 \frac{\lambda}{\lambda_0} P_{He}\right)$$
$$\frac{T_{sr}^{afp} - T_{sr}}{T_{sr}^{afp} + T_{sr}} = (1 - 2\epsilon_{sr})P_n \tanh\left(nl\sigma_0 \frac{\lambda}{\lambda_0} P_{He}\right).$$