NEUTRON POLARIZERS BASED ON POLARIZED ^3He :
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With the support of a 1996 grant from the Office of Energy Research (DE-FG02-96ER45587), we have developed and tested neutron spin-filters based on the large spin dependence of the cross section for neutron capture by ^3He . In addition, we have gone beyond the originally-stated goals of the project to perform the first demonstration of ^3He -based polarization analysis in small angle neutron scattering (SANS). ^3He spin-filters can yield broadband neutron polarizers and analyzers that can be used for cold, thermal, and epithermal neutrons. Such polarizers promise to make possible new classes of neutron scattering experiments, and are particularly relevant to the needs of the Spallation Neutron Source.

As of this writing, our prototype polarizers have achieved up to 89% neutron polarization with 9% transmission of the incident flux, for 5 cm diameter neutron beams. We have produced the high density of polarized ^3He gas (10^{19} - 10^{20} cm $^{-3}$) required for an effective neutron polarizer using two optical pumping methods: spin-exchange [CHL95, LAR91, CHU87, BCV60], which is performed directly at high pressure (2-10 bar), and metastability-exchange [GEM93, CSW63], in which the gas is polarized at low pressure (~1 mbar) and then compressed [BEC94]. We have tested neutron spin filters based on the spin-exchange method with cold neutrons at the NCNR [JON] and with thermal and epithermal neutrons at LANL [SNO, RIC]. Using a diaphragm compressor developed at the NCNR, we have also tested spin-filters based on the metastability-exchange method with cold neutrons at the NCNR [JON]. We have also produced polarized ^3He gas with a piston compressor at Indiana University [KBF98]; this apparatus is similar to the highly successful Mainz design that is being employed at the Institut Laue-Langevin in Grenoble, France [HEI, KUL98, HEI98, SUR97]. Finally, we have well-developed plans to continue this work and perform several neutron scattering experiments using neutron polarizers and analyzers based on polarized ^3He .

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1. Spin Exchange Neutron Polarizers

The apparatus for the spin-exchange technique is shown schematically in Fig. 1. Cell construction is perhaps the most technically difficult part of producing these polarizers. To date we have constructed most of our cells using either of two aluminosilicate glasses, GE180 or Corning 1720. Both are known to have low ^3He permeability and resistance to chemical damage from alkali metals, but they are difficult glasses with which to work. The cells are cleaned, evacuated, baked, and then filled with rubidium, nitrogen, and ^3He gas and sealed off at just below atmospheric pressure. To achieve room temperature pressures above one bar, the cells are cooled with liquid nitrogen or liquid helium before filling. The filled cell is heated to 175 C. using hot air to obtain the required density of rubidium and illuminated by 15-30 W of light from a diode laser array. The ^3He polarization is monitored using NMR.

The spin-exchange method is most efficient for cell pressures of several bar or two reasons: First, for the same total amount of ^3He gas, the amount of rubidium vapor that must be kept highly polarized is minimized for higher ^3He pressure. Second, the absorption of the relatively broadband diode laser light (typically 1000 GHz) is increased due to pressure broadening of the rubidium atomic transition. However, the need for high pressures is in direct conflict with the mechanical stability of large cells. Consequently, the pressure of spin-exchange cells must be chosen to strike a balance between optical pumping efficiency and mechanical stability. The shape of these cells must also satisfy a compromise between structurally stable curved windows and a uniform path length of polarized gas. We have typically chosen pressures of 3-4 bar, and use short, rounded cylinders.

Using the spin-exchange method, we have obtained ^3He polarization approaching 50% in cells up to 6 cm in diameter with a relaxation time of over 100 hours. We have recently constructed a 10 cm diameter cell that withstood 5.4 bar of internal pressure (about 5 bar is required for efficient optical pumping of a heated spin-exchange cell).

2. Metastability Exchange Neutron Polarizers

Figure 2 shows a schematic diagram of the systems at NIST and Indiana which use the metastable method. A polarized ^3He compression system for filling of cells with polarized ^3He gas for neutron polarizers has been constructed at Indiana University and is now in operation. The polarized gas compressor is located in a large-volume (8 m^3) coil system, which produces a 20 G field with a transverse gradients less than 10^{-3} G/cm . The optical pumping takes place in four 1 m long cylindrical cells, giving a total optical pumping volume of about four liters. The cells are interconnected so that we can install the optics needed to optically pump all four volumes simultaneously (so far in our work we have only optically pumped gas in one cell). The compression system is constructed out of pyrex glass and aluminum. It consists of a two-stage piston compressor with an intermediate storage volume and air-actuated nonmagnetic valves and pistons. The pistons slide on the inside surface of honed aluminum cylinders on Viton quad rings lubricated with a low vapor pressure fluorinated grease. Similar design on a smaller scale applies to the valves. The compression system achieves a compression ratio of 6000 starting from 1.3 mbar. A LABVIEW program controls the air-actuated compression and recirculation system. The 160 cm^3 cylindrical storage cell made from Corning 7056 glass is detachable from the system to allow eventual transport to a scattering instrument. Glass flow lines connect both the target cell and the intermediate volume back to the optical pumping volume so that the ^3He polarization can be measured optically at each step of the compression process.

Fig. 1. Schematic diagram of the spin-exchange apparatus. The spin filter cell is heated to 175° C. using hot air to obtain the required density of rubidium and illuminated by 15-30 W of light from a diode laser array. A uniform magnetic field is provided by a pair of Helmholtz coils.

Fig. 2. Schematic diagram of the metastable apparatus. For the low pressure part of the apparatus we show the Nd:LMA laser, circular polarizer, RF discharge antenna (gray), and the optical polarimeter used to measure the ^3He polarization. The polarized gas is compressed from a pressure in the optical pumping cell of ~ 1 mbar up to several bar in the high pressure cell.

The device now compresses gas from 1.3 mbar pressure at 35% polarization in the optical pumping cell to 1 bar pressure at 20% polarization into the target cell in 30 minutes. This represents a production rate of polarized gas of 1 bar-l in 8 hours. The fractional loss of polarization in the two compression stages is comparable. When we are able to raise the polarization by a factor of two, as the Mainz experience proves is possible, then the polarization at high pressure will scale to 40% in the current version of the apparatus, which is sufficient for some neutron polarization applications. With a high pressure cell of sufficiently long relaxation time, we would be capable of filling the target cell to about 9 bar. We have concentrated our efforts to this date on reducing the polarization losses in the compression system by a judicious choice of valve timing in the compressor operation and have begun to address the question of the lower-than-expected optical pumping cell polarization, which we expect to be associated with the discharge. We fully expect that the solution to this problem will not require any fundamental reconstruction of the apparatus.

At the NCNR we have developed a modified commercial diaphragm pump to compress polarized gas. This device satisfies the foremost criterion to be successful: reasonably high preservation of the polarization. In recirculation mode, we have found that the ratio of the polarization obtained in the storage cell to that obtained in the optical pumping cell can exceed 0.7. We have obtained 30-50% ^3He polarization with this apparatus at a typical storage cell pressure of 0.8 bar. Cells constructed for the metastable method presently have relaxation times of 25-50 hours.

The primary limit on the polarization was the relatively high gas pressure of about 3 mbar in the optical pumping cell. This pressure is increased further when the compressor is operated at the relatively high flow rates for which high preservation of polarization is obtained. In addition the high flow rates allow less time for the gas to be polarized in the optical pumping cell. Recent improvements in the compressor have allowed us to reach lower pressures in the optical pumping cell which have led directly to improvements in the ^3He polarization after compression.

We have obtained higher polarization values by using ^3He - ^4He mixtures. These mixtures are suitable for neutron polarizers because ^4He has a negligible total cross section for neutrons. For the same total gas pressure, such mixtures allow higher optical pumping cell polarization than can be obtained in pure ^3He . Using a ^3He : ^4He =1:3 mixture, we have obtained 32% polarization in recirculation mode and 43% in fill mode (0.8 bar). Using the mixture requires a greater total amount of gas to be produced, but we have found the results to be better with the mixture than with pure ^3He gas.

Although the outlet pressure of the compressor can be well above one bar, the inlet (optical pumping cell) pressure rises correspondingly, so we have generally restricted operation to the range between 0.5 and 1.1 bar. To quadruple the density of the gas without additional compression, we have operated the apparatus with the cell immersed in liquid nitrogen. However, we have observed a temporary drop in the relaxation time of the cell, for example from 35 hours to 17 hours. This is most likely due to impurities that freeze on the cell walls. Because this simple cooling approach can greatly extend the capabilities of any compression system we will investigate whether the observed degradation of the relaxation time can be avoided. Using a combination of the mixture and cooling techniques, we produced the cold neutron spin-filter that is described in the next section. We have also obtained 37% ^3He polarization in a 9.5 cm diameter, 15 cm long cell (1.1 liter volume).

CURRENT RESULTS FOR NEUTRON SPIN-FILTERS

Results to date using neutrons fall into three categories: polarization tests on a cold monochromatic beam at the NCNR, a polarization measurement experiment with thermal and epithermal neutrons at LANSCE, and polarization analysis on the NCNR NG3 SANS instrument.

A. NCNR Cold Neutron Polarizer Tests

Polarizers based on both spin-exchange and metastability-exchange optical pumping were tested on the new monochromatic beam line (NG6M) in May 1998 [JON]. A 4 cm ID spin-exchange cell made from GE 180 glass was placed in a neutron beam and polarized over the course of five days. A neutron polarization of 0.885 with an absolute transmission of 0.081 was achieved. A neutron experiment was then performed using gas polarized by the metastability-exchange method. The cell was transported in a portable solenoid to the beamline where it replaced the spin exchange cell. A neutron polarization of 0.67 with an absolute transmission of 0.185 was achieved. For both experiments the ^3He polarization was about 45%. This work is described in the Jones et al paper referenced in the publication list.

B. LANSCE Thermal And Epithermal Polarizer Test

At the LANSCE pulsed neutron source we have measured the neutron beam polarization with an absolute accuracy of 0.2% in the energy range from 40 meV to 10 eV using a ^3He spin-filter and a relative transmission measurement technique. The ^3He was polarized using the spin-exchange method. The measurement method exploited the simple relation between the neutron polarization and the transmission ratio for a polarized and unpolarized target. The measurement established that the ideal relations discussed in the introduction between the neutron polarization and the ^3He polarization hold to high accuracy in practical devices. Higher accuracy is possible: the accuracy in this experiment was limited by counting statistics and not systematic effects. This work is described in the Rich et al paper referenced in the publication list.

C. SANS Polarization Analysis

The goal of this experiment was to test ^3He analyzers for SANS by performing a standard application of polarization analysis: separation of coherent scattering from spin-incoherent scattering [DCW76]. Using separate sources of reasonably pure coherent and spin-incoherent scattering, we were able to make a combined sample with a known mix of each. To observe primarily spin-incoherent scattering we used six layers of cellophane tape, and for primarily coherent scattering, we used a silica gel. Mixed scattering was obtained by putting both of these samples in together. Experiments were performed using analyzers prepared off-line with each optical pumping method, and transported to the SANS apparatus.

This work is described in the Gentile et al paper referenced in the publication list. In March 1999, we continued this work with a series of experiments to separate magnetic from nuclear scattering. These data are presently being analyzed. In collaboration with NCNR materials science staff, we have several experiments planned.

Related Activities

To inform the materials science community of progress in ^3He spin filters and to establish contacts and ideas for applications, we organized an informal meeting that was held at the NCNR (1/99) and reported in Neutron News. Participants have commented that the meeting was quite instructive, and revealed the importance of interaction between communities. W.M. Snow, T.R. Gentile and G.L. Jones visited the IPNS (3/99) to discuss the role of ^3He spin filters in instrument design for the Spallation Neutron Source.

NIST is collaborating with LANL in the application of ^3He polarizers to a DOE-funded nuclear physics experiment at LANSCE to search for parity violation in polarized neutron capture on protons. This interaction has led to two developments: a "double" spin-exchange cell (ie. separate volumes for optical pumping and spin filtering) that was employed in a recent LANSCE test run, and the aforementioned 10 cm diameter spin-exchange cell.

Finally, NIST has collaborated with researchers in the area of magnetic resonance imaging to develop medical applications of polarized ^3He . For this work the polarized ^3He gas production was supported in part by funds from this grant.

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