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TRI-PP-86-62
Jul 1986

PROTON TARGET POLARIZATION MEASURED WITH A POLARIZED NEUTRON BEAM AT 477 MeV

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ABSTRACT

The polarization of a proton target is determined with elastic neutron-proton scattering at 477 MeV. The results agree well with the nuclear magnetic resonance measurements at the error level of 4%.

(Letter to Nuclear Instruments and Methods)

TRI-PP 86-62
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Dynamically polarized proton targets are available at intermediate-energy and high-energy accelerators for the study of spin-dependent nuclear reactions. To normalize the measurements of the polarization-dependent parameters, the value of the target polarization is always determined with a nuclear magnetic resonance (NMR) system. A requirement for the NMR electronics is that the output varies linearly with the nuclear polarization of the target as this polarization is increased by microwave irradiation. Deviation from linearity can be a source of systematic error and estimates of the deviations are usually based on computer simulation of the NMR circuit (e.g., see the extensive descriptions in ref. [1,2]). It is very hard to verify the results of this modeling experimentally.

A second systematic error can originate from a non-uniformity of the polarization over the volume of the sample, which might be due to inhomogeneities in the microwave or particle beam irradiation. Because the NMR system samples different parts of the target with unequal weight, the NMR output can indicate a polarization that is different from the average value for the sample. The magnitude of this error can be estimated by using several configurations for the NMR pick-up coil. From measurements with a partly filled target space, deviations of 1 part in 35 were derived in ref. [3]. Sampling the target with two [4] or eight [5] NMR coils showed variations of a few percent.

Finally, a systematic error can arise from the temperature measurement near 1 K if the NMR system is calibrated with the thermal equilibrium (TE) method. The polarization of the nuclear spin system, that is in thermal equilibrium with the lattice, is derived from the Maxwell-Boltzmann statistics. This distribution contains the magnetic field and the temperature as parameters. The intensity of the magnetic field is determined with high accuracy from the Larmor frequency. The absolute temperature value is derived from a thermometer calibration which can introduce an error of a few percent in the polarization.

It is very difficult to check these sources of error independently of the NMR system. However, at TRIUMF the target polarization can be derived from an absolute value for the beam polarization. An experiment has recently been completed in which charge symmetry was tested in the elastic scattering of neutrons by protons at an energy T_{Lab} = 477 MeV [6]. The analyzing power was measured over a range of the neutron scattering angles $\theta_{Lab} = 27° - 37°$ with either the proton target or the neutron beam polarized. The charge symmetry breaking difference in analyzing power for these parts can be neglected for purposes of the present letter. This implies that the measured scattering asymmetries are the same for equal beam and target polarization. The calibration of the neutron beam polarization is based on an accurate determination [7] of the analyzing power in p-p scattering at $\theta_{Lab} = 17°$, and knowledge of the spin transfer parameters in (p,n) quasi-free scattering from deuterium at 9.0° in the laboratory. Consequently, the scattering data yield an absolute target polarization that is compared with the value from the NMR measurements.

The NMR system is calibrated with the TE method at a target temperature of 1.6 K in a magnetic field of 2.55 T. The polarized proton target is mounted in the mixing chamber of a vertical dilution refrigerator. An X-ray of the target chamber is shown in ref. [8]. The sample consisted of 55 cm^3 of butanol beads with a diameter of 1.4 mm and a doping of 4 and 6×10^{19} EHBA molecules/cm^3 [15] for the runs 1, 2 and 3, 4 respectively in table 1. This material is contained in a vertical cylinder of copper foil with a diameter of 4 cm. Above and below the sample cup vacuum spaces of about 50 cm^3 each are located to minimize the neutron scattering from background materials. The NMR coil was embedded in the sample and had three turns with a diameter of 2 cm. It was wound of 2.2 mm diameter copper tubing that was covered with a teflon tube of 3 mm outer diameter. One end of the NMR coil is grounded in the mixing chamber while at the other end a series resonant capacitor was connected to the semi-rigid coaxial transmission line that carries the RF (radio-frequency) signal outside the cryostat. There, a similar empty coil was connected where the RF current has a phase difference of 180°. The sum of the RF voltages in both coils is amplified, and the real part of the complex RF signal is stored through an ADC in an LSI-11 computer.

The detailed specifications of the polarized neutron beam have been reported previously [9]. A polarized proton beam passes through a polarimeter and hits a liquid deuterium target. After a quasi-elastic charge exchange reaction, the neutrons are taken off and collimated at 9° relative to the proton beam. During the charge symmetry testing experiment the left-right neutron scattering asymmetry $\varepsilon(\theta)$ was measured over the angular range $\theta_{Lab} = 27° - 37°$ with either the beam (ε_N) or the target (ε_P) polarized. The detection equipment is described in ref. [10].

After binning the data in steps of $\Delta\theta = 0.2°$ the derivatives

$$\varepsilon'_i = \frac{d\varepsilon_i}{d\theta} = P_i \frac{dA_i}{d\theta} \qquad (i = N,P)$$

are determined. The ratio of the polarizations equals the ratio of the derivatives $\frac{P_N}{P_P} = \frac{\varepsilon'_N}{\varepsilon'_P}$ if the difference between $\frac{dA_N}{d\theta}$ and $\frac{dA_P}{d\theta}$ is sufficiently small. The charge symmetry breaking difference in the analyzing powers $\Delta A = A_N - A_P$ that was reported recently [16], was explained very well theoretically by Ge and Svenne [17]. Their result for the angular dependence of ΔA leads in the laboratory reference frame to $\frac{dA_N}{d\theta} - \frac{dA_P}{d\theta} \approx 0.0004/\text{deg}$, from which a correction of 1.5% follows in view of $\frac{dA}{d\theta} = -0.0284/\text{deg}$ [12]. The neutron beam polarization P_N is derived from the proton beam polarization that is measured with the polarimeter in the beam line:

$$P_N = P\sqrt{r_t^2 + r'^2_t}\ .$$

Here, r_t and r'_t are the Wolfenstein p-n polarization transfer coefficients after correction for final state interactions. These parameters are obtained from phase shift analyses of the available scattering data. In the analysis by Bugg et al.,[11] a value 0.731 ± 0.044 is derived for $\sqrt{r_t^2 + r'^2_t}$. The work of Arndt et al. [12] gives 0.784 based on all available scattering data and 0.787 ± 0.013 if the data set is restricted to the energy interval between 450 MeV and 550 MeV. The Saclay-Geneva phaseshift analysis yields 0.748 [13]. A fair representation of these four results seems to be the average 0.763 ± 0.013, where the error is taken from the analysis of Arndt et al. This error is treated below as systematic. Our data were collected during four runs that were each about three weeks in duration. Once a week a TE calibration of the NMR system was obtained. Every day the scattering asymmetry was measured for about four hours with a polarized target and an unpolarized beam. The target was in a magnetic field of 0.257 T and at a temperature of about 60 mK. Consequently, the polarization decay times were around 150 hours which led to average polarizations of approximately 0.8. For the part of the measurement with an unpolarized target, the only change in the set-up was an increase of the target temperature to about 0.8 K where an upper limit for the

decay time of a few seconds was measured. For about 15 hours, alternating every few minutes, polarized and unpolarized beam was scattered from the target. The average neutron beam polarizations were about 0.5.

In table 1 the average values for each run are listed. The statistical error in the proton beam polarization is negligible [9]. A systematic error of 1% arises from the uncertainty in the analyzing power [7]. The ratio of the derivatives is obtained from an analysis of the scattering data that is described elsewhere [14]. The errors are statistical. The error in the target polarization P_T from the NMR measurement is mainly determined by the uncertainty in the thermal equilibrium calibration which contains two components of about equal size. These are the absolute temperature calibration of the resistance thermometers and the long term (typically 1 week) stability of the NMR set-up.

The weighted average of the four measurements of the polarization ratio R is 0.976. Including the 1.5% difference in the derivatives of the analyzing powers, gives the final result 0.961 ± 0.024 (±0.027). The systematic error of ± 0.027 is due to the spin transfer parameters (0.017) and the p-p analyzing power (0.010). It is obvious that the results from both techniques to measure the polarization agree very well. This shows that our NMR technique provides results that are free of systematic errors on the 4% level.

This work was supported by the National Research Council of Canada and the Natural Sciences and Engineering Research Council of Canada.

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Table 1: Comparison of the target polarizations that are obtained from the neutron scattering and from the NMR measurements.

Run	P	$\varepsilon'_p/\varepsilon'_N$	P_P	P_T	$R=P_P/P_T$
1	0.661	1.374 ± 0.071	0.693 ± 0.036	0.677 ± 0.011	1.024 ± 0.056
2	0.664	1.728 ± 0.094	0.875 ± 0.048	0.846 ± 0.014	1.034 ± 0.059
3	0.678	1.514 ± 0.054	0.783 ± 0.028	0.804 ± 0.010	0.974 ± 0.037
4	0.683	1.377 ± 0.065	0.718 ± 0.034	0.789 ± 0.015	0.910 ± 0.046