Measurement of Spin Observables Using a Storage Ring with Polarized Beam and Polarized Internal Gas Target


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We report the first measurement of analyzing powers and spin correlation parameters using a storage ring with both beam and internal target polarized. Spin observables were measured for elastic scattering of 45 and 198 MeV protons from polarized 3He nuclei in a new laser-pumped internal gas target at the Indiana University Cyclotron Facility Cooler Ring. Scattered protons and recoil 3He nuclei were detected in coincidence with large acceptance plastic scintillators and silicon detectors. The internal-target technique demonstrated in this experiment has broad applicability to the measurement of spin-dependent scattering in nuclear and particle physics.

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Polarized internal gas targets in storage rings offer significant promise for measurement of spin observables in nuclear and particle physics [1] in that they realize the interaction between polarized beam and polarized target in the most ideal way. They comprise a source which generates a flux of chemically and isotopically pure polarized nuclei directed into a windowless conductance limiter (the storage cell) through which the circulating beam of the storage ring passes. The storage cell increases the dwell time of the polarized atoms near the interaction region, significantly enhancing the target thickness. In contrast to solid polarized targets, which are characterized by cryogenic storage of chemical compounds (e.g., NH₃, butanol) in strong magnetic holding fields [1], polarized internal targets consist of pure samples of highly polarized nuclei in a low holding field. Thus, the polarized target nuclei are present as pure atomic species and hence there is no dilution of the spin-dependent term in the scattering cross section. Furthermore, the internal target polarization can be reversible on a time scale of seconds. Consequently, the systematic errors associated with this technique should be reduced from those of conventional solid-state targets. In addition, the storage cell wall may be thin which allows for the detection of heavily ionizing recoil particles. Finally, the luminosities associated with polarized internal targets are well matched to large acceptance detectors where scattered particles can be detected over a broad kinematic range. Motivated by these advantages, significant effort is at present being directed towards realizing the potential offered by the polarized internal-target technique. The first pioneering measurements have been carried out at VEPP-3 in Novosibirsk [2]; high-flux sources of ¹H, ²H, and ³He nuclei are under development using both the atomic beam technique [3] and laser optical pumping [4]; polarimeters to measure target polarization have been successfully constructed [5] and large collaborations have formed to construct detectors and carry out experiments which utilize polarized internal targets at the electron storage rings at VEPP-3 [2], MIT-Bates [6], NIKE-HF [7], and DESY [8] as well as proton rings such as UNK [9] and IUCF [10]. The ³He nucleus is a particularly interesting target because Faddeev calculations [11] indicate that a polarized ³He nucleus has 87% (2.7%) probability for the neutron (protons) to be polarized along (opposite to) the nuclear spin direction. Thus, it is expected that a polarized ³He internal target can be used to measure the charge and spin distributions of the neutron. Such experiments, using an electron storage ring, will address some of the most fundamental problems in baryon structure. In this Letter we report the results of an experiment that demonstrates for the first time all the major aspects of this powerful technique, namely, the measurement of spin observables with a polarized beam incident on a polarized internal target.

We have developed a polarized ³He internal target and used this in conjunction with stored and cooled polarized and unpolarized proton beams to carry out a series of elastic scattering measurements. Here the spin-dependent differential cross section when both beam and
target spins are oriented normal \( (n) \) to the scattering plane can be written as [12]

\[
\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_0} (1 \pm A_{00\alpha 0} P_0 \pm A_{00\alpha 0} P_1 + A_{00\alpha 0} P_0 P_1), \tag{1}
\]

where \( P_0 \) and \( P_1 \) are the polarizations of the beam and target, the + and − distinguishes between beam right and beam left regions of the scattering plane, \( d\sigma/d\Omega_0 \) is the unpolarized differential cross section, \( A_{00\alpha 0} \) is the spin-correlation parameter, and \( A_{00\alpha 0} \) and \( A_{00\beta 0} \) are the beam and target analyzing powers, respectively.

Elastic scattering of protons on \( ^3\text{He} \) was measured at incident proton energies of 45 MeV (unpolarized beam) and 198 MeV (polarized beam). The experiment was carried out in the A section of the Indiana University Cyclotron Facility (IUCF) Cooler Ring [13] where the stored beam properties are optimal for location of a storage cell. The proton polarization was directed normal to the scattering plane. The circulating beam current was continuously measured using a Bergoz parametric current transformer [14] which was calibrated every 16 s (8 s) at 45 (198) MeV using a 20 \( \mu \text{A} \) reference current. The average current on target during the experiment was 35 \( \mu \text{A} \) (45 MeV) and 10 \( \mu \text{A} \) (198 MeV). By fitting the measured asymmetry to the beam analyzing power for \( p-^3\text{He} \) elastic scattering known from the literature [15], the average polarization of the 198 MeV proton beam was determined to be \( 0.65 \pm 0.02 \).

To carry out the experiment a new type of polarized internal gas target, schematically shown in Fig. 1(a), was developed [16]. The \( ^3\text{He} \) atoms were polarized through metastability-exchange optical pumping [17] in a Pyrex optical pumping cell which was connected by a Pyrex precision capillary to an aluminum storage cell. The storage cell was an open-ended tube of 40 cm length and of rectangular cross section \((13 \times 17 \text{ mm}^2)\) with sides of 1.7 \( \mu \text{m} \) thick aluminized Mylar foil. The \( ^3\text{He} \) atoms were directed to the pumping cell through a second precision capillary so that the equilibrium pressure in the pumping cell was 0.5 Torr at a flow rate of \( F = 1.2 \times 10^{17} \text{ atoms/s} \) (see Fig. 1) resulting in a target thickness of \( 1.5 \times 10^{14} \text{ atoms/cm}^2 \). The metastable population was created in the pumping cell by maintaining a weak discharge. The optical pumping light was supplied by a LNA (Nd-doped lanthanum hexaluminate) crystal pumped by a krypton arc lamp in a Lasermetrics 9650 cavity. Typical output power was 3 W at \( \lambda = 1.083 \text{ \mu m} \), the wavelength of the optical pumping transition. The output light was circularly polarized using a polarizing beam-splitter cube followed by a Pockels cell. The target assembly was mounted on a single aluminum flange, which was attached to an aluminum ultrahigh vacuum chamber. The target was positioned along a 1 mT magnetic field provided by 1 m diam Helmholtz pair. A three-stage differential vacuum pumping system isolated the target from the storage ring vacuum. The average polarization in the pumping cell was \( 0.45 \pm 0.02 \) and was measured using detection of the 667 nm line in the \( ^3\text{He} \) discharge [18]. \( ^3\text{He} \) is a closed shell atom and so depolarization effects due to wall collisions and interactions with the stored beam are negligible [19]. Thus, the polarization of the atoms in the storage cell is taken to be equal to the polarization of the atoms in the pumping cell. The target polarization was reversed every 300 s by reversing the circular polarization of the laser light.

Detector arrays were positioned symmetrically on each side of the beam [see Fig. 1(b)]. Elastic scattering was identified as an outgoing proton detected in coincidence with its associated \( ^3\text{He} \) recoil. At 45 (198) MeV circulating proton energies, the scattered protons stopped in the 1 cm (15 cm) thick \( \Delta E (E) \) plastic scintillator detectors, located at the sides of the vacuum chamber. The detectors provided a correlation between the proton's total energy and energy loss as well as a determination of its time of flight. The position on the detector along the beam direction was measured to \( \pm 6 \text{ cm} \) by reading out the scintillators at both ends with photomultiplier tubes.

FIG. 1. A schematic layout of the experiment: (a) side view and (b) front view along the beam direction.
located outside the magnetic holding field of the target. The $^3$He nuclei were observed in 295–350 $\mu$m thick fully depleted silicon strip detectors. A total of six silicon strip detectors, each 6 cm long and 4 cm high, enclosed in a Faraday cage, were located 3 cm from the axis of the storage cell. The effective solid angle subtended by the silicon detectors for the entire target length, weighted by the triangular target density distribution, amounted to 3.1 sr. Simultaneous energy calibration was provided by $\alpha$ particles from a $^{226}$Th source, positioned beneath the storage cell. The center-of-mass scattering angle was determined to $\pm 2^\circ$ from the measured $^3$He energy and this allowed the complete reconstruction of elastic scattering kinematic quantities. The main contributions to the total systematic error of our measurement are due to uncertainties in the integrated charge (~3% for each spin state) and the beam polarization (~3%). The systematic errors for beam and target analyzing powers were minimized by use of a left-right symmetric detector configuration [20].

Figure 2 shows the correlation between the measured scattered proton and recoil particle energies at 45 MeV incident proton energy. In a single setting we cover the center-of-mass angle, $\Theta_{c.m.}$, in the range of $25^\circ$–$125^\circ$, because of the extended target and the detector configuration. The absolute $p^{-3}$He elastic scattering cross section extracted from our measurements was in good agreement (within 10%) with previous data [21] over the complete angular range. At both 45 and 198 MeV incident energies, the $p^{-3}$He elastic scattering events could be clearly distinguished from the low-energy background originating from the breakup channels. Scattering from the storage cell walls is a potential source of background

[22] and will dilute the scattering asymmetry. Thus, the dimensions of the storage cell were chosen to exceed the acceptance of the Cooler Ring. Further, at 198 MeV circulating proton energy the $^3$He gas was replaced by hydrogen and $p-p$ elastic scattering measurements were carried out. With comparable target thickness, the rate in the $p^{-3}$He elastic scattering energy-energy correlation locus was less than 1% of the rate observed with the $^3$He target. The $p-p$ elastic locus is well removed from the $p^{-3}$He locus and therefore only background processes contribute into the $p^{-3}$He gate. This provides an upper bound for the scattering rate from the storage cell walls.

The spin observable $A_{000n}$, measured at 45 MeV with unpolarized beam, is shown as a function of $\Theta_{c.m.}$ in Fig. 3(a) while $A_{000n}$ and $A_{000m}$, measured at 198 MeV with both beam and target polarized, are shown in Figs. 3(b) and 3(c), respectively. The data are shown in Fig. 3 with total errors (statistical and systematic added in quadrature) and were obtained over the complete angular range in 1 h (45 MeV) and 6 h (198 MeV) of data acquisition. At 45 MeV our measurement can be compared with the large body of existing data at nearby energies. In this energy region the analyzing powers are known to be only weakly energy dependent and so we have carried out a phase-shift analysis of previous data [21,23,24] at 35

![Figure 2](image1.png)

**FIG. 2.** The energy in the scintillators vs the energy deposited in the silicon strip detectors on the opposite side of the storage cell at 45 MeV incident proton energy. The dashed curve encloses the events in the $p^{-3}$He elastic scattering locus.

![Figure 3](image2.png)

**FIG. 3.** Spin observables for $p^{-3}$He elastic scattering: (a) The target analyzing power $A_{000n}$ at 45 MeV. The curve represents the result of a phase-shift analysis of 35 MeV data. (b) The target analyzing power $A_{000n}$ at 198 MeV. (c) The spin correlation parameter $A_{000m}$ at 198 MeV.
MeV for the cross section, and the beam and target analyzing powers. The curve shown in Fig. 3(a) is a good fit to the published 35 MeV target analyzing powers ($\chi^2 = 6.94$ for 12 data points for $A_{000m}$). As seen from Fig. 3(a), the agreement with our results is good. We conclude from a comparison of the data shown in Fig. 3(a) that there is no evidence for depolarization of the atoms in the target cell within the normalizations of the respective data sets.

In summary, we have performed the first experiment with a polarized beam incident on a polarized gas target internal to a storage ring. For the first time the polarized atoms were fed from a laser optically pumped source yielding the thickest operating polarized internal gas target. We have shown that the internal target technique leads to practically background-free measurements of undiluted asymmetries for protons scattered elastically from $^3$He. Where comparison is possible, the results are consistent with those from previous conventional techniques and demonstrate the promise of polarized internal targets for future experiments at nuclear and high-energy physics facilities.

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