Development of a Hydrogen and Deuterium Polarized Gas Target for Application in Storage Rings

1. PROGRESS REPORT

1.1. TARGET TEST BY LOW-ENERGY pp SPIN CORRELATION

Last year we reported on the results of the atomic beam development. These results showed a beam intensity of 6.7×10^{16} atoms/s into a 1 cm dia. x 13 cm long tube located 26 cm from the last six-pole magnet, in good agreement with a model of the source. We have also reported on studies of storage cell surfaces that preserve over 90% of the atomic polarization after 400 or more wall collisions. In the present test we directed the polarized atomic beam into the entrance tube of a thin walled storage cell and measured the polarization of the resulting gas target. The purpose of this test was to study depolarization in a cell suitable for experiments in a proton storage ring and to test the detection of low energy recoils passing through the thin walls. Associated target cell equipment, including holding fields, vacuum system, cell alignment, and recoil detection electronics were also tested and improved at this time. The test of the thin walled storage cell was conducted at the University of Wisconsin tandem accelerator using a method described below. Studies of wall depolarization on thin stretched teflon foils have not been reported previously.

The atomic beam source (ABS) was temporarily moved to the high energy beam line of the tandem accelerator. The ABS was aligned to inject the polarized atomic beam into the entrance tube of a storage cell. The storage cell, the silicon strip detectors surrounding the cell, the vacuum chamber, and the holding field coils are shown in Fig. 1. These items were designed and constructed in collaboration with a group at IUCF with the intent to eventually install the apparatus along with the atomic beam source on the IUCF proton storage ring to produce a polarized gas target there.

The cell polarization was probed with a 7.6 MeV polarized proton beam passing through the cell. At a proton energy of 7.6 MeV and scattering angles near $\theta_{cm}=90^\circ$, the pp spin correlation parameters A_{yy} and A_{xx} are both -0.99 ± 0.01 and the analyzing power $A_y \approx 0$ [1]. Therefore, for vertical beam and target polarization, the pp cross section at 90° to a very good approximation becomes

$$\sigma(90^\circ) = \sigma_0(90^\circ) (1 - p_b p_t) \quad (1)$$

where σ_0 is the unpolarized cross section, p_b is the beam polarization, and p_t is the target polarization. The target polarization for spin up ($p_t^\uparrow$) and spin down ($p_t^\downarrow$) can easily be determined from the yields in the various polarization states

$$p_t^\uparrow = \frac{1}{p_b} \frac{Y_{\downarrow\uparrow} - Y_{\uparrow\uparrow}}{Y_{\downarrow\uparrow} + Y_{\uparrow\uparrow}} \quad \text{and} \quad p_t^\downarrow = \frac{1}{p_b} \frac{Y_{\downarrow\downarrow} - Y_{\uparrow\downarrow}}{Y_{\downarrow\downarrow} + Y_{\uparrow\downarrow}} \quad (2)$$

For the yields in eq. 2, the first arrow indicates the direction of the beam polarization and the second arrow the direction of the target polarization.

Figure 1. Layout for test of thin wall polarized H target on the Wisconsin tandem accelerator.

ONE QUADRANT of STORAGE CELL

Figure 2. Thin wall storage cell assembly (top) and quadrant detail (bottom).

Polarized protons were produced by the UW colliding beam polarized ion source [2]. After acceleration the proton beam passed through the storage cell and into a polarimeter (Fig. 1). The polarization was found to be $P_p = 0.85 \pm 0.02$, where the error is dominated by a 2% uncertainty in the analyzing power [3]. The beam was centered on the cell by maximizing the current through the cell while keeping the background scattering rate in the silicon detectors to a minimum.

A small fraction of the accelerated protons is scattered from polarized hydrogen atoms in the storage cell target. Both scattered and recoil protons are detected in coincidence by silicon strip detectors. As seen by the beam, the silicon detectors are located in the upper-left and lower-right quadrants.

A schematic of the cell construction is shown in Fig. 2. The cell was designed to permit the detection of relatively low energy recoil particles ($E > 0.5$ MeV) by stretching 5 mm teflon foils over knife edges. The assembly consists of four quadrants, two of which have mating half cylinders to form the entrance tube for the storage cell. The lower half of Fig. 2 shows one quadrant in detail. The entrance tube is angled 30° in the backward direction to provide clearance for recoil particles near 90° . The thin windows were oriented at 45° to the horizontal because entrance tube to the cell stops a large fraction of the recoil particles in the horizontal plane. The possibility of a kinked entrance tube was investigated but the loss in target thickness resulting from the kink was found to be unacceptable. The entire cell and detector assembly is attached to an adjustable mount. The mount provides complete freedom to adjust the position and orientation of the cell and detectors, thereby permitting simultaneous alignment of the cell to both the tandem and atomic beams.

A pp elastic event is defined by a coincidence between the upper-left and lower-right detectors. Fig. 3 shows a plot of the energy in the upper-left detector E_L vs. the energy in the lower-right detector E_R for each beam spin state. The target polarization direction in Fig. 3 is down. The pp elastic events are clearly evident along the diagonal. The large difference between the number of coincidence events in the left and right plots of Fig. 3 results from the large cross section difference between polarization states (eq. 1). In the left plot the beam and target polarization are antiparallel and in the right hand plot the spins are parallel. Detector yields are determined from the E_L vs. E_R plots. The background is typically 4% of the total number of events and is determined from measurements with an empty cell. The background arises from beam halo striking the target. Note that the mass of the polarized H gas in the cell is $\sim 10^{-10}$ grams compared to the mass of the target walls of $\sim 10^{-2}$ g.

The target polarization was determined by measuring the four yields for elastic scattering events as defined in eq. 2. The polarization was first measured with the Medium Field RF transition (Fig. 1) turned off. In this situation, atoms in states 1 and 2 are focused by the separation magnets and enter the storage cell. If we assume an average vertical guide field value of $B = 1.5$ mT and no polarization losses in the cell, the nuclear polarization, a , of the state 2 atoms in the cell is expected to be [4] $P_{\max}(\text{MF Off}) = 0.485$. The measured value is 0.436 ± 0.022 which is $90 \pm 4\%$ of the expected maximum.

Fig. 3. E_L Vs E_R for pp coincidences with target polarization down. The right (left) plot is with beam and target spins parallel (anti-parallel).

The target thickness can be determined from the rates in the silicon detectors, the known pp cross section at 7.6 MeV, and the measured beam current through the cell. The results indicate a thickness averaged over the entire cell of 2×10^{13} atoms/cm². This is lower than what we ultimately expect to achieve for two reasons. (i) The aperture of the cell used in these measurements is 10 mm by 10 mm. However in Ref. 5 the optimal cell size for use at the IUCF ring was found to be closer to 8 mm X 8 mm. The gas conductance for this smaller cell size is almost a factor of two less than the present cell. (ii) Two pumps on the ABS failed which increased the scattering losses of the atomic beam, leading to a lower intensity at the entrance of the feed tube. Once these problems have been remedied, we are expecting a target thickness in two spin states of 7.2×10^{13} atoms/cm².

When the medium field RF unit is turned on, a transition is made from atoms in state 2 to state 3. The second magnet group of the ABS then defocuses state 3 atoms. This reduces the flux of atoms into the feed tube by about a factor of two, but increases the polarization of atoms in the cell. Assuming no loss of polarization in the cell, the polarization is then given by:

$$p_{\max}(\text{MF On}) = \frac{1 - \epsilon a - (1 - \epsilon)R}{1 + \epsilon + (1 - \epsilon)R}, \quad (4)$$

where $a = -0.03$ is the polarization of state 2 atoms in a 1.5 mT magnetic field, $(1 - \epsilon)$ is the efficiency of the MF transition unit, and R is the fraction of state 3 atoms that are not sufficiently defocused by the second magnetic group and enter the feed tube. The MF transition efficiency has been measured previously [6], yielding a value of $\epsilon = 0.04$. The value of $R = 0.052$ was

determined from transport calculations of the magnet system. With these values inserted in eq. 4, the expected polarization with the medium field transition on is $P_{\max} = 0.871$. The measured polarization is 0.722 ± 0.021 or $83 \pm 3\%$ of the expected maximum. The polarization is sufficiently large for experiments at the IUCF cooler to begin. A paper describing these tests has been submitted to NIM.

From the point of view of target development one of the important results from the tandem tests was the demonstration of the negative effect of the use of stainless steel in the construction of storage cells. The target polarization of several thin wall cells were tested. In the first version, (cell A), The cell framework and the teflon coated entrance tube were constructed entirely from stainless steel. The results show that this target was far from satisfactory as described below. The entrance tube was replaced with teflon coated aluminum (cell B) and finally the junction between the entrance tube and cell was also replaced with teflon coated aluminum (cell C). In version (C) there still remains stainless steel close to the stored atoms along the stainless longitudinal knife edge supports of the teflon foil.

Polarization for the three cells are listed in table 1. $P_{\uparrow}$ and $P_{\downarrow}$ in the table refer to the target polarization with guide field pointing up and down respectively. The values listed in the table are the measured polarization divided by the ideal polarization for this case of 0.485.

	$P_{\uparrow}/P_{\max}$	$P_{\downarrow}/P_{\max}$
Cell A	0.60 ± 0.12	0.41 ± 0.10
Cell B	0.46 ± 0.06	0.77 ± 0.06
Cell C	0.88 ± 0.06	0.92 ± 0.06

Table 1. Target polarization in two spin states for three cells. The values listed are the measured polarization divided by the ideal value of 0.485.

Two effects are seen in these results. The improvement in target polarization as stainless material is replaced with aluminum is clearly apparent. There is some evidence to support the conclusion that stainless steel is a poor substrate for Teflon coatings. The thesis work of Scott Price [7] included a brief test of one storage cell with teflon on a stainless steel substrate. The test resulted in a low target polarization. Also included in the thesis work were tests of bare nickel cells. These tests resulted in nearly zero cell polarization. We suspect that local magnetic fields on the surface of the stainless steel extend past the thin surface coating and depolarize atoms during their dwell time on the surface. The second effect is an asymmetry in polarization with holding field direction. This asymmetry was found to be a result of residual magnetization of stainless material particularly near the stored atoms.

In light of these results, all future thin wall cells will be constructed entirely from aluminum and other non-magnetic materials. It is possible that some of the unexplained loss in target polarization for cell (C) will be regained with an all aluminum cell. Tests of such cells are included in the proposed work section. Several other questions about these thin targets remain and are also included in the proposed work.

These results show that it is important to conduct off line tests before final installation in a ring where access is severely restricted.

1.2 ATOMIC BEAM SOURCE PROGRESS

a) Publication on Atomic Beam Source

A paper describing the design and construction of this ABS has been accepted for publication in NIM. We report the emittance of the atomic beam from the source to be 155π mm mrad for 90% of the beam. The emittance is substantially smaller than the corresponding values for previously reported atomic beam sources. The beam intensity passing through this emittance (7.7×10^{16} atoms/s) implies a beam of very high brightness.

b) Installation of ABS on IUCF Storage Ring

During the last year the atomic beam source and the scattering chamber with the thin wall cell and detector system were moved to the IUCF storage ring. The first objective of this experiment is to measure the polarization and thickness of the thin wall polarized gas target that we have installed and to study possible radiation damage to the cell walls. The target installation is completed and two test runs have occurred. Several difficulties related to the interaction of the target with the ring were encountered. During injection of particles into the ring the cell was exposed to scattered beam from the injection process which also caused activation of the cell. Problems with cell alignment and beam position monitors were also encountered. Steps have been taken to correct these problems. We expect to measure the target polarization during the next scheduled run.

c) Atomic Beam Monitor

In order to monitor the atomic beam intensity when ABS and target cell are installed in a ring (e.g. HERA) a beam-intensity monitor that does not obstruct the beam is needed. Last year we proposed a new type of atomic beam detector using a hot tungsten wire on a balanced Wheatstone bridge. Recombination of atoms on the tungsten surface raises the temperature of the wire slightly and increases its resistance by a small amount. The resulting change in the bridge balance is detected. We were able to pursue development of this detector simultaneously with the other ABS tests described above by using the old Stanford atomic beam source we have had on loan for a number of years. This older source produces roughly a factor 10 times less beam than the new source but nevertheless proved to be useful for the detector development.

The bridge is formed by four commercial UHV compatible light bulbs. The four bulbs are carefully selected to make the bridge circuit nearly balanced. The glass cover is broken and all four bulbs are placed in the vacuum. Only one of the filaments is in the beam path. The bulbs we selected have a resistance of about 3 ohms at the operating temperature (550K) and a detection area of 0.25mm X 2.5mm.

Fig. 4. Change in the bridge balance for current on vs. off.

FIGURE 5. Detector signal vs. sixpole sixpole current.

We found that it was necessary to briefly flash the filament at 1725K to clean the tungsten surface before beam measurements. Without flashing the imbalance signal was low and dependent upon the heating history of the filament. After a flash cleaning the imbalance signal became very stable. A very short refreshing flash was required once every half hour. Some results from these tests are shown in Figures 4-6. In Fig. 4 the difference in bridge imbalance between six-pole separation magnet on and off is plotted vs. voltage across the bridge. One can see that the signal is quite insensitive to the applied bridge voltage. The results were obtained after flashing the filament at 1725K for 30 s. Fig. 5 shows the detector signal vs. current in the separation six-pole magnet with the old Stanford electromagnet source. The increase in beam with increasing gradient in the six-pole magnet and the effect of magnet saturation is clearly visible. Fig. 6 shows the time response of the detector to a sudden change in beam intensity. The change was accomplished by turning the separation magnet off at $T = 8$ s. The observed time constant is on the order of 10 s. After a step function in the beam intensity a new measurement can be obtained after 30 seconds. In this particular example the data also show a drift in the bridge signal before the magnet was turned off. This drift came from thermal recovery from a cleaning flash but could have been reduced to an insignificant level by allowing more time between the flash and the measurement. In final usage with the new ABS it is anticipated that after flashing and waiting for stability, a measurement of the beam intensity will take about two min.

Design and construction of a working UHV compatible monitor to be use on the new ABS will be undertaken in the next funding period. We have included the necessary equipment items in the budget request.

Figure 6. Response of hot wire detector to a step in atomic beam intensity.

1.3 WEAK FIELD TRANSITION DEVELOPMENT

In some cases, including experiments in the HERA ring and for some experiments at the IUCF cooler, it will become necessary to reverse the sign of the target polarization without any changes of the guide field at the target. In that case a weak field transition (WF) will be required between the last magnet and the entrance to the storage cell. The conditions imposed on an RF transition at this location are somewhat stringent. In the case of a strong guide field, e.g. 0.34T at HERA, stray guide fields must be well shielded for the transition to work properly. Even in the case of weak guide field over the storage cell (≤ 1.5 mT), stray fields will extend into the region of the RF transition. In experiments where the direction of the target polarization needs to be changed, e.g. from transverse to longitudinal, the corresponding change in the guide field affects the RF transition unless the transition region is well shielded from external fields. Openings in the shielding are required to permit passage of the atomic beam. At the same time the shielding of the device should not distort the guide fields at the storage cell and the transition must be UHV compatible.

A prototype shielded WF transition compatible with UHV vacuum requirements has been constructed. It is housed within a double-walled magnetic shield. Recently this prototype was tested by insertion into the atomic beam of the Wisconsin polarized ion source. After ionization

the beam was accelerated to 6 MeV and its polarization was measured using a proton polarimeter calibrated to an accuracy of 2% [8]. The polarimeter measures the proton polarization to a statistical accuracy of 0.5 % in about five minutes. At these rates it was possible to optimize RF power and magnetic field strength in a reasonable time. These tests resulted in several improvements to the design which were immediately implemented. In particular there was evidence for an undesirable second transition occurring in the fringe field at the exit of the magnet. This was remedied by reducing the length of the RF coil and by providing grounded screening downstream of the coil to truncate the RF field. Fig. 7 shows the measured polarization for two lengths of RF coil. In order to measure the absolute transition efficiency we compared the measured beam polarization with RF transition on to the maximum possible polarization taking into account the effects of the finite field strength in the ionizing solenoid and the finite state rejection of the atomic beam source. Roughly 1% of the atoms in the atomic beam are in states 3 and 4 and the remainder are in states 1 and 2. A weighted average of the polarization of the four states, assuming that the WF transition exactly interchanges the populations of states 1 and 3, yields a maximum possible value of $P = -0.895 \pm 0.02$. The uncertainty is dominated by the estimate of atoms in states 3 and 4. With the prototype transition we measured a polarization of -0.855 from which we deduce a transition efficiency of 95%. The double-wall shielding can was shown during these tests to provide adequate shielding in only two out of three guide field directions. We are currently designing improvements to the shielding.

Figure 7. Beam polarization vs. RF power for two lengths of RF coil.

1.4 HERMES

The contribution to the HERMES experiment consisted of work on the H/D target development, of evaluation of cell coatings and studies of the role of recombination on wall depolarization. In addition we worked with the Heidelberg group on plans for the hydrogen target polarimeter and have been involved in the design work for the H and D scattering chambers. The experiment has advanced to the stage where a more extensive activity is planned for the next year.

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