HORIZONTALLY POLARIZED PROTON BEAMS AT IUCF*

E.J. Stephenson, A.D. Bacher, J.D. Brown, M.S. Cantrell, V.R. Cupps, D.L. Friesel, J.A. Gering, D.A. Low, R.S. Moore, C. Olmer, A.K. Opper, P. Schwandt, and S.W. Wissink
Indiana University Cyclotron Facility, Bloomington, IN 47405

Introduction

During the past year we have completed the development of a system to accelerate and monitor a horizontally polarized proton beam at IUCF. This beam has been used in a first experiment with the QDDM magnetic spectrometer to measure the spin rotation parameter for 200-MeV protons elastically scattered from ^{12}C.

This system, now implemented for the QDDM spectrometer, is the first phase in a larger project involving both proton and deuteron beams and several target stations. At present, the system uses a simple solenoid to precess the beam into the horizontal plane prior to acceleration. The spin precesses a large number of times during acceleration in the injector and main stage cyclotrons, and emerges with polarization intact provided each machine has good single-turn extraction. Two polarimeters are used on the high-energy beam line to measure all three proton spin components for the beam emerging from the cyclotron. These polarimeters are designed to run concurrently with an experiment.

In this system, the final direction of the proton spin in the horizontal plane depends on the cyclotron magnetic field (corrected for relativistic effects) integrated over the time required for the proton to accelerate to full energy. The spin direction on target may be altered by changing the detailed history of the acceleration process. This technique provides a large degree of flexibility in choosing the spin direction, but maintaining that spin direction fixed during an experiment requires very stable cyclotron operation.

Precessing the proton spin in the high-energy beam line would provide us with considerable independence from the quality of the machine operation, but would require expensive superconducting solenoids. By using a modest solenoid to precess prior to acceleration, we were able to test high-energy polarimeter designs and to have a brief look at the scientific value of the experiments before considering a large investment in apparatus. With the present IUCF beam line arrangement, locations can be found for high-energy solenoids so that each crucial target station has a full range of options for the proton spin direction. This is not true for polarized deuterons as the deuteron magnetic moment is close to one, and precession prior to acceleration will have to be used whenever spin-precessed deuteron beams are needed.

Horizontally polarized proton beams will likely find the largest use in polarization transfer experiments involving elastic scattering, as well as (p,p') and (p,n) reactions. Because efficient polarimeters (with low intrinsic energy resolution) will be needed, these experiments will be staged either on the QDDM magnetic spectrometer or the Beam Swinger, where reaction products from various nuclear levels can be separated either spatially in the spectrometer focal plane detector, or temporally with a long neutron time-of-flight path. Experiments using each of these reaction types are currently under development. Future applications may include the measurement of spin correlation parameters with a polarized target, and the preparation of polarized deuteron beams for the measurement of a full set of tensor analyzing powers.

Detailed Component Description

Polarized Beam Preparation

The polarized proton beam at IUCF is generated in an ANAC atomic beam source. Beam currents at the ion source are typically 6-8 μA with polarizations of 0.75-0.85. The path followed by this beam through the cyclotrons and to the QDDM target is shown in Fig. 1. Beam currents on target have been as large as 250 nA.

The spin precession solenoid (see Fig. 1) is located downstream of the ion-source terminal acceleration column where the beam energy is typically 600 keV. The solenoid consists of two sections, each with 112 water-cooled turns in a roughly square cross section. These magnets have an internal diameter of 10 cm. Depending on the terminal potential, roughly 200 A are required to precess the vertical spin into the horizontal plane. This magnet current is adjusted until the vertical polarization component vanishes when measured in the high-energy beam line.

High-Energy Beam Line Polarimeters

Detectors placed in the horizontal or vertical plane can give us information on the normal and sideways polarization components, respectively. To measure the component that is longitudinal at the QDDM spectrometer target, we chose to mount a third pair of polarimeter detectors ahead of a 36° bend in the beam line (see Fig. 1). Because the proton spin precesses about three times faster than the proton trajectory bends in a magnetic field, a polarimeter in this location is sensitive predominantly to the longitudinal component. For 200-MeV protons, the precession angle relative to the proton momentum is ϕ = 78.3°. The small contribution from the sideways component can be extracted using the equation

$$p_L = \frac{p_R - p_S \cos\phi}{\sin\phi} = \frac{p_R - 0.2028\, p_S}{0.9792} \qquad (1)$$

where p_R is the "sideways" component measured by the upstream polarimeter.

The polarimeters observe elastic scattering from a natural carbon target to determine the components of the beam polarization. The scattering angle was chosen to be 20°; because there both the cross section and the analyzing power are large between 140 and 200 MeV. The targets are thin, typically 400 μg/cm^2, and may be placed in the beam while data is being accumulated with

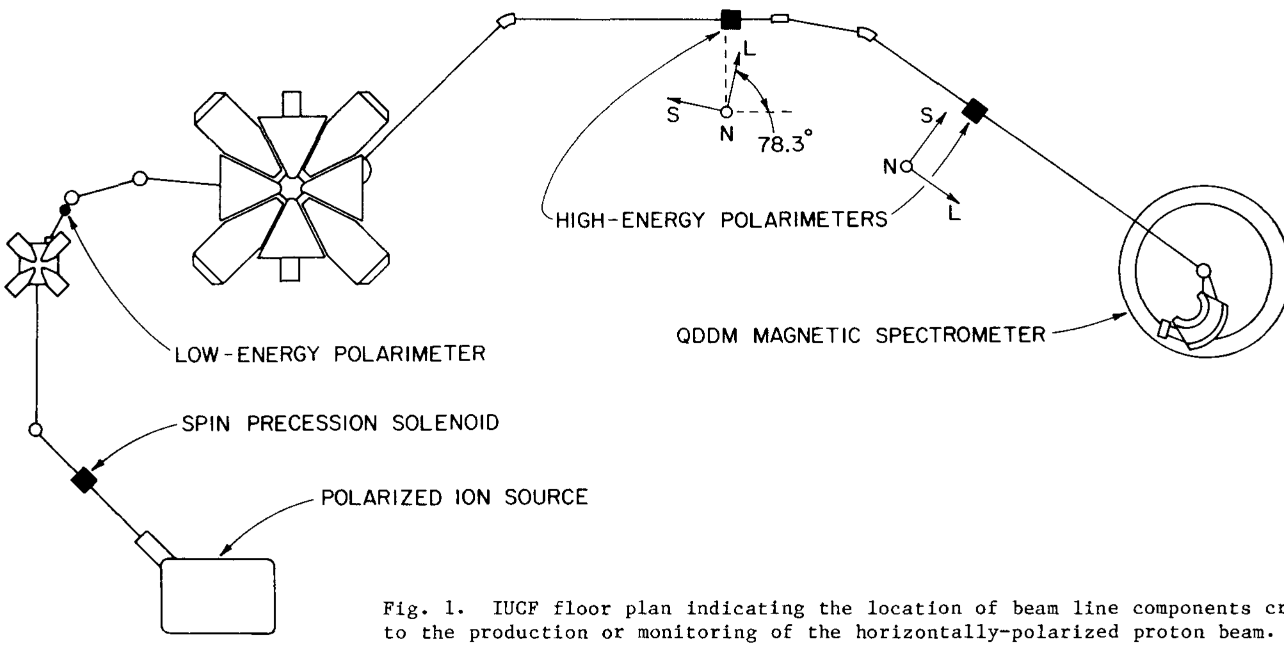

Fig. 1. IUCF floor plan indicating the location of beam line components crucial to the production or monitoring of the horizontally-polarized proton beam. The sideways (S), normal or vertical (N), and longitudinal (L) vectors indicate the orientation of a right-handed coordinate system describing the proton spin as it passes through the QDDM spectrometer target. For the upstream high-energy polarimeter, this coordinate system is shown rotated by an amount equal to the proton spin precession in the bending magnets for the QDDM beam line.

the spectrometer. An upper limit on the total target thickness of 2-4 mg/cm^2 is placed whenever it is necessary to maintain high resolution for a dispersion-matched beam. The detectors subtend a solid angle of 1.2 msr. With beams of a few nA, it is possible to obtain the polarization components with statistical errors less than 0.01 in a few minutes of running time.

The polarimeter detectors are 2" × 5" crystals of NaI(Tl). Each crystal is preceded by a brass collimator with interior slit walls tapered at 5° to reduce the low-energy tailing associated with slit-edge scattering. The phototube signals are integrated in a pre-amplifier and sent through a pulse shaping amplifier to convert total light output into pulse height. The pulse height spectrum from one such

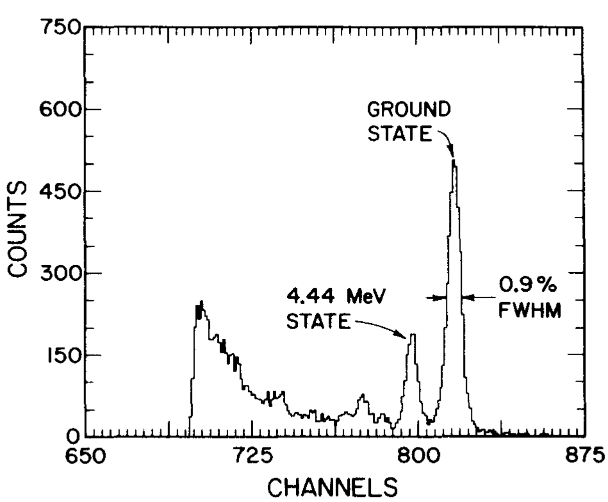

Fig. 2. Pulse height spectrum from a high-energy polarimeter NaI detector. The ground and first excited state are easily resolved. Resolution of the ground state is 0.9% FWHM.

counter is displayed in Fig. 2. The FWHM resolution is due primarily to the large number of photons associated with each stopped proton. The collimator reduces the variation in light collection efficiency from various proton tracks through the crystal, thus contributing to good resolution.

The NaI(Tl) counters have a long decay time for the light output for each pulse, and pileup becomes a problem. In this application, most pileup contributions arise from background processes at a few MeV rather than primary scattering from the target. Within the spectrometer hall, most of the background arises from neutrons whenever the beam is stopped inside the scattering chamber. This limitation has been counteracted by moving that polarimeter as far upstream as possible. For both polarimeters, beam halo striking the beam pipe is occasionally a problem that can be easily remedied by making small adjustments to the beam line steering and focusing elements.

The polarimeters are located at points in the beam line where the beam spot is less than 3 mm in diameter. At this time, we do not have position stabilization for the beam spot on each polarimeter target. If the beam spot moves off-center, an instrumental asymmetry is introduced at the rate of 0.04/mm. In an actual experimental run, this problem is addressed by periodically (usually every 30 s) reversing the spin direction at the ion source. A polarization transfer experiment is sensitive only to the difference between the polarizations measured in each of the two spin states. In this difference, the instrumental asymmetry cancels in first order. To reduce the second order corrections, it is also crucial to ensure that the spin polarization is nearly the same in magnitude for the two states. This was checked by using a polarimeter in the low-energy transfer line between the two cyclotrons where the beam spot is stabilized dynamically on-line. Small adjustments to the RF transition units in the polarized ion source are usually sufficient to make spin "up" and "down" polarizations equal for a given

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setup. The use of the well-known p + α elastic scattering as an analyzer for this polarimeter provides an important check on the absolute magnitude of the polarization.

High-Energy Polarimeter Calibration

The reference reaction for the calibration of the high-energy beam line polarimeters was proton elastic scattering from ^{12}C at 12.5°. This reaction was measured in the QDDM magnetic spectrometer to provide a value of the beam polarization. Each polarimeter was mounted so that each pair of detectors in turn assumed a left-right orientation, and the count rate asymmetry for each pair was measured simultaneously with the beam polarization from the QDDM.

The operating range of the polarimeters for upcoming QDDM experiments is from 170 to 200 MeV. Within this range, there are no reference standards for proton polarization from double-scattering experiments. We therefore calibrated against a standard extrapolated upward in energy[1] to 185 MeV from double-scattering points measured near 138 and 154 MeV. Comparisons between the high-energy polarimeters and the QDDM reference were made at 10 MeV intervals between 170 and 200 MeV, and the reference analyzing powers at 12.5° were taken from a straight line connecting the extrapolated standard point and the double-scattering points at lower energy. We found that the polarimeter analyzing powers agreed well with previous measurements at 200 MeV.[2] In addition, there is a maximum of the analyzing power angular distribution from ^{12}C that comes very close to unity between 15° and 20°. Our calibration places this maximum at 0.96 for 170 MeV and 0.99 for 200 MeV. The results for all three detector pairs are also in close agreement. The average calibration (pending a more thorough analysis) is indicated by the shaded band in Fig. 3. The normalization error, including the contribution from Ref. 1, is about 3%.

Machine Operation and Spin Management

Machine Requirements

Since the proton spin precesses a few thousand times during acceleration, there are significant

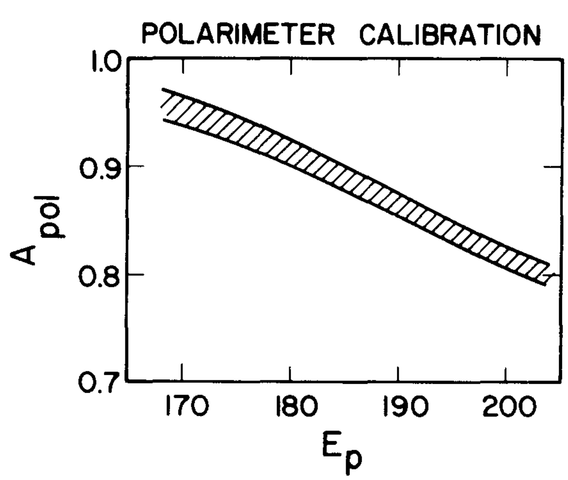

Fig. 3. Analyzing power calibration for the high-energy beam line polarimeters as a function of proton beam energy. The band follows the mean of the calibration for each pair of detectors and has a width given by the statistical errors in the calibration process.

constraints on the stability of the cyclotrons in order to maintain the proton spin direction on target. Stability for the spin direction to within a few degrees implies that the main field and RF frequency (and phase) are regulated at the level of 1 ppm. It is essential that the magnitude of the polarization remain high, which means that the beam must be extracted from both cyclotrons on a single turn. In addition, experiments with the horizontally polarized beam require that both sideways and longitudinal components be available on demand.

Tuning the Spin Direction

The amount by which the horizontal component of the proton spin precesses during acceleration depends on the integral of the vertical magnetic field along the proton's path. Changing the spin direction on target is accomplished by changing the history of the acceleration process. The most effective way to do this without disturbing the quality of the beam is to add or remove a turn from the acceleration pattern in the main stage cyclotron. The spin orientation angle Φ then changes in discrete jumps with turn number N at a rate given by the formula

$$\frac{d\Phi}{dN} = 2\pi\left[\mu + \frac{\langle T\rangle}{m}(\mu-1)\right] \qquad (2)$$

where $\langle T\rangle$ is the average kinetic energy of a turn in the main stage, and μ(m) is the proton magnetic moment (rest mass). In the IUCF main stage cyclotron, the Dee voltage increases with radius in such a way that the turn spacing is roughly constant throughout the machine.[3] This means that the energy gain per turn is lower during the early part of the acceleration process, and $\langle T\rangle$ is about 42% of the extracted beam energy. (This factor is low enough that there is no energy for IUCF where the spin direction cannot be tuned. The spin direction becomes stable with changing turn number when $\langle T\rangle$ = 108 MeV.)

We have found in actual operation that good turn separation is enhanced if the turns are made to cross near extraction in groups of 4. Of the four, only one is actually extracted. To change the spin direction, jumps are made from one bunch to another, and the real angle of change is 4 times the value given by Eq. 2.

Numerous tests have been made of the ability to change spin direction through turn number manipulation. One example is shown in Fig. 4. At 200 MeV, we expect to see 16.8° of spin rotation per turn, and if steps of 4 are made, the spin should change by about 67° every time a new turn (bunch) is brought out of the cyclotron. The observed period, 65°/bunch, agrees well with this expectation. An error of a few degrees is present because of instabilities in the regulation of the Dee voltage over the time of these tests. By selecting turns, it is possible for the experimenter to choose a spin polarization that is predominantly either longitudinal (fifth turn in Fig. 4) or sideways (fourth turn). For the experiments now underway, both components must be used, and in general any pair of approximately perpendicular spin orientations is adequate.

Tests have shown that some limited adjustment of the spin is possible in a continuous way through adjustments of the relative phase of the RF between the injector and main stage cyclotrons. Unless a purely sideways or longitudinal beam is required, this technique had limited utility, since it will leave the tune of the turn pattern altered, mixing turns and reducing the magnitude of the polarization.

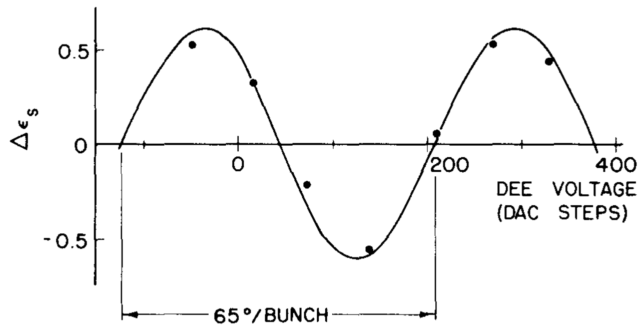

Fig. 4. Measurements of the sideways asymmetry from the QDDM beam line polarimeter as the turn bunch is changed at extraction. This change is made by altering the Dee voltage in the main stage cyclotron. The sine curve is a guide to the eye representing 65° of rotation per bunch. The magnitude of the sine wave is consistent with no horizontal depolarization.

Machine Stability

Our experience so far indicates that the spin direction is held on target with enough stability to be useful (drift rates of a few degrees/hour). This, along with the quality of the tune for single turn extraction, depends on temperature and regulation variations in the magnetic field power supplies. Conditions clearly improve when diurnal temperature variations are small and the cyclotrons are operated for a long time at one field setting.

Ultimately, we need to improve the regulation of the main field and Dee voltage through the installation of feedback loops. For the main field, regulation to better than 1 ppm can be achieved by sensing the phase of the beam pulse relative to the RF voltage at extraction. It is also important that the Dee voltage be regulated so that a single turn remains well-centered at extraction. Any centering error is amplified downstream, and a readout of the left-right deflection can be used to fine-tune the voltage. At this time, the maintainance of these two conditions is done manually by the operations staff. The Dee voltage is the least well-regulated of these two systems, and turn changes are possible if continual attention is not given to tracking the variations in the required Dee voltage regulation.

Off-Axis Spin Components

During the development of the spin precession system, we often measured all three components of the nominal vertically-polarized beam. Between 150 and 200 MeV, we routinely found that the spin direction was tilted with respect to the true vertical direction by angles that varied between a few degrees and 26°. A typical value was 10°. Our tests indicate that both cyclotrons contribute to the problem, although a detailed mechanism for producing the off-axis components is not known. The size of the effect varies with machine tune, and thus may change during the course of an experiment.

Most polarized beam experiments at IUCF employ a detection geometry that is symmetric through the horizontal plane, and, by parity conservation, should be insensitive to the presence of horizontal polarization components. However, changes in the angle of spin tilt between the polarimeter in the transfer line between the two cyclotrons (the one currently used for polarization monitoring) and the target would change the magnitude of the vertical component by a few percent. For most experiments, this is within the size of the systematic errors usually quoted. (It was this problem that led us to seek an independent method for calibrating the analyzing power of the polarimeters used in the high-energy beam line.)

Summary

We have developed a system for delivering a horizontally polarized proton beam to the QDDM magnetic spectrograph target station. In the future we expect to deliver this beam to the Beam Swinger and Polarized Neutron lines as well. The beam can be set for predominantly longitudinal or sideways polarization. This beam has been used at 200 MeV for the measurement of the spin rotation function in proton elastic scattering from ^{12}C.

All components of the spin direction are monitored continuously during the course of an experiment by a set of high-energy beam line polarimeters. These polarimeters have an analyzing power in excess of 0.8 at energies between 170 and 200 MeV.

The present scheme of precessing the spin prior to acceleration allows us the flexibility of orienting the spin in any direction for any target station. It is limited by the quality of the cyclotron tune. Turn patterns without well-separated turns at extraction can depolarize the beam, and drifts in the settings of cyclotron components may cause the spin direction to change on target. At present, these problems are under sufficient control to permit useful data acquisition. We intend to improve the feedback in the regulation of both the main cyclotron field and the Dee voltage in order to achieve greater long-term stability for the acceleration of horizontally polarized beams.

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