Development of an Optically-Pumped Polarized H^- Source for a Parity Nonconservation Experiment.

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Abstract

The optically-pumped polarized H^- ion source at TRIUMF is to be used in a parity nonconservation experiment measuring the longitudinal analyzing power A_z in the scattering of polarized protons from a liquid hydrogen target to an accuracy of $\pm 2 \times 10^{-8}$. The requirements for ion source stability are very high, particularly with respect to helicity-correlated changes in beam current, energy, position and width. Measured energy and beam profile modulations are shown to be within experimental requirements.

1 INTRODUCTION

The aim of the TRIUMF parity nonconservation (PNC) Expt. 497 is to measure the $^3P_2 - ^1D_2$ partial wave contribution to the longitudinal analyzing power A_z in proton-proton scattering at 223 MeV, where the $^1S_0 - ^3P_0$ amplitude crosses zero[1]. The absolute value of A_z at 223 MeV is expected to be only 4-7 $\times 10^{-8}$, and an accuracy of at least $\pm 2 \times 10^{-8}$ is required.

In Expt. 497, the liquid hydrogen target is preceeded and followed by transverse electric field ionization chambers (TRICs) which measure the beam current. During data taking, a precision subtractor circuit will be adjusted to compensate for differences between the two TRICs, producing a zero difference signal for unpolarized beam. The output will then be recorded while reversing the polarization of the beam. The difference signal will be a measure of A_z, provided that helicity-correlated modulations of beam current, energy and intensity profile meet extremely low levels. The upper limit on helicity-correlated current modulation (CCM) is $\pm 0.001\%$. The limit on both helicity-correlated beam position and beam width modulation at the LH_2 target is approximately ± 0.1 μm. Originally, the limit on helicity-correlated energy modulation (CEM) was expected to be ± 5 eV. However, energy modulation of the injected 300 keV beam affects the beam position and beam width at the target, and the limit is actually an order of magnitude smaller.

The operation of the optically pumped polarized H^- ion source (OPPIS) at TRIUMF[2] is briefly summarized as follows. A hydrogen plasma is generated in an electron-cyclotron-resonance (ECR) chamber by 800 W of 28 GHz microwave power, resonant at a magnetic field strength of 1.0 T. A 20 mA, 2.8 keV proton beam is extracted by an accel-accel electrode system and passes through optically pumped, polarized Rb vapour having a thickness of approximately 3×10^{13} atoms cm^{-2}, in a magnetic field of 2.5 T. A fraction of the protons pick up an electron from the Rb to become a fast beam of electron polarized atomic hydrogen. Deflection plates sweep out any charged species and the atomic H beam passes through a field reversal region, where a Sona transition transfers the polarization from the electron to the nucleus. The nuclearly polarized atomic hydrogen then passes through a thick sodium vapour target, where about 10% of the atoms are negatively ionized to form H^- and then accelerated to 300 keV for transport to the TRIUMF cyclotron.

Part of the original motivation for constructing the OPPIS at TRIUMF was that there are no helicity-correlated modulations caused by changing electric or magnetic fields, since spin flip is accomplished by altering the frequency and helicity of the circularly polarized optical pumping laser light. However, many known and unknown mechanisms can produce small helicity-correlated modulations if the Rb polarization or laser power are not identical in "up" and "down" states[3]. Our approach to date has been to measure CCM and CEM under various source conditions, searching for the optimum operating regime, while in parallel continually upgrading the laser controls and diagnostics to minimize laser induced differences. Beam position and width modulation induced by energy modulation has been investigated by applying modulations to the 300 kV accelerating voltage and observing the effects at the two intensity profile monitors (IPMs) in the Expt. 497 beam line.

2 CURRENT MODULATION

CCM has been measured and described in detail previously[3]. It was shown experimentally that CCM could be kept within the specifications of the PNC experiment, although more effort was required to improve the source controls to do this consistently. Optimum source parameters were at a beam energy of 2.8 - 3.0 keV and a Rb thickness of 2-3 $\times 10^{13}$ atoms cm^{-2}.

Two systems were designed for producing current modulation uncorrelated with helicity, as required for calibrating the precision subtractor circuitry. The first consists of a rotating wire mesh having two semi-circular sections of differing transparencies, placed in the 300 keV beam line after the source, producing 10% modulation of the current. Unfortunately the induced modulation at the Expt. 497 target depended on the beam line and cyclotron tunes.

The second system relies on photoneutralization of the 300 keV H^- and produces smaller modulation, as required for calibrating the subtractor over a wide range. A 20 W multi-line argon laser beam was steered down the 300 keV injection beam line so as to copropagate with the H^- beam over a distance of ~30 m. Chopping the laser beam produced a modulation of the H^- current of 0.42%, measured in the TRIC, in good agreement with estimates of photoneutralization of the H^-. Adjusting the laser power provides a variable means of modulating the current in the 4×10^{-3} to 10^{-5} range without changing other beam properties.

3 ENERGY AND BEAM PROFILE MODULATION

CEM was measured at 2.8 keV beam energy using electrostatic apparatus consisting of two pairs of bender plates followed by a Faraday cup. Figure 1 shows the signal modulation at the Faraday cup as a function of bender voltage. The solid line is the instrumental response to a calibration modulation of ±30 mV on the benders, without optical pumping. The open circles show the helicity-correlated signal modulation produced by optical pumping alone. The bender voltage is one third of the beam energy, and the fit between the two data sets implies that the CEM induced by spin flip is $3 \times 30(\pm 10)$ meV = ±90 (±30) meV. The error is estimated from the calibrated change in the instrumental response for a given change in applied voltage modulation. CEM between polarized and unpolarized spin states was also measured. In that case the sign of the CEM was independent of helicity, and the CEM was about five times higher than shown in Fig. 1. The cause of CEM is not well understood but is probably due to variations in space charge conditions in the Rb cell caused by CCM. The conditions for minimum CEM are close to those for minimum CCM.

Energy modulation of the 300 keV injected beam produces changes in the beam profile at the Expt. 497 target. Tests involving an applied modulation of the 296 kV accelerating voltage showed that beam profile modulation was much greater with bunching (used to increase beam transmission through the cyclotron) than without. Figures 2(a) and (b) show beam profile modulations measured at the two IPMs. The applied voltage modulation with bunching was ±6 V, and without bunching it was ±30 V. Profile modulation in the latter case was much less, and current noise was dramatically reduced. The lengthy beam transport from buncher to injection gives rise to this sensitivity to injected beam energy. A change in beam energy results in a change in the timing (with respect to the cyclotron rf) of bunched beam injection, affecting in turn the cyclotron acceptance. Other results showed that profile modulation was approximately proportional to energy modulation, so extrapolating down to a CEM of ±90 meV gives helicity-correlated position and width modulation within Expt. 497 limits only without bunching. Currents of 6-8 μA at the source are necessary to overcome the reduced beam acceptance when running without bunching, at the same time as CCM constrains us to use relatively thin Rb targets of

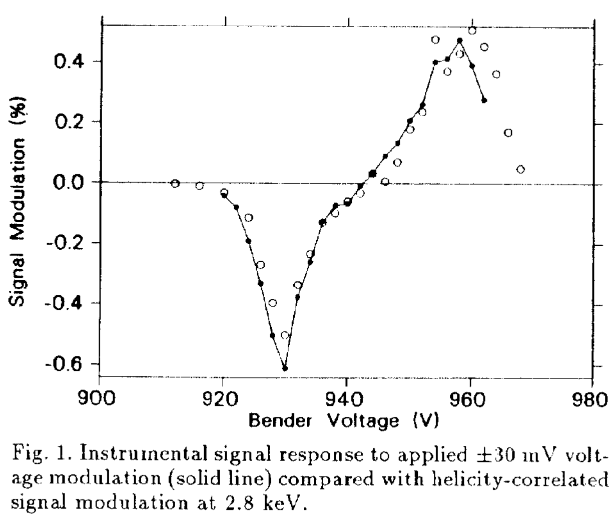

Fig. 1. Instrumental signal response to applied ±30 mV voltage modulation (solid line) compared with helicity-correlated signal modulation at 2.8 keV.

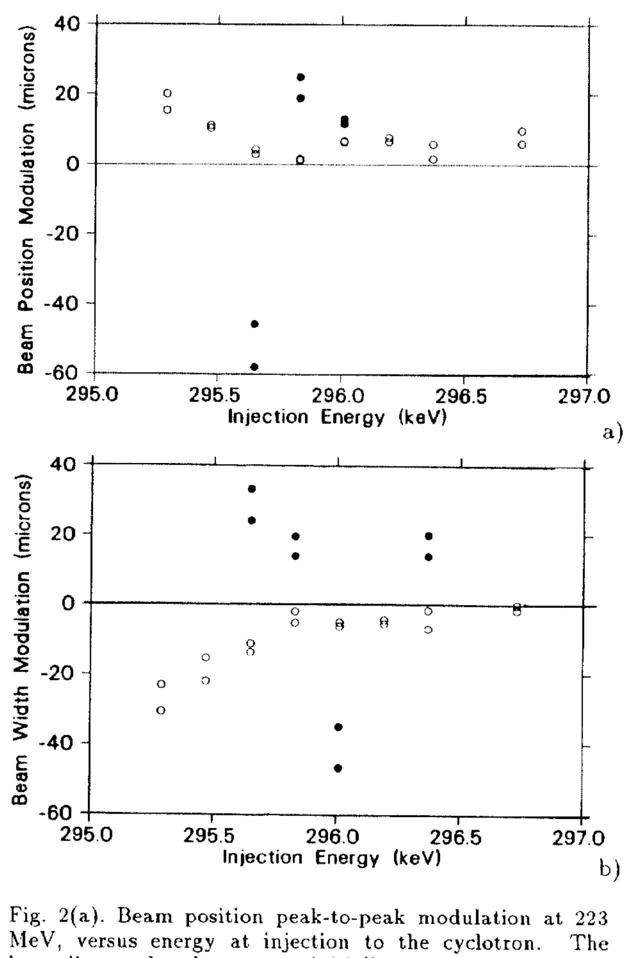

Fig. 2(a). Beam position peak-to-peak modulation at 223 MeV, versus energy at injection to the cyclotron. The beam lines and cyclotron were initially optimized for approximately 296 keV injection energy. Solid circles, bunchers on, ±6 V applied modulation. Open circles, bunchers off, ±30 V applied modulation. (b) Beam width peak-to-peak modulation, same conditions as 2(a).

2-3 $\times 10^{13}$ atoms cm^{-2}. In addition, the beam diameter in the source must be small to eliminate spatial variations in polarization across the beam. These very demanding requirements have been met, but more work needs to be done on improving the long term source current stability and improving the match between the 3 keV source beam and the 300 keV injection beam line optics, where large losses occur. The latest high current records for the source are 120 μA at 78% polarization within a normalized emittance of 1 π mm mrad at a Rb thickness of 8×10^{13} atoms cm^{-2}, and 56 μA at 85% polarization in a smaller emittance.

4 SOURCE CONTROL

Development of source controls has concentrated on producing optimum laser tuning, while keeping the laser power identical in both spin states. In addition, the spin-flip rate must be as high as 120 s^{-1}, since such high rates are essential for synchronous detection techniques used to increase the signal to noise ratio in the PNC experiment. The upgrade of the laser system first described in Ref. 4 has been completed, and has proven to be extremely reliable. The high spin flip rates have increased the accuracy of all the laser diagnostic systems. Laser frequency switching times are 0.5 ms or less. The on-line measurement of Rb polarization, using a gated Faraday rotation technique[4], is very well suited to fast spin flip operation, and has permitted us to automate the laser fine frequency tuning. In our technique, linearly polarized probe light is split into two orthogonally polarized beams after passing through the source. The intensity ratio between the two beams depends on the input polarization, and can be continually monitored. Appropriate gating of the photodetector signals allows separate measurements for spin "up", "down" and "off". At present we are working on improving the system to give the required 0.5% measurement accuracy in polarization that is necessary to ensure that current modulation is kept within acceptable limits. One source of error, now eliminated, was varying Faraday rotation caused by damage to an anti-reflection coating on an optic inside the 300 keV beam line.

The previous laser frequency analogue controllers have been replaced by a digital system that is more accurate, reliable and flexible. The long term laser frequency stability is estimated to be ± 100 MHz, limited by the stability of the hermetically sealed, temperature stabilized reference cavities and associated electronics. Remote control has been added to the mirrors steering the optical pump light into the source, and we plan to automate the fine alignment of these mirrors, again using on-line Rb polarization measurements.

The angle between the optical pump beams and the probe beam has been reduced from 2.5 mrad to approximately 0.75 mrad, and both are closer to the source axis. This has increased H^- polarization by a few percent, by reducing the systematic error in pump laser alignment caused by probe laser displacement from the source axis..

We plan to practically eliminate fluctuations caused by varying Rb vapour thickness, by replacing resistive heaters with a precision hot water circulator. A newly installed external loading system for Rb employs a syringe and heated tubing. This has eliminated oxide formation in the Rb reservoir, which in the past was responsible for long term instability in the vapour thickness.

5 CONCLUSION

The TRIUMF OPPIS has demonstrated in principle the present beam stability requirements for the PNC Expt. 497. Further refinements will continue, with the aim of ensuring reliable delivery and long term stability. Data taking runs for Expt. 497 are scheduled for late 1994 and early 1995.

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