SPIN CORRELATED CURRENT MODULATION IN OPPIS

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ABSTRACT

The modulation of polarized current correlated with spin-reversal has been measured for the first time in an Optically Pumped Polarized Ion Source (OP-PIS). The modulation amplitude depends on the density of the optically pumped Rb vapour and the energy of the primary proton beam in OPPIS. Several physical processes contribute to the current modulation. By optimizing some of the source parameters, the current modulation was reduced to less than 10^{-5} , as measured at 220 MeV in a transverse electric field ionization chamber, part of a parity violation measurement detector system. This is close to the stated requirements of the approved parity violation experiment. A technique of laser control for fast (up to 200 times per second) spin-flip has been developed which should provide for precision control of optical pumping and maintain the spin correlated current modulation below the 10^{-5} level.

INTRODUCTION

The measurement of the parity-violating (PV) analyzing power A_1 in proton-proton scattering to an accuracy of 2×10^{-8} is a challenge for the polarized ion source community, because of the extremely high beam stability requirements, especially with respect to any current or beam energy modulation correlated with spin-reversal.

At Los Alamos a Lamb-shift source produced a low current (less than $1 \mu\text{A}$ at the source) polarized H^- beam for experiments at 15 MeV and 800 MeV. The current, emittance and beam position fluctuations due to the alternating magnetic and electric fields (required for fast spin reversal) were the major factors in the resulting experimental errors - $A_1 = (2.4 \pm 1.1) \times 10^{-7}$ (see Ref.¹).

Atomic beam polarized proton sources were used for A_1 measurements at 13.6 MeV at Bonn University and at 45 MeV at PSI. The use of different rf transitions for spin-reversal gives rise to differences in the proton polarization. An asymmetry in ionization efficiency by polarized electrons leads to some current modulation. The difference between polarized and unpolarized current could be about 1% and is proportional to polarization.² Hence, the current modulation is proportional to the difference in polarization for opposite spin states. As a result a current modulation correlated with spin flip of magnitude $(2-8) \times 10^{-5}$ was observed at PSI.³ The electron beam, or ECR ionizers used in the atomic beam source produce unstable ionization efficiency and beam position. The

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low beam velocity and long relaxation time of the electron polarization in the ionizer are basic limitations, which restrict the spin reversal rate to less than 100 times per second. Nevertheless, after a careful, detailed study of the errors the measurements of A_1 yielded a most impressive level of accuracy with $A_1 = -(1.5 \pm 0.22) \times 10^{-7}$ at 45 MeV at PSI³ and $A_1 = -(1.5 \pm 0.5) \times 10^{-7}$ at 13.4 MeV at Bonn.⁴

The aim of the TRIUMF experiment is to measure the $^3P_2 - ^1D_2$ partial wave contribution to the PV longitudinal analyzing power in proton-proton scattering at 222 MeV, where the $^1S_0 - ^3P_0$ amplitude crosses zero. The absolute value of the PV amplitude at 222 MeV is expected to be only $(4-7) \times 10^{-8}$, less than at 45 or 800 MeV, and a corresponding accuracy of at least $\pm 2 \times 10^{-8}$ must be achieved in the experiment.⁵ In particular, a new approach in polarized beam production is required to meet PV experiment specifications.

In recent years, optically pumped sources of polarized H^- ions have been developed which overcome many of the above problems. The dc OPPIS at TRIUMF reliably produces $20 \mu\text{A}$ of H^- ion current with a proton polarization in excess of 80%.⁶ This has substantially enhanced TRIUMF's facilities for polarization experiments. Data taking has recently been completed in a second generation experiment measuring charge-symmetry breaking in neutron-proton elastic scattering at 350 MeV. A polarized proton beam of about $2.5 \mu\text{A}$ was delivered to a liquid deuterium target in a phase-restricted mode of cyclotron operation, which allowed a reduction in the time-spread of the incident proton beam to less than 0.8 ns (FWHM). A maximum current of about $10 \mu\text{A}$ could be extracted, with slightly lower polarization. In pulsed operation, currents of 10 to $20 \mu\text{A}$ were obtained at LAMPF,⁷ 60 μA at KEK⁸ and 400 μA at INR, Moscow,⁹ with decreasing duty factors respectively, at polarizations of 65 to 70%. The significance of optically pumped sources to PV experiments was realized from the beginning of their development. Spin reversal in OPPIS is achieved by reversing the circular polarization of the pump laser light and adjusting the laser frequency to allow for the Zeeman shift of about 94 GHz at 2.5 T in the alkali-metal vapour charge exchange target. The high field is required to minimize spin-orbital depolarization as excited state hydrogen atoms decay to the ground state. It would appear this should have no effect on the beam current. In addition, the high beam velocity and short polarization rise time of 3 μs allows spin reversal rates up to 1 kHz. Synchronous detection techniques can be used to cancel drifts of the polarized beam, target and detector parameters.

Problems of laser power and frequency stabilization do exist particularly if the highest spin reversal rates are required. It is of course possible to use different lasers for each spin state, although this does not eliminate the need for producing identical power, linewidth and alignment. However, a change in the absolute magnitude of the polarization is not so important in itself, but only insofar as it produces a spin-reversal Correlated Current Modulation (CCM).

BASIC PROCESSES AFFECTING CURRENT MODULATION

Contrary to naive expectations, we have found optical pumping affects the OPPIS current, due to a variety of atomic collision processes. Consequently,

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a difference in optical pumping conditions for opposite polarization directions will give rise to CCM. The sensitivity of these processes to optical pumping is a function of many OPPIS parameters, such as: optically pumped vapour density, energy of the primary proton beam, laser power, polarization relaxation time, proton neutralization on residual gas, etc. As a result, a complicated dependence of CCM on the OPPIS parameters is expected. There are a number of atomic collision processes in the optically pumped vapour which contribute to CCM. H^- production by double charge exchange with ground state Rb: The best understood process is the CCM caused by asymmetry in H^- production in polarized and unpolarized alkali-metal vapour. In an unpolarized vapour, after neutralization, some of the hydrogen atoms can undergo a second charge exchange reaction to become H^- . Since H^- has a single bound state $1S_0$, it cannot be formed by a polarized hydrogen atom picking up an electron from Rb polarized in the same direction. The H^- yield in the optically pumped Rb is given by¹⁰:

$$I(H^-) \sim I_0 C \sigma_0 NL (1 - TP^2) \quad (1)$$

where I_0 is the atomic hydrogen yield in the Rb, $\sigma_0 = 3 \times 10^{-16} \text{ cm}^2$ is the cross section for H^- production, NL is the Rb cell thickness, P is the Rb polarization, and $T = 0.94$ is the polarization transfer ratio between Rb and hydrogen at a magnetic field of 2.5 T. C is a correction factor accounting for integration of H^- production along the length of the cell. The H^- ions which are produced in the Rb cell are swept out of the beam by deflection plates between the Rb cell and the sodium negative ionizer cell (see Fig. 1), giving rise to a dependence of the final polarized H^- ion current on Rb polarization. For Rb polarization P_{up} and P_{down} (P_u and P_d), and corresponding polarized H^- currents I_u , I_d , the following is true:

$$CCM_d^u = \frac{I_u - I_d}{I_u + I_d} \sim \frac{1}{2} CT \sigma_0 NL (P_u^2 - P_d^2) \sim CT \sigma_0 NL (P_u - P_d) \quad (2)$$

since $P_u^2 - P_d^2 \sim 2(P_u - P_d)$, $P_u \sim P_d \sim 1$. For useful PV measurements, in order to exclude the nonlinear response of the ionization chamber detector to the current modulation, the CCM must be of the order of 10^{-5} or less. The above estimate implies that an upper limit on Rb polarization asymmetry is about 0.5%. It can be realized for a thin Rb target with highly saturated polarization, by precision control of laser frequency, power and circular polarization. Later, we will discuss a technique which has been developed for this control in the fast spin-flip mode of OPPIS operation.

Proton neutralization on Rb atoms in excited states: During optical pumping, there is some equilibrium density of Rb atoms in excited states $N^* = N(Rb^*)$, where $Rb^* = Rb(5P_{\frac{1}{2}})$. This density depends on Rb vapour density, laser power and polarization relaxation time. At a typical Rb cell density of about $2 \times 10^{12} \text{ atoms/cm}^3$, radiation trapping gives rise to an increase of the effective spontaneous decay time to more than 10 times the natural 28 ns decay time. We can estimate the density of Rb^* from measurements of absorbed laser power and the effective spontaneous decay time. It is about 1-3% of the full Rb vapour density.

The cross section of electron capture from Rb atoms in excited states is less than the neutralization cross section in collision with Rb atoms in the ground state $-\sigma_{+0}(H^+ + Rb^*) \sim 0.6 \sigma_{+0}(H^+ + Rbg)$ at a hydrogen beam energies of 1-5 keV.¹¹ Therefore, the CCM caused by this effect has an opposite sign to the "double polarized electron capture CCM" discussed above.

H^- production on Rb atoms in excited states: Part of the primary proton beam is neutralized by capture of electrons from residual gas (mostly hydrogen). As a result, unpolarized hydrogen atoms are produced giving rise to a loss of polarization. This unpolarized current depends on the ECR operation, gas efficiency, cell geometry and vacuum pumping. It can be estimated from the H^- ion polarization dependence on optically pumped Rb cell vapour thickness, in particular from polarization drop at low vapour thicknesses. This current is about 3-5% for the TRIUMF OPPIS. For these unpolarized atoms, the capture of a second polarized electron is not forbidden. When Rb vapour is optically pumped, there is some density of Rb atoms in excited states. The yield of H^- ions for $H^0 - Rb^*$ collisions is much higher than in collisions with Rb in the ground state.¹² This effect gives rise to CCM of opposite sign to the above considered CCM due to double polarized electron capture. This is because more H^- ions are produced in collisions with excited Rb atoms and then swept out of the beam by the electric field of the deflection plates. This effect will dominate at low Rb thicknesses, where the background current becomes significant and the "double capture CCM" is small. These two effects should cancel each other at some Rb density which apparently will be optimal for OPPIS operation with PV experiments.

Associative ionization of Rb atoms: Another process producing coherent current modulation is the ionization of Rb vapour by resonant D1 line laser light. Current modulation due to this effect was first seen in sodium at INR, Moscow.¹³ A reduction in current of close to 100% was observed when the sodium density was more than $5 \times 10^{13} \text{ atoms/cm}^3$ and high pulsed laser power was used. The ionization is caused by a process involving collisions between excited state atoms, and is highly non-linear with respect to both laser power and vapour density. Since the ionization process decreases the effective vapour density and hence the polarized current, this modulation is also opposite in sign to the double charge exchange process. It is difficult to calculate the magnitude of the modulation directly, although, from the experimental results at INR, it is estimated to be at the level of 1-2% for 9 W of laser power and a Rb density greater than $5 \times 10^{12} \text{ atoms/cm}^3$. The modulation will tend to zero as the density is increased to very high values, given a finite laser power.

EXPERIMENTAL RESULTS

A detailed description of the laser system upgrade for fast spin reversal is presented in Ref.⁶

The current modulation inside the source at H^- beam energies of 2-3 keV, at 300 keV in the cyclotron injection beam line and at 220 MeV in an ionization chamber (part of the PV detector system), has been studied.

CCM measurements at 2.3 keV. Most of the experiments were done at low energy inside OPPIS. Downstream of the ionizer are electrostatic bender plates which can deflect either H^- or H^+ ions into a low energy polarimeter. Current is measured with a Faraday cup, which intercepts the beam just after the bender plates. The CCM between polarized I_{on} and unpolarized I_{off} currents is defined as follows:

$$CCM_{off}^{on} = \frac{I_{on} - I_{off}}{2I_{off}} \quad (3)$$

In the first experiments the unpolarized current was measured with a blocked laser. A rotating laser beam chopper (Princeton Applied Research M197) modulated a pump laser at a rate of 50-200 times per second. The H^- current from the Faraday cups or ionization chamber was converted to a frequency in a linear current digitizer (with a 4 MHz clock). The frequency signal was gated with laser states "on" and "off", or if fast spin-flip was being used, with "up" and "down" spin states. The gate lengths were identical for both laser states and shorter than the laser modulation times, so that the Rb polarization had time to reach equilibrium. The gated signals were integrated in two CAMAC scalars. The clock frequency was gated by using the same gates and integrated in another two scalars and used to compensate current measurements for the difference in integration time for opposite spin states. Two Ti:sapphire lasers, each pumped by a 20 W Coherent argon laser produced about 9 W of light at 795 nm for optical pumping of Rb. The resulting proton polarization was high and fairly constant over a wide range of Rb vapour thickness. The highest proton polarizations of 75 - 80% were attained at Rb thicknesses of $(2-6) \times 10^{13}$ atoms/cm².

The results of current modulation measurements are shown in Fig. 1. Over the thickness range of $(2-8) \times 10^{13}$ atoms/cm², the current asymmetry rises linearly as expected due to the double charge exchange process and shows quantitative agreement with the above estimates. At still higher thicknesses, modulation changes sign. At a thickness of 9×10^{13} atoms/cm², the CCM has a maximum negative value of about 1%, within expectations. The sudden change from one dominant process to the other at high Rb density (N about 3×10^{12} atoms/cm²) may be evidence of strong nonlinearities of radiation trapping and other processes discussed above. Increasing the density of Rb* states produces larger negative CCM, due to the lower neutralization cross section in collisions with Rb*, and the decrease in the Rb atom density due to associative ionization in Rb*-Rb* collisions. At higher Rb densities, the absolute value of CCM decreases because of rapid laser power attenuation in the vapour. At low Rb density CCM decreases and becomes negative due to the lower neutralization cross section for protons on Rb* and the higher cross section for H^- production from collisions of unpolarized hydrogen atoms with Rb atoms in excited states. In Fig. 1 we can see some indications an even more complicated behaviour of CCM at Rb thicknesses of $1-2 \times 10^{13}$ atoms/cm². Fine CCM structure was resolved using improved temperature control of the Rb cell, as shown in Fig. 2. The temperature of the Rb cell was accurately controlled in this case with circulating hot ethylene glycol solution regulated by a thermostat. Such behaviour of

Fig. 1. Modulation of H^- source current correlated with the laser state "on" and "off", as measured at 2.8 keV beam energy in FC inside the OPPIS.

Fig. 2. Spin-correlated current modulation CCM_{off}^{on} dependence on optically pumped Rb vapour density with improved cell temperature control. Energy of primary proton beam 2.8 keV.

CCM at low Rb density was very surprising so we investigated other processes which could simulate CCM. For example, in CCM measurements at low energy, the real current modulation could not be separated from the spin-reversal correlated beam energy modulations. Our current measuring system, consisting of an electrostatic bender (which allowed the polarized beam to be moved off the laser axis) and Faraday cup, has energy resolution. Therefore, coherent energy modulation could be detected as a current modulation. The CCM measurements at 300 keV are much less sensitive to the beam energy modulations since the first beam bend is at 300 keV and the relative energy modulation is 100 times smaller. A comparison of results at low and 300 keV energies is another way of distinguishing CCM from coherent energy modulations.

Coherent current modulation measurements at 300 keV. Results of CCM measurements at 300 keV are presented in Fig. 3. For these experiments, the fast spin-flip technique was used instead of the rotating-wheel laser beam chopper. In general, the CCM dependence on Rb vapour thickness at 300 keV is similar to that as measured at 2.8 keV, but strong oscillations at low thickness disappeared. A possible explanation of this difference is the energy modulation influence at low energy. More experiments are planned to answer this question. At low Rb density we can calculate the CCM by combining the effects of: double polarized electron capture; neutralization on Rb in excited states; and H^- production from unpolarized hydrogen beam, as follows:

$$CCM_{off}^{on} \sim -\frac{N^*}{N} \left(1 - \frac{\sigma_{+0}^*}{\sigma_{+0}} + B \frac{\sigma_{0-}^*}{\sigma_{0-}} \right) + CT\sigma_{0-}NL P^2 \quad (4)$$

where $\sigma_{0-}^*/\sigma_{0-}$ is the ratio of the H^- production cross sections in excited and ground states; $B = I_0/I^+$ is the fraction of the primary proton beam I^+ which is neutralized by the residual gas. This equation contains all the above discussed qualitative features of CCM. For example, at low Rb density, the first negative term determines the negative sign of the CCM. However, for a detailed quantitative analysis there are too many parameters: N^* , B , σ_{0-}^* , which are not known to the required degree of accuracy.

A CCM dependence on primary proton beam energy could be also explained by using the equation (4) and cross section dependence on beam energy. Experimental results are presented in Fig. 4. Measurements were taken inside the source. At low energy and low Rb thickness the term $B(\sigma_{0-}^*/\sigma_{0-})$ dominates, since the σ_{0-}^* cross section maximum occurs at a lower energy than for σ_{0-} . At higher energy, the "double polarized electron capture" term is responsible for the positive maximum of CCM, and then CCM is decreased due to the drop. This behaviour strongly depends on Rb density. At higher density, the ratio N^*/N increases due to radiation trapping. Therefore, at higher beam energy, where σ_{0-} is smaller, the first negative term might change the CCM sign again to negative. From the expression (4), the CCM(up-down) may be represented as follows:

$$CCM_{off}^{on} \sim C_1 \left(\frac{N_u^*}{N} - \frac{N_d^*}{N} \right) + C_2(P_u - P_d) \quad (5)$$

Ionization effects have not been included. They could be represented as a quadratic term of (N^*/N) and therefore is small at low Rb density. There is no simple relation between the Rb atom polarization and the density of Rb atoms in excited states. Both depend on the Rb density, laser power and polarization relaxation time. To minimize the current modulation at spin-reversal, both terms should be minimized, since cancellation at some point will be inherently unstable. For example, only increasing the laser power for better saturation of Rb polarization (and hence reducing the second term in (5)) is not enough for CCM reduction, since at higher laser power, the ratio N^*/N could also increase, resulting in a larger CCM. At low Rb density, the CCM caused by double polarized electron capture is smaller, but N^*/N is not, in the absence of radiation trapping. Therefore it is necessary to reduce the factor $B(\sigma_{0-}^*/\sigma_{0-})$.

Fig. 3. CCM_{off}^{on} dependence on optically pumped Rb vapour thickness.

Fig. 4. Spin-correlated current modulation CCM_{off}^{on} dependence on energy of primary proton beam.

CCM measurements at 220 MeV. Results of CCM_{off}^{on} measurements are presented in Fig. 3. They are similar to the results of CCM measurements at 300 keV. At 220 MeV the CCM_{off}^{on} was studied for optimal OPPIS parameters, where CCM_{off}^{on} is minimal. During injection, acceleration and extraction of the polarized beam, some additional fluctuations might be introduced. The synchronous detection technique should, in principle, cancel these fluctuations if their frequency is not correlated with the spin-flip rate. A major fluctuation frequency is ac line frequency of 60 Hz. To reduce the influence of this frequency on the CCM measurements, one spin state duration was 18 ms and the length of the measuring gate equal to the period of the ac line (about 16 ms). The spin direction was reversed 25 times per second. Under these conditions, any modulations caused by the ac line must average to zero in a first approximation. As a result at optimal

OPPIS parameters: proton beam energy of 2.8 keV and Rb vapour thickness of 2.5×10^3 atoms/cm² - the following CCM have been measured:

$$CCM_{\text{off}}^{\text{on}} = (45 \pm 8) \times 10^{-5}$$

$$CCM_{\text{f}}^{\text{f}} = (0.9 \pm 0.8) \times 10^{-5}$$

The possibility of reducing CCM to the level specified for PV experiments has thus been experimentally proven. But the problem of OPPIS stabilization and on-line control of CCM at the 10^{-5} level is not completely solved. A much more detailed study of all the basic physical processes must be undertaken to determine the sensitivity of CCM to changing OPPIS parameters. An appropriate system of OPPIS parameter controls and stabilization will be developed to meet these requirements.

CONCLUSIONS

In the first measurements of correlated current modulation in the optically pumped polarized ion source, a complex dependence of CCM on the polarized target density and beam energy has been observed. This dependence may be described as a combined effect of at least four different atomic collision processes. An estimate was made of the degree of optical pumping stability needed to meet the requirements of PV experiments. For optimal OPPIS parameters, CCM was reduced to less than 10^{-5} . CCM measurements at low (2-3 keV) beam energy indicate that modulation of the beam energy during spin flip also occurs. We are now planning a direct measurement of such energy modulation, since a strong limitation on this modulation (less than 3 eV) is specified by the PV experiments.

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