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LAMPF Beam Line Polarimeters

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LAMPF BEAM LINE POLARIMETERS

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ABSTRACT

Polarimeters have been built to measure the polarization of the LAMPF beam (400 to 800 MeV). The polarimeters are simple and reliable and give a 1% result (limited by counting statistics) within a few minutes. The design, calibration, and use of these devices are described.

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I. INTRODUCTION

This report describes the beam line polarimeters that are used in the primary P^- beams at LAMPF to monitor and measure the polarization of the beam. The devices are secondary standards of polarization and are calibrated primarily by the ion source quench ratio technique (Section VII). Some independent checks of this technique are discussed in Section VIII and IX.

II. SCATTERING EXPERIMENTS

The polarization P of a beam of nucleons is given by

$$P = \langle \sigma \rangle = (\uparrow - \downarrow) / (\uparrow + \downarrow) , \quad (1)$$

where $\uparrow, \downarrow$ denote number of particles with spin up, down. If a polarized beam, $P > 0$, scatters from a nucleus then more particles scatter left (L) than right (R), giving an asymmetry

$$e = (L - R) / (L + R) . \quad (2)$$

The analyzing power A is defined by

$$e = AP . \quad (3)$$

The subscript n or y is often added to indicate that the polarization direction is perpendicular to the scattering plane; we shall be concerned with no other case, and will assume that the other cases, $A_x = A_z = 0$ (by parity conservation). The term "polarization" is sometimes used to refer to the polarization produced in a recoil beam by scattering an unpolarized beam from a nucleus. Since this quantity is equal to the analyzing power (by time reversal) the symbol

A will be used for the polarization (or analyzing power) of a reaction, and P for the polarization of a beam.

A beam polarized up and scattered right is equivalent to a beam polarized down and scattered left, so that the yields of two detectors (left and right) may be replaced by the yields in one detector for beam spin up and down. If we combine these two techniques and scatter both left and right simultaneously while also periodically flipping the beam spin, we have four yields, $L\uparrow$, $L\downarrow$, $R\uparrow$, $R\downarrow$. If we redefine

$$L = \sqrt{L\uparrow R\downarrow} \quad \text{and} \quad R = \sqrt{R\uparrow L\downarrow}, \quad (4)$$

then almost all experimental uncertainties and instrumental asymmetries cancel to a high order¹. This technique has been used to measure asymmetries to ± 0.002 , the error being determined solely by counting statistics^{2,17}.

III. THE BEAM LINE POLARIMETERS

In order to obtain the analyzing power (A, which contains the physics) from the experimentally observed asymmetry (e) it is necessary to know the beam polarization P [Eq. (3)]. The beam line polarimeters are secondary standards of known analyzing power. A typical experiment measures the asymmetry for the reaction of interest relative to the asymmetry of the polarimeter.

The reaction chosen for the polarimeters is basically $pp \rightarrow pp$. The reasons for this choice are as follows:

- A. Near 800 MeV the analyzing power for $pp \rightarrow pp$ is the highest of any known reaction.
- B. The broad maximum near 17° lab makes the device insensitive to small errors in angle.
- C. The angle of this maximum remains almost unchanged over a wide range of energies, minimizing the need for geometrical changes to accommodate energy changes.
- D. Detecting both final state protons at conjugate angles gives a very clean signal of elastic scattering.
- E. CH_2 makes a very convenient target.

The same reaction is used at TRIUMF³ and ZGS. The possible need to detect recoil protons at very low energy led TRIUMF to choose a reaction angle of 24°

lab. The large beam at the ZGS led to the detection of only one final state particle.

The LAMPF line EPB and LB polarimeters are shown in Figs. 1 and 2. Protons elastically scattered from CH_2 are detected near 17° and 67° lab in each of four directions, left, right, up and down (the coincidence of 17° left and 67° right is known, by convention, as "Left"). The left-right detectors measure the vertical (y) component of beam polarization while the up-down detectors monitor the horizontal-transverse (x) component. It is impossible to monitor the longitudinal (z) component directly.

The detectors in all cases are plastic scintillators mounted on LAMPF standard photomultipliers chosen to allow narrow time coincidence windows, and for simplicity and reliability. Energy deposited in the EPB and Line B detectors is about 3 MeV. The only essential differences between the beam line polarimeters are in geometry, necessitated by the different beam geometries in the different locations (see Table I).

The electronics consists in principle of HV power for the phototubes ($\approx 1700\text{V}$), discriminators for the anode signals, and fast coincidences. Typical performance is illustrated in Figs. 3 and 4. Each coincidence (L,R,U,D) is scaled in two CAMAC scalers, one gated for "Normal" beam spin (N), the other for "Reverse" (R). The L-R and U-D asymmetries are calculated from the four numbers using the formalism of Section II [Eqs. (2), (4) and reference 2].

IV. SOURCES OF ERROR IN THE POLARIMETERS

The EPB polarimeter has been shown to be reproducible to better than 0.5% .^{2,17} Some precautions regarding possible errors are in order, however.

For accurate work, a delayed coincidence (80 ns) is included, recorded and subtracted. Random coincidences can be calculated approximately knowing that the singles rate in each detector is about 20 times the coincidence rate and that the resolving time is about 10 ns (see Fig. 4). Thus, the randoms rate (for 0.08 duty factor)

$$R \approx \frac{(20 \times C)^2}{0.08} \times 10^{-8} \quad ,$$

where C is the coincidence rate. If C is 10^3 Hz for example then $R = 50$ Hz. Randoms have an asymmetry about half that of true coincidences.

In the case of chopped beam, some care should be taken to ensure that randoms are correctly monitored. The delay is set to 80 ns to accommodate 1 in 16 chopped beam.

Normally, data from the scattering experiment and the polarimeter are collected over exactly the same time period so that variations in the polarization of the beam are exactly compensated for. This might not be the case, however, if the beam polarization changes within the macropulse and dead times are such that the experiment and the polarimeter on average sample different parts of the macropulse. It is conceivable that the beam polarization (which is a function of phase space^{4,5}) could differ between the polarimeter and the experimental target especially if one target does not intercept all of the beam. A 4% difference has been observed at LAMPF between LB and EPB⁵; consequently, comparison between different beam lines should be made with caution.

It should be noted that the magnitude of the beam polarization need not be the same for beam spin Normal and Reverse. (With slow spin reversal this is typically a result of a drift in the tune of the spin filter. With rapid reversal a few percent depolarization of the adiabatically reversed state is inevitable.) It is very difficult to distinguish such a difference between polarizations and an instrumental asymmetry in the polarimeter. For example, yields of $L\uparrow = R\downarrow = 150$, $L\downarrow = R\uparrow = 50$ would indicate $e = 0.5$. A different set of readings $L\uparrow = 155$, $R\downarrow = 145$, $L\downarrow = 55$, $R\uparrow = 45$ could indicate either a larger polarization for $\uparrow$ than $\downarrow$ or an instrumental asymmetry favoring the left detector (e.g., beam steered left). Data with unpolarized beam can be used to investigate the instrumental asymmetry and hence resolve this ambiguity.

A full two-arm experiment (scattering left and right simultaneously) is insensitive to this ambiguity, since writing the beam polarizations as $(P + \delta)$ and $-(P - \delta)$ and taking the geometric means [Eq. (4)] gives (to first order)

$$e = AP(1 + A^2\delta^2/2) \quad .$$

In a single-arm experiment (or if cross sections are to be extracted from polarized beam data), however, such differences may be significant.

$$e = \frac{AP}{1 + A\delta} \quad .$$

Events are detected not only from the reaction $pp \rightarrow pp$ but also from $C(p,2p)$ (quasi-free scattering). The quasi-free events from the carbon in CH_2 are about equal in number to those from the two hydrogen nuclei, but the angular correlation

is spread over about 10° by the Fermi motion in the nucleus. Consequently, about 5% of the prompt events are from carbon, depending on the geometry. Since these events have about half the asymmetry ($A = .275 \pm .015$ at 800 MeV) this leads to an effective analyzing power for each polarimeter that is a few percent lower than for $pp \rightarrow pp$ (differing for each polarimeter, e.g., 3% for EPB at 800 MeV).

This correction could change, however, as a result of the following circumstances:

- A. Substantial misalignment or unusually large beam spots would reduce the combined solid angle of primary and conjugate detectors for $pp \rightarrow pp$ but scarcely affect the solid angle for $C(p,2p)$. This is minimized by making the forward detectors define the solid angle for typical beam spots (see Table I). (See also note 1 of Table 1.)
- B. Substantial depletion of hydrogen from the CH_2 would also increase the ratio of C/H events. (Reference 5 estimates .1%/nA-hr H depletion ($= .1\% \times .03$ change in A for EPB polarimeter) for a 1 mm radius beam spot).

ϕ dependence can enter in two ways, both of which are normally negligible. Taking the simplest case, namely, vertical polarization, if the U-D asymmetry is non-zero then the polarization vector is tilted from the vertical (y). (There may, of course, be a z component, as well as the x component sensed by the U-D asymmetry.) If both the main experiment and the L-R polarimeter asymmetry are sensitive only to the vertical (y) component, then the possible existence of x or z components requires no correction. An important exception, however, is a quench ratio experiment where the quench ratio measures the length of the polarization vector, while the L-R polarimeter asymmetry measures only the y component.

The second ϕ dependence concerns the average value of $\cos \phi$ over the ϕ acceptance of the detectors. For the EPB and LB polarimeters, the ϕ acceptance is about 7° (Table I), for which $\langle \cos \phi \rangle = .999$, a negligible correction. The ϕ acceptance of the main experiment may, however, be significant at forward angles.

V. THE RECOIL PROTON POLARIMETER

The recoil proton polarimeter (which may also be used for neutrons) is designed for double- and triple-scattering experiments. (A triple-scattering experiment is the same as a double-scattering experiment, but using polarized

beam; historically an extra scattering was required to produce the polarized beam.) The device is similar to those at TRIUMF⁷, SIN⁸, and ANL⁹, and consists of MWPCs to define the particles before the (second) target, and MWPCs to define a charged particle after the target²¹.

The standard target is carbon (up to 25 cm thick) with the reaction being $C(p,z)$ (z-charged). Though this target lacks the advantages listed in Section III for CH_2 , it has the essential advantage of high cross section. The analyzing power is about half that of hydrogen near 800 MeV, but twice that of hydrogen at lower energies (few hundred MeV). Carbon was historically chosen because of the possibility of separating elastic from inelastic events at lower energies. The SIN device selects nearly elastic events by range or dE/dX selection, with a gain of about 20% in analyzing power⁸. No such selection is attempted at TRIUMF or ANL (the difficulty of such selection increases rapidly at higher energies). Carbon is retained as the standard target because of the advantages of cross calibration with previous work. There are indications, however, that comparable analyzing powers may be obtained from a variety of targets^{10,11}.

The device is mentioned here because of its potential use for double-scattering calibrations, which would be an independent check of the quench ratio calibration.

VI. DOUBLE-SCATTERING CALIBRATIONS

Double-scattering calibrations of the polarimeters have been discussed in Ref. 12 and 13 but not yet performed.

VII. QUENCH RATIO CALIBRATIONS

The Lamb-shift ion source at LAMPF possesses the capability, unique above Van de Graaff energies, of measuring the beam polarization from the atomic physics properties of the source. This technique, known as the "quench ratio," was developed at the Los Alamos Van de Graaff accelerator⁴ where it has been used and cross checked against $p\text{-}^4\text{He}$ scattering¹⁴ to obtain a calibration to $\pm 0.4\%$.

The method has been described in detail² and so will only be described briefly here. The LAMPF ion source consists of three major components: cesium cell, spin filter, and argon cell. The cesium cell provides a beam rich in hydrogen atoms in the 2s excited state. The spin filter "quenches" to the ground state all but those in one electron-proton spin configuration. The argon cell

preferentially ionizes the 2s-state atoms, giving a beam consisting primarily of polarized particles from the 2s state, but with some unpolarized background from ionization of ground-state atoms.

When the spin filter is detuned, all 2s atoms are quenched so that only this unpolarized background remains. The ratio of beam intensities for these two cases, known as the "quench ratio Q", yields the beam polarization $P = 1 - 1/Q + P_q/Q$. [Since P_q is typically -0.03, the term P_q/Q is a small (0.3%) correction for the slight polarization P_q of the quenched beam.] Figure 5 shows the effect on both polarization and intensity of detuning the spin filter by changing the magnetic field B (known as a " ΔB quench").

The major assumptions behind this measurement of the beam polarization are as follows:

- A. The unpolarized component must be unperturbed by the quenching. We have compared the ΔB quench with a ΔE quench obtained by changing the spin filter electric field, expecting any perturbation to be different in these two cases. Comparison of the two results indicates a 0.2% to 0.5% correction in the ΔE case.
- B. There must be no depolarization between spin filter and experimental target. The quench ratio measures the polarization as it existed in the spin filter. Subsequent depolarization would not affect the measured quench ratio and would therefore lead to error.

The possibility of depolarization is difficult to check empirically. A calculation was made in 1968¹⁵ which indicated that depolarization in the accelerator would be of the order of 0.1%. Our empirical checks of depolarization have been limited to a comparison of different phase-space components measuring in each case the ratio of polarization measured by the quench ratio and by the EPB polarimeter. This "effective analyzing power" should not change. If depolarization occurs, we expect that different phase-space components of the beam will be differently affected. Furthermore, since the entire H^- beam spends much of its time off axis in the accelerator, magnetic depolarizing effects should also precess the average spin direction, and should vary from one cycle to the next depending on the accelerator tune. These empirical checks so far indicate that depolarization is $0 \pm 1/2\%$.

Within the ion source, we have observed up to 30% depolarization under extreme conditions (e.g., spin filter and argon cell fields opposed). With

reasonable settings, we do not observe any change as a function of field, indicating $0 \pm 1/2\%$ depolarization in the source.

It has been observed^{4,5} that the polarized and unpolarized components of the beam have different phase space so that phase-space selection by beam stripping can change the average polarization. It is therefore essential to measure the quench ratio at the scattering target. Unfortunately, we are then at the mercy of accelerator noise which causes intensity fluctuations unconnected with the quench ratio that we wish to measure. Averaging out the accelerator noise is time consuming and limits the accuracy that we have obtained at this time.

VIII. POLARIZED TARGET CALIBRATION

The pp analyzing power can be measured by scattering polarized beam from unpolarized target or unpolarized beam from polarized target. By comparing these two results one can compare the calibrations of the polarized beam and the polarized target. Such a comparison was made using the data from the spin correlation experiment (Experiment 27) of 1977^{12,16}. The results are consistent within experimental errors with the quench ratio calibrations^{2,17}.

The polarized target calibration is entirely independent of the quench ratio calibration. During the scattering, the target material ($C_3H_8O_2$) is polarized (enhanced $P \approx 0.83$) by optical pumping in a 2.5t magnetic field, while cooled to about 0.4K in liquid 3He . The polarization is proportional to the integrated NMR signal as a frequency modulated RF field passes through the proton resonance. The absolute calibration is obtained by comparing this signal with the "thermal equilibrium" signal obtained after the proton spin temperature has been allowed to equalize with the temperatures of the 3He bath. The polarization is then known from Boltzman statistics, knowing the magnetic field and temperature (≈ 1 Kelvin, from the 3He vapor pressure).

Repeated measurements spanning several months were consistent to about 0.5%. The average ratio of the independent calibrations from the quench ratio and the NMR was

$$\frac{P(\text{quench})}{P(\text{NMR})} = 1.002 \pm 0.005 .$$

The ± 0.005 error represents the internal consistency only. Overall systematic errors that might arise in the NMR calibration are discussed in Ref. 16, and are estimated to be no more than $\pm 2\%$.

IX. COMPARISON WITH OTHER LABORATORIES

A calibration of the P^- beam polarization at 428 MeV was performed in 1978¹⁷ to compare with recent calibrations at TRIUMF^{18,19}. The quench ratio technique was used to calibrate the EPB polarimeter at 428 MeV. Standard techniques were then used to measure the asymmetry in $pp \rightarrow pp$ at 24° lab. The LAMPF result $A_y = 0.387 \pm .008$ at 428 MeV, compares reasonably with the TRIUMF calibrations of $0.381 \pm .006$ at 410 MeV and $0.400 \pm .004$ at 440 MeV¹⁸, and the phase shift fit, 0.385 at 425 MeV²⁰. The performance of the ion source during this period was, however, unusual. Of particular concern was the observed polarization of 0.18 for the quenched beam, which necessitated a 3% correction to the quench ratio calibration. Two calibrations at 796 MeV performed at the same time were 0.6% and 1.5% lower than usual. Consequently, a correction factor of $1.01 \pm .02$ has been applied to the 428 MeV data.

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Fig. 1 - EPB polarimeter.

Fig. 2 - LB polarimeter.

Fig. 3 - Detector performance as a function of phototube HV.

Fig. 4 - Detector performance as a function of coincidence timing.

Fig. 5 - Asymmetry ϵ and intensity I as a function of spin filter magnetic field (solenoid current). This illustrates the ΔB quench.

TABLE I - POLARIMETER GEOMETRY. [Width, etc., refer to horizontal detectors (L-R); the U-D detectors are identical.]

Polarimeter	Angle (deg)	Radius (inch)	Width (inch)	Height (inch)	Thick (inch)	Typical ² Target (inch)	Rates/pc		Max. Beam Spot (rms, mm)	
							Singles	Coincidence	Width	Height
EPB	17.0	18.75	.75	.75	.50	2 X 2 X .01	10	1	10	5
EPB	66.4 ¹	6.8	.75	1.625	.25	2 X 2 X .01	20	1		
LB ³	17.0	21.4	.75	.75	.50	2 X 2 X .002	1	.1	20	10
LB ³	68.0	6.75	1.0	3.0	.25	2 X 2 X .002	5	.1		

¹ This angle should be changed for low energy operation.

² Maximum target thickness = 0.25 inch.

³ Note that the 16° bend (LB-BM-05) between the polarimeter and LD₂ targets precesses horizontal spin components through 53° at 800 MeV.

TABLE II - POLARIMETER DATA

<u>Reaction</u>	<u>Angle (lab)</u>	<u>Energy</u>	<u>Analyzing Power</u>
EPB Polarimeter	17.0	796	.481 $\pm$.002
EPB Polarimeter	17.0	787	.486 $\pm$.003
EPB Polarimeter	17.0	643	.538 $\pm$.002
EPB Polarimeter	17.0	428	.465 $\pm$.010
LB Polarimeter	17.0	800	.46 $\pm$.01
pp $\rightarrow$ pp	16.9	796	.495 $\pm$.003
pp $\rightarrow$ pp	16.9	787	.501 $\pm$.003
pp $\rightarrow$ pp	17.4	643	.548 $\pm$.004
pp $\rightarrow$ pp	17.0	428	.476 $\pm$.011
pp $\rightarrow$ pp	24.0	428	.387 $\pm$.008