

Systematic Errors in measurement of b_1

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Abstract. A class of spin observables can be obtained from the relative difference of or asymmetry between cross sections of different spin states of beam or target particles. Such observables have the advantage that the normalization factors needed to calculate absolute cross sections from yields often divide out or cancel to a large degree in constructing asymmetries. However, normalization factors can change with time, giving different normalization factors for different target or beam spin states, leading to systematic errors in asymmetries in addition to those determined from statistics. Rapidly flipping spin orientation, such as what is routinely done with polarized beams, can significantly reduce the impact of these normalization fluctuations and drifts. Target spin orientations typically require minutes to hours to change, versus fractions of a second for beams, making systematic errors for observables based on target spin flips more difficult to control. Such systematic errors from normalization drifts are discussed in the context of the proposed measurement of the deuteron b_1 structure function at Jefferson Lab.

1. Introduction

The deuteron tensor structure function b_1 has been measured at intermediate x with HERMES [1]. An experiment at JLab (E12-13-11 [2]) seeks to improve upon this measurement, taking advantage of the substantially higher luminosity that can be achieved with solid targets. b_1 can be related to the tensor asymmetry A_{zz} by

$$b_1 = -\frac{3}{2}F_1^d A_{zz}. \quad (1)$$

This asymmetry is obtained from the difference of inclusive electron scattering cross sections on deuterium in tensor polarized (with polarization P_{zz}) and unpolarized states.

$$A_{zz} = \frac{2}{P_{zz}} \frac{(\sigma_p - \sigma_u)}{\sigma_u} = \frac{2}{fP_{zz}} \frac{(Y_p - Y_u)}{Y_u} = \frac{2}{fP_{zz}} A_{zz}^{\text{raw}}. \quad (2)$$

As the proposed JLab measurement uses an ND₃ target rather a pure deuteron target, the experimentally observed asymmetry must be divided by a “dilution factor” f which represents the fraction of the total yield due to scattering on deuterium. For an ND₃ target, which includes impurities such as helium and target wall materials, the dilution factor is

$$f = \frac{N_D \sigma_D}{N_N \sigma_N + N_D \sigma_D + \sum A N_A \sigma_A}. \quad (3)$$



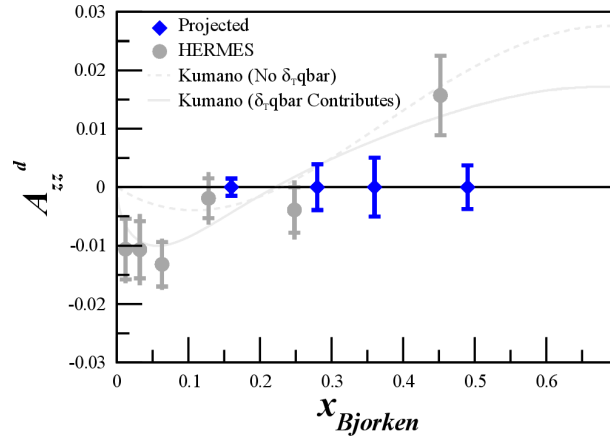


Figure 1. Projected A_{zz} statistical errors for the JLab b_1 experiment.

The dilution factor does vary as function of scattered electron energy (or x), particularly at kinematics where nucleon resonances are prominent. However, for the purpose of discussing systematic errors, it is reasonable to assume that $\sigma_A/\sigma_D = 14/2$ and that the \sum term (accounting for other materials such as helium and target wall material) can be neglected. These assumptions then give a dilution factor of $f \approx 3 \times 2/(14 + 3 \times 2) = 0.3$.

2. Measuring beam asymmetries

The expression for the A_{zz} asymmetry is similar to the expression for asymmetry based on flipping beam helicity,

$$A = \frac{1}{P_b} \frac{(\sigma_+ - \sigma_-)}{(\sigma_+ + \sigma_-)}, \quad (4)$$

where P_b is the polarization of the beam and σ_+ and σ_- are the (doubly differential) cross sections of the process of interest for two opposite beam polarization directions. Measurement of such asymmetries are attractive, because in the method of converting scattering yields to cross sections,

$$\frac{d\sigma(E_b, \theta, E)}{dE d\Omega} \leftarrow N(E_b, \theta, E) \frac{1}{\Delta\Omega} \frac{1}{\Delta E} \frac{e}{Q} \frac{A}{t\rho N_A} \frac{1}{\epsilon}, \quad (5)$$

the various normalization factors and the kinematics (beam energy, scattered particle angle, scattered particle energy) are naively identical (even if not accurately known) for the two polarization states. (Q is accumulated beam charge passing through a target, t is target thickness, ϵ is the overall detector efficiency, while $\Delta\Omega$ and ΔE are the solid angle and energy acceptances of the detector.) If the normalization factors and kinematics are indeed identical for the two spin directions, then errors in the asymmetry are only from statistics and any errors in the beam polarization P_b .

All of these normalization and kinematic quantities can and do drift or fluctuate with time to varying degrees and can even be correlated with spin direction. Effects that lead to errors in the asymmetry are generally referred to as false asymmetries or systematic errors. In many classes of measurements, the asymmetry is large enough that these effects are negligible. But in the push to access fundamental nucleon properties with parity violating electron scattering, asymmetries smaller than 1×10^{-6} are being routinely targeted. Some examples of effects that can give false asymmetries at this level are:

- Density fluctuations in a liquid target that exceed statistical fluctuations.

- Helicity correlated beam properties so that σ_+ and σ_- are measured at different beam energies or kinematics
- Fluctuations in the calibration of beam current measuring devices

While the systematic errors from any of these uncertainties can easily swamp the asymmetry, good planing and experiment design can overcome these issues. Techniques employed in experiments such as HAPPEX, G0 [3], and Qweak [4] include rapid helicity reversal, attention to target design, beam diagnostics, beam property feed back systems and others.

3. Fixed Target Asymmetries

While fundamentally the same, measuring asymmetries between different fixed target spin states differs in one important manner, namely that the time required to change the magnitude or direction of target spin ranges from minutes to hours. Experimental parameters and conditions that may be stable at the one second level may fluctuate at longer time scales due to environmental effects including temperature, barometric pressure and power conditions.

Potential contributors to systematic errors include:

- Beam
 - Current measurement** Instability of the calibration of beam charge measurement devices.
 - Beam energy** Relative yield changes from the strong Q^2 dependence of electron scattering cross sections can be comparable to raw target asymmetries.
 - Beam direction** A change in beam direction changes the scattering angle, changing yield.
- Target
 - Thickness stability** The ND₃ is composed of beads, which allows liquid helium to flow around the target material. With time, the position of these beams can shift, causing the amount of material seen by the beam to change.
 - Beam motion** For a target of non-uniform thickness, such as ND₃, a change in beam position will change the target thickness seen by the beam.
- Detection
 - Detectors** Drifts in photomultiplier tube (PMT) gain can change the number events above a discriminator threshold or that pass particle identification (PID) cuts. Atmospheric pressure and temperature changes can affect drift chamber efficiency.
 - Spectrometer field** A drift in spectrometer analyzing field will change yields both due to cross section dependence on scattered electron energy and due to the changed momentum acceptance.
 - Target holding field** For polarized targets with large holding fields, drifts in this field can change the kinematics (scattering angle and energy) of particles reaching the detectors.

The extent to which any of the above contribute to systematic errors in a target asymmetry depends upon the desired accuracy in the asymmetry measurement, the time-scale at which the target spin state can be cycled, and the degree to which the stability of the above factors can be controlled or monitored.

4. Systematic errors in b_1 measurement

Measurement of b_1 will push the requirement to understand and control instabilities in normalization factors and experimental conditions. The existing measurements, which used a polarized deuterium gas jet target, show a typical physics asymmetry A_{zz} of ~ 0.01 (Fig. 1). The JLab b_1 experiment proposes to measure this asymmetry with an error $\Delta A_{zz} \sim 0.005$ or better, taking advantage of the higher available luminosity. The trade-off with the increased

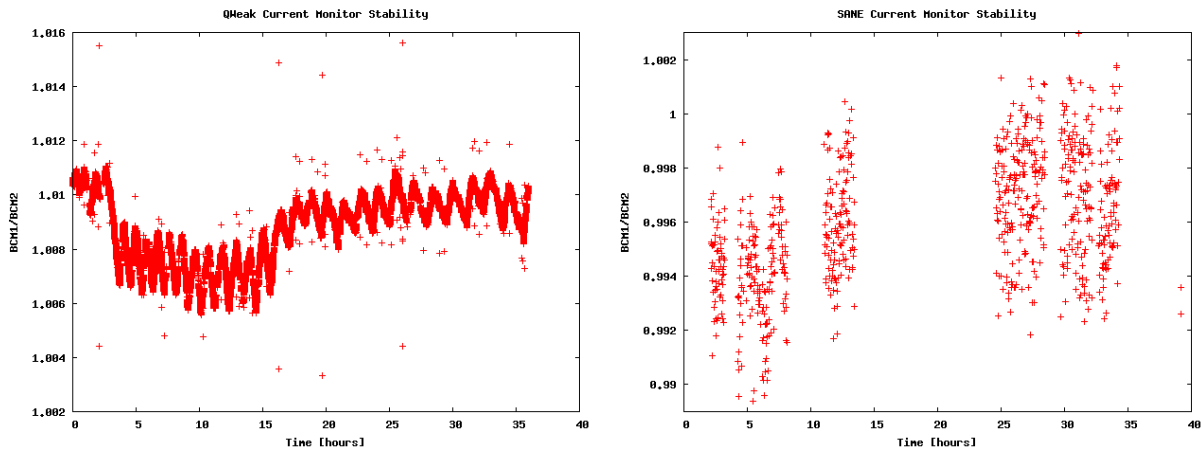


Figure 2. The left figure shows the ratio of the two standard Hall C beam current monitors over a 40 hour period during the Qweak experiment with a beam current of $\sim 180 \mu\text{A}$. The right figure shows the ratio of these same current monitors over a 40 hours period during the SANE experiment with a beam current of $\sim 100 \text{ nA}$. In both cases, the relative stability of the current monitors is worse than 1×10^{-3} , showing oscillations with a period of about an hour and longer term drifts on the scale of a day.

luminosity is that the scattering yield from deuterium in a polarized ND_3 target is diluted by the nitrogen and the deuterium tensor polarization is less than what is available from gas jet targets. With the dilution and assuming that $P_{zz} = 0.20$, Eq. 2 implies that a raw asymmetry precision of better than $\Delta A_{zz}^{\text{raw}} = \frac{f P_{zz}}{2} \Delta A_{zz} = \frac{0.3 \times 0.2}{2} 0.005 = 1.5 \times 10^{-4}$ is required.

The polarized ND_3 target takes about an hour to achieve full polarization from an unpolarized state. Therefore, it is impractical to change the target polarization state more than 2 or 3 times per day without losing significant beam time. This both subjects the measurement to diurnal drifts and limits the number of times that the polarization state can be changed in order to average out fluctuations.

An example of an issue which, if unaddressed, would render the b_1 measurement impossible, is the stability of the beam current monitors (BCMs) used to measure charge incident on the target. Figure 2 shows the ratio of current measured by two different BCMs in Hall C at JLab. The relative calibration of these two BCMs shows instabilities greater than 1×10^{-3} at time scales of both an hour and a day. It is important to note that the BCMs and the data acquisition have not been optimized for target asymmetry experiments, but rather only to have a stability better than 0.5%, which is sufficient for cross section measurements.

Some of the more subtle potential contributions to systematic errors in A_{zz} are instabilities in beam energy, beam direction and magnetic field of the detection spectrometer. The contributions of each of these depends on the sensitivity of the yield to each of these parameters and the precision to which these parameters can be controlled or measured over times scales of hours to days. Table 1 shows the sensitivity of the deuterium electron scattering cross section (from the Bosted/Christy [5] cross section fit) to these parameters. These sensitivities indicate that in order to keep the systematic errors on A_{zz} less than 1×10^{-4} , both the beam energy and the scattered electron energy must be controlled to better than 1×10^{-4} . Similarly, because a change in beam direction is a change in scattering angle, the beam direction must in some cases be held stable to better than 5×10^{-6} radians. (Note: There are no strong requirements on energy/angular spread or on the accuracy of the absolute determination of these parameters.)

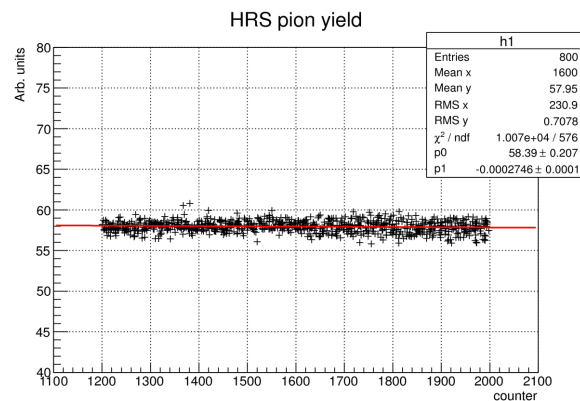


Figure 3. The pion yield in the HRS spectrometer over a 15 day period during Hall A Transversity Experiment, E06-010 [6]. The primary measurement during this experiment was $(e, e'\pi)$ coincidence events. Higher rate pion singles were monitored during experiment, providing a check on the stability of the product of beam current calibration, target thickness and detector efficiency. A straight line fit to the yield (pion counts normalized by beam charge and dead time) shows a drift of 0.38% over 15 days, or a drift of 2.5×10^{-4} per day.

5. Controlling Systematic Errors

The Hall A Transversity experiment [6], E06-010, demonstrated that the stability requirements of the b_1 experiment may be achievable. This experiment measured target asymmetries of the $(e, e'\pi)$ reaction on a polarized ^3He target. As this was a coincidence measurement, the high singles rate in one of the spectrometers (from the inclusive reaction $^3\text{He}(e, \pi)$), could be used as a stability monitor. Figure 3 shows the singles rate normalized only by beam current and deadtime, providing a monitor of the combined stability of BCM calibration, target thickness, detector efficiency, spectrometer optics and beam properties. The long term trend of this normalized yield is a drift of 2.5×10^{-4} per day, which is near the stability requirement of b_1 measurements.

As the b_1 experiment is a singles measurement, there is no higher rate background reaction (with a null or known target asymmetry) that can be used as a simultaneous measure of the combined stability of beam, target and detector parameters and calibrations. Further study of

Table 1. Estimates of the sensitivity of the $d(e, e')$ cross section and yield to variations in beam energy (E_b), scattered electron energy (E_o) and scattering angle θ for the kinematics of the b_1 proposal, calculated from the Bosted/Christy fits to electron-deuteron scattering cross sections [5]. The fourth column, the yield sensitivity to spectrometer field changes, includes the change in the momentum acceptance from the change in spectrometer momentum. The last column, the sensitivity to scattering angle, is in units of inverse radians.

x	$\frac{d\sigma}{dE_b} \frac{E_b}{\sigma}$	$\frac{d\sigma}{dE_o} \frac{E_o}{\sigma}$	$\frac{dY}{dE_o} \frac{E_o}{Y}$	$\frac{d\sigma}{d\theta} \frac{1}{\sigma}$
0.16	-2.03	0.28	1.28	-9.6
0.30	-1.08	-1.07	-0.07	-14.0
0.45	-0.73	-2.22	-1.22	-18.7
0.55	-0.37	-4.06	-3.06	-20.9

previous and future experiments which have long periods of data acquired at fixed kinematic settings can be useful. These studies can help to determine what experimental parameters are the most unstable and thus require the most effort to develop techniques to mitigate the resultant systematic errors.

In order to control the systematic errors on the measurement of b_1 , a number of techniques will need to be developed to monitor the stability of the various experimental parameters that can contribute to these errors. Some possible measures include:

- Take periodic measurements of yield using higher currents on a solid target to provide a periodic check of the stability of the combination of beam current calibration and detector efficiency. Since inclusive nuclear cross sections have similar dependencies on incoming energy, outgoing energy and scattering angle as deuterium cross sections, these measurements also fold in the stability of those quantities. These high yield measurements could be made during periods in which the polarized target is being repolarized.
- Improve Beam Current Monitors. The stability of the standard JLab BCMs can be improved by providing better temperature stabilization of the BCM cavities, stabilizing the temperature of analog cables and minimizing the length of those cables. Averaging multiple BCMs, with independent temperature stabilization can further improve the stability of current measurement.
- Independent current measurement techniques should be explored. As the ND₃ target limits the beam current to about 100 nA, a Faraday Cup can continuously monitor current and provide a stability check on other beam current measurements.
- Luminosity monitors, small integrating detectors placed at small scattering angles downstream of the target, provide a relative monitor of the product of beam current and target thickness. While luminosity monitors have a high statistical precision, care must be taken to demonstrate that the luminosity detectors have a long term efficiency stability that is better than the stability requirement of the experiment. However, even in the absence of this stability, such detectors can be used to detect sudden changes in target thickness from shifting of the ND₃ beads or a change in beam position on the target.
- The gain of PMTs should be stabilized as much as possible by keeping stable temperature and high voltage. Several PMTs could be instrumented with good temperature and voltage probes in order to establish that these quantities are stable. The thresholds on discriminators should be set as low as practical and PID cuts in analysis should be set as wide as possible to minimize the sensitivity to drifts in PMT gain.
- Existing techniques to stabilize beam energy and orbit should be extended. Techniques that focus on long term stability, including careful monitoring of transport dipole magnetic fields and a Synchrotron Light Interferometer, have been developed for low rate spectroscopy measurements such as the hypernuclear program [7].

In the above, the emphasis needs to be on stability and the accurate monitoring of changes. Requirements on the absolute determination of experimental parameters such as beam energy, current, target thickness, solid angle, etc. are similar or more relaxed than the requirements of typical spectrometer experiments. For some parameters, such as detector efficiencies, it may not be possible to monitor their stability with sufficient accuracy during the measurement. For such cases it may be necessary to use other higher rate reactions to study the stability of the parameter and its sensitivity to measurable environmental conditions such as temperature and air pressure.

6. Conclusion

Measurements of quantities such as b_1 that are derived from target asymmetries present unique challenges when measuring raw asymmetries with an accuracy of the order of 1×10^{-4} .

Comprehensive identification of all potential sources of systematic errors, some of which are described here, will be required. New instrumentation and techniques will need to be developed well in advance of experiments that seek to measure such asymmetries. Use of these techniques in other experiments with less stringent requirements will help to gain experience and establish the feasibility of controlling and monitoring experimental conditions over long time periods.

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References

- [1] Airapetian A *et al* 2005 *Phys. Rev. Lett.* **95** 242001
- [2] Slifer K *et al* 2013 E12-13-011: The deuteron tensor structure function b_1 *Proposal to Jefferson Lab PAC40*
- [3] Androic D *et al* 2011 *Nucl. Instr. Methods A* **646** 59
- [4] Androic D *et al* 2013 *Phys. Rev. Lett.* **111** 141803
- [5] Bosted P E and Christy M E 2008 *Phys. Rev. C* **77** 065206
- [6] Allada K *et al* 2014 *Phys. Rev. C* **89** 042201
- [7] Tang L *et al* 2014 *arXiv*:1406.2353