Sources of Helicity-correlated Electron Beam Asymmetries

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Abstract. The availability of high current, high polarization electron beams from laser-driven GaAs photocathodes has enabled a broad program studying parity violation in electron scattering. Precision measurements of the tiny (<1 part per million) parity-violating beam-helicity asymmetry are used to study the structure of nuclei or to test the Standard Model of electroweak interactions. As these experiments grow ever more precise, asymmetric beam properties between the two beam helicity states threaten to become the leading source of experimental uncertainty.

These helicity-correlated beam asymmetries are predominantly created in the conversion of circularly polarized laser light to a polarized electron beam. In recent experiments at Jefferson Lab, improved techniques for configuring the laser optics of the polarized source have been used to control beam asymmetries to such a level as to be a negligible source of systematic uncertainty. This successful result serves as a promising start for the next generation of parity-violating electron-nuclear scattering measurements, which strive to improve precision by a factor of twenty.

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INTRODUCTION

The study of parity violation in electron scattering provides a way for isolating the weak neutral-current interaction between an electron and nucleus. It is also employed as a search for interactions beyond the electroweak Standard Model, which would be indicated by measurements which deviated from precisely predicted values based on the known quark and electron electroweak charges. In these experiments, longitudinally polarized electrons are scattered from unpolarized targets. For elastic scattering, or for fully inclusive measurements detecting only the electron, a cross-section asymmetry under change in the electron helicity violates parity, and in the Standard Model this difference in cross-section can only arise through the weak neutral current. This asymmetry, $A_{PV} = (\sigma_R - \sigma_L)/(\sigma_R + \sigma_L)$, ranges between $10^{-3}$-$10^{-7}$ for published experiments.

One challenge of these experiments is that changes in the beam properties (intensity, position, profile) will change the detected scattered flux. If the changes in the beam are correlated with the electron helicity, the result can mimic the tiny parity-violating asymmetry. Corrections for these changes are typically made with precision of around 10%. Helicity-correlated beam asymmetries (HCBAs) are therefore a potential systematic error in the measurement of small asymmetries.

The PREX experiment, to run at Jefferson Lab in Hall A in early 2010, and the QWeak experiment, which will start in mid-2010, have precision goals which are approximately an order of magnitude better than what has been previously achieved in scattering from nuclei. Of the two experiments, the PREX experiment, which aims for a precision of
$15 \times 10^{-9}$, is more demanding in terms of helicity-correlated beam changes due to the form-factor of the heavy lead nucleus which enhances the sensitivity of cross-section to scattering angle. The PREX experiment aims to keep helicity correlated beam motion to $< 1$ nm (as was accomplished for HAPPEX-II) and the bound the beam spot difference to $< 10^{-4}$ of the intrinsic beam size.

**POLARIZED ELECTRON BEAM ASYMMETRIES**

The polarized electron beam is created using a technology first developed at SLAC to enable the original measurement of parity violation in electron scattering [1]. (For a recent review of the development of the polarized electron photoemission source, see [2].) Laser light illuminates a semiconducting photocathode, the surface of which has been chemically treated to produce a negative work function. Laser light promotes electrons from the valence band to the conduction band of the semiconductor, where they are drawn out by an electrostatic potential for injection to an RF accelerator. Circularly polarized laser light will preferentially promote a specific electron spin-state, and splitting the valence band (with doping or substrate lattice mismatch) can enhance this selectivity. Electron beam polarizations of 85% are now routinely used at Jefferson Lab.

Since the electron polarization is fully determined by the circular polarization of the incident laser light, it is possible to rapidly flip the helicity of the electron beam by changing the laser polarization. This is accomplished using an electro-optic Pockels cell, acting as a quarter-wave plate to produce circularly polarized light from an initial linear polarization. This rapid reversal is critical for the precision measurement of small asymmetries, as it randomizes any slow-variations in the accelerator and detection apparatus across both helicity states.

There is significant operational experience in using the polarized electron source for parity-violation experiments at Jefferson Lab [3]. A sophisticated understanding of the sources of HCBA at JLab has been achieved. The dominant effects stem from imperfections in the laser beam polarization. Although the laser is highly circularly polarized it is very natural for there to be a small component of linear polarization which switches sign under helicity reversal, as described below. The strain induced in the photocathode, which is key to achieving high polarization, also introduces a “preferred direction” for the crystal, creating a variation in quantum efficiency which depends on the linear polarization of the incident light. This quantum-efficiency anisotropy of the photocathode (or analyzing power) interacts with the changing linear polarization of the laser light to produce a helicity-correlated intensity change in the electron beam.

Figure 1 illustrates relevant components of the laser optics of a polarized electron source. Initially linearly polarized light is converted to circular polarization, of either handedness, with a $\pm \pi/2$ phase shift in the electro-optic Pockels cell. If the applied voltage is too small, the result will be elliptic polarization, with the linear component in the same direction as the original laser polarization. If the applied voltage is too large, the residual linear component will be orthogonal to the original polarization. A small contribution from linear polarization which doesn’t change when the beam helicity changes is not problematic, however, differences in the residual linear polarization
between the states can create significant differences in beam intensity, position, or profile.

Consider the introduction of a small, constant birefringence, with axes aligned to the Pockels cell. This increases the net phase-shift magnitude for one handedness state and reduces it for the other, implying equal degree of ellipticity but orthogonal orientation of the major ellipse axes in the resulting polarization state. This sort of constant birefringence offset is referred to as a "asymmetric" phase shift, since it produces opposite residual linear polarization between the handedness states. One source of such an asymmetric phase shift is the intrinsic, stress-induced birefringence of the Pockels cell. Each element along the laser optics path may also contribute a constant birefringence offset. In particular, the vacuum window, being under mechanical stress, is significantly birefringent.

If, for one of the handedness states, the residual linear polarization is aligned to the preferred photocathode axis, then this state will have a maximal net quantum efficiency, the corresponding state of opposing handedness will have a minimal quantum efficiency, and the result will be that the electron beam will change intensity between the two polarization states. If the residual linear polarization components for each state are at ±45° to the cathode analyzing power, then there is no difference in the effect between the two electron helicity states. The orientation of the polarization ellipses, relative to the photocathode analyzing power, is illustrated in Fig. 2. The rotatable halfwave plate (RHWP) (illustrated in Fig. 1) is used to tune the orientation of the residual linear polarization. Note that linear polarization from birefringence of downstream elements is not changed by rotation of this waveplate. A common technique is to use the rotating waveplate to keep the sensitivity to asymmetric phase shift in the Pockels cell small but not zero, and then use an asymmetric voltage shift on the Pockels cell setpoints to counteract the effects from downstream elements.

The residual linear polarization component is also not constant over the laser beam spot. This creates a varying intensity asymmetry over the beam spot. It is useful to picture the spatial moments of this asymmetry distribution; the zeroth-moment simply averages the intensity asymmetry over the entire spot. First spatial moments describe the movement of the centroid of the beam under helicity reversal (referred to as position differences), while second moments describe the change in root-mean-square size of the beam (referred to as spot-size differences). Variations in the linear polarization component, or variations in the quantum efficiency anisotropy, are the most important
FIGURE 2. Polarization ellipse representation for right (solid) and left (dashed) handedness laser states. The figure on the left shows an orientation of the asymmetric residual linear light which is maximally sensitive to the cathode analyzing power, the figure on the right shows the configuration with minimal sensitivity.

It has long been appreciated that this non-uniform linear polarization component arises due to imperfections in the Pockels cell or in other optical components on the laser path. Recent work has demonstrated the critical role played by the alignment of the optic axis of the Pockels cell and the divergence of the laser spot. In a simple ray-trace view, the diverging optic rays across the beam spot can be seen to be subject to varying birefringence. This ultimately creates a position-dependent intensity asymmetry in the electron beam. If the beam is perfectly aligned to the optic axis of the Pockels cell, the net effect is a shape distortion between the two helicity states along orthogonal axes. The average zeroth, first, and second moments do not change between the helicity states. If the beam is off-axis of the Pockels cell, there are significant zeroth, first, and second moments of the intensity asymmetry. This effect is expected to scale with the beam divergence. For misalignments of around 1 milliradian or larger, this is expected to be the dominant mechanism in the laser optics for creating spot size and position differences. Data from a study of this effect is shown in Fig. 3.

A careful alignment algorithm was implemented for the HAPPEX-II experiment, which ran in Hall A in 2005, to minimize this and other similar effects [4]. The resulting helicity-correlated differences in beam trajectory, measured in the experimental hall, averaged over the month-long run, were less than 2 nm and 0.3 nanoradian in angle. The position and angle differences are plotted in Fig. 4. Similar results have since been obtained for subsequent parity-violation experiments at Jefferson Lab.

**SLOW REVERSALS**

A valuable technique for these experiments is the introduction of a beam helicity reversal, relative to some potential source of HCBA. The statistical consistency of data sets taken in different states of the reversal can be used to demonstrate the absence of large, unknown systematic errors, and the combination of data sets (appropriately sign-corrected) provides a method for further canceling possible unmeasured or poorly-corrected HCBA effects.

At present, only one slow-reversal is commonly employed at CEBAF. As shown in
Fig. 1, a half-wave plate can be inserted into the laser path to reverse the sign of laser polarization, relative to the voltage applied to the Pockels cell. This slow-reversal is particularly effective for canceling effects related to electrical signals, either from the logic or Pockels cell high voltage, which correlate to helicity. This was evident in the 2005 run of the HAPPEX-Helium experiment, when insufficiently grounded elements in the polarized source induced large beam motion coincident with the helicity logic signal. These beam asymmetries cancelled very closely under halfwave-plate insertion. However, the effects of residual linear laser polarization, which are typically the dominant mechanism for HCBA, change sign along with the beam helicity under waveplate insertion. For this reason, this insertable waveplate is not generally an ideal method for control of the largest sources of HCBA.

Another common slow helicity reversal would be the introduction of an additional half-cycle g − 2 rotation, which would reverse the electron beam helicity at target with respect to the helicity of the beam created in the polarized source. This can be accomplished with a small energy change, if a high-energy beam is bent significantly in a magnetic field. Such a reversal was used for the E158 experiment at SLAC [5], where a 22° bend brought the beam into the end station. However, this technique is not feasible at the lower beam energies used at Jefferson Lab, and is anyway inconvenient at a multi-user facility.

A similarly effective slow reversal can be created using spin manipulation in the injector. Spin manipulation is necessary at most accelerators to align the in-plane launch angle for optimized longitudinal polarization at the experimental target. Typically, in the low energy portion of an injector, solenoids are used to rotate transverse beam
polarization, and a Wien spin rotator, with crossed E and B fields, is used to rotate transverse into longitudinal. These fields also focus the beam. In particular, the effect of the Wien fields on the beam are quite severe, and accomplishing a full $\pi$ spin rotation would badly perturb the beam parameters, ruining the value of this rotation as a slow reversal. However, the focussing property of the solenoids go as the square of the B-field, implying that a pair of solenoids can be used to for a $\pi$ spin rotation on a transversely polarized beam without changing the beam optics. The subsequent Wien rotation to optimize the launch angle would be unchanged for both states.

An upgrade of the 100 keV injector at Jefferson Lab is being designed to enable this slow reversal for future experiments. This is expected to provide a powerful new tool at JLab for the control of HCBA.

REFERENCES