**Responses to the Issues Raised by the JLAB LDRD Panel Regarding AESOP**

**Marcy Stutzman, Timothy Gay**

**10 July 2014**

**(1)** *“The proposal does not provide a summary of previous experience in the construction and use of AESOP polarimeters. This would be useful background to the reader, as well as a way of detailing the systematic uncertainties in previous measurements and how one intends to reduce them.”*

This is a joint research proposal developed by the PI and the research group of Timothy Gay at the University of Nebraska. It represents a collaborative effort between the JLab CIS personnel, with experience in high polarization electron beam generation, and the Nebraska group, providing the necessary optics and atomic physics experience, and forms a team with complementary skills to work toward building the first high accuracy AESOP polarimeter.

AESOP: A Brief History

Following a suggestion by Farago and Wykes in the late 60s, Eminyan and Lampel (PRL **45**, 1171 (1980)) used an effusive Zn target to make the first optical observation of electron spin polarization. They had a first-generation bulk GaAs source, and measured the polarization, Pe, to be 28(2)%, corresponding to an accuracy of 7%. (In the rest of this discussion, we will only quote the percentage accuracy, that is, δPe/Pe). This was a very difficult experiment, and the emphasis was on demonstrating the proof-of-principle, not pushing for the highest possible accuracy.

Subsequently, Gay (JPB **16**, L553 (1983)) pointed out that Farago and Wyke’s requirement that the atomic target be heavy enough for its fine-structure to be resolved spectroscopically was unnecessary, and that one could use helium as a target instead. This idea was subsequently verified by Kessler’s group (PRL **59**, 1413 (1987)), with an accuracy of 2%, again with a bulk GaAs source. Subsequently, in the process of calibrating a Mott polarimeter (RSI **60**, 872 (1989)), they made a purely optical measurement of Pe to 0.8% (statistical + systematic). A more recent paper by Kessler’s group revised their general He polarimetric accuracy estimate up to 10% (RSI **66**, 4885 (1995)), but this revision appears to have been based on the assumption that the analyzing power of the optical polarimeter should be independent of the beam energy in the cascade-free region above threshold. It isn’t; the energy dependence of the linear polarization affects the analyzing power. Moreover, their results in the cascade-free energy range exhibit non-statistical scatter not seen in their earlier data. Similar experiments done in William’s group at the University of Western Australia using He determined Pe to 4% (Meas. Sci. Technol. **3** 884 (1992). Finally, Gay’s group suggested the use of heavy noble gases as targets, which have the advantage of higher efficiency and analyzing power (PRA **47**, 3775 (1993) and PRA **53**, 1623 (1996)). In the latter study (again using a bulk GaAs source), Pe was measured with, in the best cases, a statistical uncertainty of 0.5% (with Kr) and a systematic uncertainty of 0.8% (with He). The latter uncertainty was dominated by uncertainties in the optical constants of the polarimetric elements being used.

We wish to emphasize that in the above measurements there were no attempts to push accuracy to its practicable limit. All of this work was done within the culture of atomic collisions physics in which 1% accuracy in polarization experiments is usually more than adequate. The most precise results, contained in the latter report from Gay’s group, involved data taking for less than half a day, without exhaustive or even terribly precise measurements of the polarimetric optical constants involved.

Since the mid-1990s, experiments involving optical polarimetry of electron polarization have been done world-wide in labs including those at the University of Münster, Tsinghua University, the University of Western Australia, the Australian National University, the University of Brisbane, the Ecole Polytechnique, and the University of Edinburgh, as well as in Prof. Gay’s labs at the Missouri University of Science and Technology and the University of Nebraska. Perhaps most relevantly, an optical polarimeter, discussed in the proposal, was built at MAMI. That device suffered from high backgrounds, spectroscopic contamination, and space constraints requiring a need for large electrostatic deceleration. Ultimately, its implementation was cancelled because of lack of manpower and space.

We believe that it will be an involved but straightforward task to improve by a factor of two or three both the statistical precision and systematic accuracy of optical polarimetric measurements of Pe. The optical polarimeter we are currently using in our lab has at least an order of magnitude better efficiency than the device mentioned above that we used to obtain a statistical precision of 0.5% in several hours of running. The most significant improvements over previous work must take place in two areas. The first will be a careful characterization of the beam energy profile and a determination of whether the beam’s polarization varies across this energy spread. These issues have been discussed in some detail in the proposal. We are optimistic that the use of thin, epitaxially-grown photocathodes (as opposed to bulk GaAs) will significantly reduce systematic error of this type. Secondly, a much more careful characterization of the polarization optics than has been done to date would be carried out. In this regard, we note that astronomical polarimeters in the visible have routinely been used to measure polarizations to an absolute accuracy better than 0.01% (see, e.g., *Planets, Stars, and nebulae Studied with Photopolarimetry*, T. Gehrels, ed. (Arizona, Tucson, 1974)).

**(2)** *“The Stokes parameters are energy dependent, as indicated in the proposal. If the strained superlattice GaAs:GaAsP results in energy spreads of larger than the expected 0.1 eV, how will this affect the final goal? Can the measurements correct for deviations?”*

This is the reason why an electrostatic spectrometer is an important component in the set-up (element 5 in Figure 1 of the proposal and section (8) of this response). We must actually measure the energy width of the photo-emitted beams from the photocathodes we use, and check to see if the polarization varies across this width. Prior work by Orlov *et al*. (ref. 7, initial proposal) measured an energy spread from their GaAs photocathodes of less than 10meV at mA currents. With the lower beam currents used at CEBAF and the strained superlattice GaAs-GaAsP photocathodes, it is highly likely that the energy spread will be sufficiently low to eliminate the need for an electron monochromator to keep the beam width below, e.g., the 830 meV width required with an Ar target gas to eliminate cascading. Nonetheless, we still need the monochromator to check these widths and to partition any given beam into narrow energy “slices” to check for energy dependence of polarization within the beam width, both with DC and CW laser illumination.

The components from the proposal necessary to test the energy spread of the electron beam are an electron source, deceleration optics, and an electron monochromator. The spin manipulation is not required to measure the beam’s energy spread. The complete transport vacuum chamber, optical elements and power supplies are estimated to cost $18k (unloaded), and this could be simplified to approximately half that cost for the proof-of-principle chamber to verify that either the energy spread is sufficiently low to avoid cascade processes, or the polarization is sufficiently uniform across the energy distribution to allow measurement even with beam energy spread.

**(3)** “*Accuracy of Stokes parameters that we have found in the references: Pirbhail et al. measure P1=0.026+/-0.005 (25% relative) and P3 = (-4.1+/-0.5)% (12% relative) for helium. Collin et al. measure Stokes parameters for Argon to lower precision P1 = 0.077+/-0.052 (67% relative), P3 = 0.112+/-0.002 (1.8% relative), but differ by 30% from other measurements. These indicate some distance before the goals for the proposal can be achieved.”*

The work of Pirbhai *et al*. and Collin *et al*. were not striving for high precision or accuracy. The measurements of Collin *et al*. were made, to put it politely, with non-optimal conditions, including spectral contamination of the signal, a huge background, and a severe deceleration leading to poor focusing conditions. A better current benchmark for assessing the potential of AESOP is what we believe to be the state-of-the-art for an AESOP measurement, described in PRA **53**, 1623 (1996), as referenced above. In this measurement a beam of constant but unknown Pe was measured using both He and Kr targets in a rather inefficient apparatus. The result was Pe(He)/Pe(Ar) = 1.031(36) (systematic plus statistical uncertainty added linearly), implying consistency of the two measurements and an inherent absolute accuracy of the method of 3%. This uncertainty was dominated by the systematic uncertainty in the Kr polarization optics parameters. The constituent He measurement had, as mentioned above, a systematic uncertainty of 0.8%, while the Kr measurement had a statistical uncertainty of 0.5%.

**(4)** ”*Note on p. 7, b = 2/9, discrepancy with Eq. 2 of Collin et al., b=2/3 x 2/9.”*

It is the proposal that is in error. Collin *et al*. agree with Gay *et al*. (PRA **53**, 1623 (1996)).

**(5)** *“How long will it take to achieve the required statistical precision?”*

Let us assume that the AESOP uncertainty is due in equal parts to systematic and statistical uncertainty. These should be added linearly. Thus our design goal of 0.4% accuracy implies a statistical uncertainty of 0.2%. The polarimeter described by Pirbhai *et al*. has a figure of merit of 270 Hz/nA. Assuming a Pe = 0.2 (which is conservative) this implies that with a current of 1 μA we could measure Pe = 0.2000(4) in 13s. It is unlikely that the device we would use at JLab will be as efficient as that of Pirbhai, primarily because we will reduce the solid angle of the fluorescence detection to improve the systematic uncertainty in our knowledge of the optical parameters. If we assume a device that is 10 times less efficient than the Pirbhai polarimeter, we obtain a data acquisition time of ~ 22m. Of course, any beam polarization higher than the 20% in the Nebraska experiment would lower this time accordingly. Such measurements would take place in dedicated runs to calibrate the Mott polarimeter, and not be in use during routine operation of CEBAF.

**(6)** *“Given the experimental method, you will probably need knowledge of electron-target luminosity. How will that be controlled over the time of the measurement, what is the length of each measurement, and what is the expected statistics?”*

The luminosity is not very important; the measurements will be normalized to the incident current and the target gas head pressure (and the linearity of this pressure with local target pressure checked). It is important that the backgrounds in the measurement be small and well characterized as a function of incident electron beam energy. This is a problem with which we have 30 years of painful experience. It is also important that the electron beam trajectories through the target not change significantly over the course of the measurement (nominally 0.5h in length – see (5) above). This is best ensured by monitoring the pointing stability of the photoemission laser and the voltage/current constancy of the power supplies used to produce the electric and magnetic fields in the apparatus.

**(7)** *“Many things must be controlled and calibrated, as it is described in detail in the cited paper by Gay et al., but even in that work systematic uncertainties are ~1%. Cited paper clearly describes difficulties, for example, in characterization of optical elements. They measured very different values from what manufacturer provided and the exact source of the discrepancy was not so clear (may be beam size?)”*

(Please see also comments in (1) above.) Accurate characterization of the optical train used in AESOP represents the biggest challenge of this project. Manufacturers of optical equipment are notorious for mis-specifying their wares. Calibration measurements must be done extensively, checked, and rechecked. Variations in the optical constants across the beam diameter of the experimental signal fluorescence must be known. The optical polarization elements themselves can either be electro-optically varied (liquid crystal retarders, AOMS, PEMS, etc.), mechanically rotated (zeroth-order quarter wave plates, Glan-air prisms, etc.), or beam-splitting comparators can be used. All of these have their advantages and disadvantages. Large acceptance angle for the target fluorescence reduces data acquisition time (with attendant improvement in one’s susceptibility to temporal drifting of the apparatus) but increases the uncertainty in one’s knowledge of the system’s optical constants. While most of our experience is with polarimeters in which elements are rotated mechanically (which are relatively inexpensive for a given acceptance angle), we will consider alternate designs. In any case, we will use only AR-coated crystalline retarders and polarizers where applicable to minimize systematic errors. The measurements described above generally used achromatic plastic sheet polarizers and retarders, which are inexpensive and fine for most of the measurements made at UNL, but will be inadequate for high accuracy work.

To demonstrate the required level of accuracy in optical polarization measurements, a first step would be to build an optical polarimeter using high quality optics, and then measure the polarization of light from a laser with varied polarization. The optical polarization would be measured using at least one of the methods described above (mechanical rotation, electro-optical elements, or beam splitter setup), and would verify that the systematic errors could be reduced to the necessary level. The complete optics setup to measure the fluorescence polarization would then require characterizing additional focusing optics, a vacuum window, and low-light signal detection with PMTs. The full optical setup is anticipated to cost $22k, but the preliminary optical setup could be built for $9k using existing lasers.

**(8)** *“Details of the detector beyond a sketch will be helpful, for example size of components like the vacuum chamber, can help assess the cost estimate.”*

The electron source can be built from existing components, though many parts such as the Cs and NF3 deposition systems will need to be purchased as there are few if any spares. The electron transport system will need to be modeled using SIMION for exact dimensions, but deflector plates and magnet coils on the several inch length scale will be required for the Wien filters, and the deceleration optics will strongly depend on what initial voltage is used. An inner diameter of approximately one inch will be used for the transport optics, and the gas load from the target to the source has been calculated including this dimension. The gas target and optics system will be modeled using the MolFlow+ Monte Carlo software package, but rough calculations show that with 1 cm holes for electron beam entrance, exit, and light exit port, the isolation between the gas and the much better vacuum of the target isolation chamber can be maintained and adequate isolation should be possible between the target and source. A separate rough pump system will be used to maintain target cell pressure, and the large system pump will be for the isolation chamber.



**(9)** *“Electron transport: How are the magnetic and electric fields in the apparatus controlled so that they do not affect the measurement?”*

Just as a rule of good, basic experimental practice, electromagnetic field noise must be monitored and minimized. This usually comes down to the use of power supplies with low ripple, Faraday cages where appropriate, and mu-metal shielding. Prof. Gay’s group has extensive experience with this from their polarized-electron chiral molecule scattering measurements, which determine beam-current asymmetries to 10-5. The specific concern in polarimetric measurements is the reduction of magnetic fields to the point that Hanle rotation does not affect the measurement of the Stokes parameters. Fortunately, in the case of well-defined collision geometry that we anticipate for these measurements, the Stokes parameters are one’s best monitor of spurious magnetic fields (PRA **60**, 1046 (1999))

**(10)** *“It is unclear from the proposal to what extent spins must be perfectly transverse and how this affects the measurement (see comments following Eq. 2 in Collin et al.)”*

Spin rotation is important to make sure that the electron spin is oriented to maximize the circular polarization (P3) of the fluorescence. This is generally accomplished with Wien filters and magnetic dipole spin rotators. One need not assume a spin orientation direction; it is established by maximizing the value of P3. Having said this, the best geometry to use is one in which the optical axis of the polarimeter is orthogonal to the beam momentum. This allows the most accurate determination of both P2 and P3 simultaneously. (One must, however include in the error budget effects due to non-perfect orthogonality of the electron and optical axes.) In this regard, Figure 1 of the proposal is misleading, implying an angle of ~30o between the electron beam and the optic axis. This geometry is useable but not ideal.

**(11)** *“Are there any uncertainties in the extrapolation of errors of the AESOP measurement to their use in the calibration of the 5 MeV Mott polarimeter?”*

No. The AESOP measurement will yield a beam polarization, whose uncertainty will transfer isomorphically to the error in the 5 MeV Mott’s analyzing power, assuming only no depolarization during the acceleration to 5 MeV.

Final notes: The scope of this project is large, but smaller proof-of-principle experiments could be performed to ensure the viability of some of the main elements prior to complete funding of the project. As noted, the electrostatic optical setup can be tested using ~$9k of equipment and the optical setup tests would require another $9k. Labor requirements, at minimum, would be a graduate student or postdoc with the assistance from the PI and guidance from the UNL collaborators.