Present and Future work in The Solid Polarized Target Group at the University of Virginia

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1 Research Statement

I have a broad interest in Spin Physics. I have ongoing analysis projects in the spin physics of photoproduction hadronic spectroscopy using Jefferson Labs (Hall B) CLAS6 and have a keen interest in trying to understanding the nature of confinement using the spectrum of resonances and the search for exotic states [1]. I also have an interest in the development of machine learning algorithms to use in conjunction with polarized observables where a broad phase-space can be exploited using multilayers of classification giving a great deal more information on the contributing partial waves. I also believe the next phase of nuclear physics analysis evolution will entail the use of increasingly sophisticated pattern recognition techniques to use in signal extraction. Incorporating experimental covariance information into these types of analyses can improve resolving power even further. Recently, I have published work on U-Spin symmetry tests [2] of the strange sector electromagnetic decays, and have extracted transition magnetic moments [3], branching ratios [1, 4, 5], and cross sections [6, 7] with the use of these types of covariance sensitive tools using photoproduction data from CLAS6. I will be migrating this effort to Hall D with the hope of expanding the GlueX project [8] to use polarized target observables in the search for exotic mesons created by the excitation of the gluonic field. Such an expansion to the GlueX experiment would allow clear determination of the single spin (beam or target), double spin (beam-target, beam-recoil, target-recoil) and tensor polarized asymmetries in pseudoscalar and vector meson production. Spin dependent measurements will complement the existing GlueX program by allowing for the determination of complete isospin amplitudes and assisting in the search for exotic mesons.

I am also interested in Nucleon Tomography and using processes like Deeply Virtual (DVCS), Time-like (TCS), and Wide-angle Compton scattering (WACS) to explore the internal nucleon structure. I am involved in exploring ways to impose more theoretical, analytical, and experimental constraints on the extraction framework with the intention of improving the resolution of the 3D nucleon picture as well as to improve and expand the method of proposing experiments to add to this picture. This work involves deep study on the phenomenological level but also exploiting all components of the helicity amplitudes for each type of process at higher twist [9]. Once this has been achieved it will be possible to propose more well define experiments that are sensitive to each of these components. At the moment the goal for DVCS and TCS is to run future experiments in Hall A and C with polarized beam and target. I have also proposed [10], with collaborators, an experiment to study the initial state helicity correlation in WACS in JLab Hall C. The measured longitudinal polarization transfer parameter is inconsistent with predictions of pQCD, yet consistent with calculations of the handbag mechanism. The WACS experiment will be able to discriminate between the various models and help to clarify the role of the power suppressed helicity flip contribution and hopefully confirm the method of factorization and connection to the generalized parton distributions. In order for this experiment to be feasible a high intensity photon beam (well over $10^{12}\gamma/sec$) had to be developed to work in combination with a new rotating target (raster) to maximize luminosity and reconstruction resolution. Our high intensity photon source collaboration is working on a publication of this configuration. There are many more photon beam, and photon beam with polarized target physics ideas of this nature that I would like to explore.

I presently have four approved experiments in Jefferson Lab's Hall C. E12-13-011 is an experiment to measure the deuteron tensor structure function b_1 [11] and E12-15-005 is proposed to measure the quasielastic tensor asymmetry [12]. Both of these experiments are conditionally approved requiring a tensor polarization of about 30%. I have recently developed an optimized solid tensor polarized target along with a polarization measurement technique directed at the necessity of these experiments. This advancement required a completely new type of target that rotates in the holding field while receiving RF irradiation to optimize quadrupole polarization in the target material. The new technology will increase the figure of merit for tensor polarized experiments by nearly a factor of 4 allowing for previously inaccessible asymmetries at Jefferson Lab. There are additional observables to explore using a tensor polarized target, such as the three additional spin-1 structure functions. The generalized deep inelastic tensor spin structure of the deuteron can only be obtained from deeply virtual Compton scattering and meson production experiments on a tensor polarized target. There are interesting connections to the total quark angular momentum sum rule for a spin-1 hadronic system within a gauge invariant decomposition of hadronic spin. In addition, polarized proton-deuteron Drell-Yan processes can be explored by studying the tensor-polarized antiquark distributions accessible only by a tensor polarized target.

In the recent past, I have taken part in many JLab experiments, however I am involved in collaborations at other facilities as well. At present, I am involved in projects with TUNL, ORNL, Jlab, LANL, and Fermilab. I am one of the two spokespersons for the SeaQuest polarized Drell-Yan experiment E1039 [13] to run at Fermilab in collaboration with LANL. This project has received full funding and is the first experiment to measure not only the sign, but also the magnitude and shape of the Sivers function with sub-percent precision directly using the dynamics of the sea quarks. This effort is very complimentary to other Transverse Momentum Distribution projects proposed at Jefferson Lab. This project is a huge undertaking and UVA has been and continues to be essential to its success. This project is also complimentary to my other Hall B proposal to study the longitudinal spin structure of the nucleon [14]. It is also possible to look at the longitudinal spin structure from the sea quark contribution in the future at Fermilab.

I am also a spokesperson of an experiment that received approval to study the analyzing powers of deuteron photodisintegration at the Duke University High Intensity Gamma-Ray Source [15]. These types of experiments are the first of their kind and with much interest from the physics and polarized target community. This experiment is unique in the sense that it will confirm an NMR lineshape measurement technique for extracting the tensor polarization of deuteron targets using RF enhancement making experiments at Jefferson Lab that rely on this technology possible. In general I very much enjoy research that opens the door to new types of experiments and allows projects to run that would not otherwise be possible.

2 Particle-Nuclear Research Activities

I have been the driving force in our group both in target research and proposing the groups future polarized target projects. Here I give a brief description of some of the recent research and target developments as well as the direction I am expecting to take after succession.

2.1 Current Polarized Target Experiments and Proposals

The present dirction of the groups research focus can be seen in the polarized target proposals listed bellow for experiments to run in the near future at Jefferon Labs, TUNL, and Fermilab.

- E12-06-109 *The Longitudinal Spin Structure of the Nucleon (JLab Hall B)*
(Full Approval) Spokespersons: K. Griffioen, M. Holtrop, D. Keller, S. Kuhn, Y. Prok, T. Forest

- HIGS-P-12-16 *Tensor Analyzing Power in Deuteron Photodisintegration (Duke TUNL)*
(Full Approval) Spokespersons: D. Keller (Contact), P. Seo, B. Norum

- E1039 *SeaQuest with a Transversely Polarized Target (Fermilab SeaQuest)*
(Full Approval) Spokespersons: A. Klein, D. Keller

- E12-13-011 *The Deuteron Tensor Structure Function b1 (JLab Hall C)*
(C1 Approval) Spokespersons: J.P. Chen, N. Kalantarians, D. Keller, E. Long, K. Slifer, P. Solvignon

- E12-14-006 *Initial State Helicity Corellations in WACS (JLab Hall C)*
(Full Approval (withdrawn)) Spokespersons: D. Day, D. Keller (Contact), J. Zhang

- E12-15-005 *Tensor Asymmetry Quasielastic Region (JLab Hall C)*
(C1 Approval) Spokespersons: D. Day, D. Higinbotham, D. Keller, E. Long, K. Slifer, P. Solvignon

- E12-17-008 *Polarization Observables in WAC Scattering (JLab Hall C)*
(C1 Approval) Spokespersons: D. Day, D. Hamilton, D. Keller, G. Niculescu, B. Wojtsekhowski, J. Zhang

2.2 The Deuteron Tensor Structure Function b_1^d

The experiment C12-13-011 [11], was proposed to measure b_1^d, the tensor spin structure of the deuteron using a solid tensor polarized target, which was conditionally approved with 'A-' rating by Jefferson Lab PAC40, to run in Hall C.

The goal of the experiment is to study the leading twist tensor structure function b_1^d using DIS of unpolarized 11 GeV electrons off a tensor polarized deuteron target. Studying the structure of the spin-1 hadrons can provide new insight into this puzzle, since it is directly related to effects arising from orbital angular momentum and differ from the case of a spin-1/2 target. For this reason, it provides a unique tool to study partonic effects, while also being sensitive to coherent nuclear properties in the simplest nuclear system. The b_1^d structure function is an observable feature of a spin-1 system sensitive to non-nucleonic components of the target nuclear wave function. The enhancement seen at higher x maybe interpreted to the deuteron having a six-quark component that is orthogonal to two nucleons. Such configurations are known to be dominated by the effects of so-called hidden-color states in which two color-octet baryons combine to form a color singlet.

At low x, shadowing effects are expected to dominate b_1, while at larger values, b_1 provides a clean probe of exotic QCD effects, such as hidden color due to 6-quark configuration. Since the deuteron wave function is relatively well known, any novel effects are expected to be readily observable. A non-zero result for b_1 depends on the presence of coherent multiquark or similar exotic configurations since it is expected to be non-zero only when the electrons scatter off nucleons in the deuteron's D-state, or through S–D interference effects. HERMES non-zero result for $b_1(x = 0.45) = (-3.8 \pm 1.6) \times 10^3$ at intermediate Bjorken x, where only incoherent *e–nucleon* scattering is expected, was surprising. A measurement of b_1 is of considerable interest since it provides a clear measure of possible exotic effects in nuclei. Tensor effects only exist in nuclear targets, so the study of b_1 bridges nucleon and nuclear physics. Experiment C12-13-011 will seek to confirm the HERMES result with greater statistical precision, and measure b_1 at additional kinematic points.

My work on tensor polarized targets [16, 17, 18, 19, 20, 21] has led to the development of a new type of rotating polarized target system that when used in combination with selectively saturation of the NMR signal, can lead to significant tensor polarization. Also required was the technique for measuring the RF manipulated lineshape. Both the NMR RF selective saturation technology and the measurement theory had to be developed in order to move forward. This innovative research was needed to meet the condition set by the PAC for full approval which were to achieve a least a 30% tensor polarization. This work is expected to have lasting contributions to fixed target tensor polarized experiments worldwide.

2.3 Quasi–Elastic and Elastic Deuteron Tensor Asymmetries

Experiment C12-15-005 [12] was proposed to measure the tensor-polarized asymmetry A_{zz} in the quasi-elastic region and was approved by JLab PAC44, but also includes the same condition of the previously outlined experiment in that a tensor polarization of greater than 30% must be demonstrated. Kinematics were also propsed so that the elactic deuteron tensor asymmetry could be measured and used to test the recent tensor target technology I developed for these types of experiments.

CR12-15-005 proposes to measure A_{zz} in inclusive electron scattering on polarized deuterium in the quasi-elastic region for Bjorken x in the range $0.3 < x < 2.0$ and momentum transfers from 0.2 $(\text{GeV/c})^2$ to 2.9 $(\text{GeV/c})^2$. In the plane-wave approximation, A_{zz} is sensitive to the ratio of the D- to S- components in the deuteron wave function, and the proposed kinematic conditions are such that large relative momenta $k >$300 MeV would be probed. This is important for understanding the nucleon-nucleon (NN) interaction at short distances and the properties of the dominant pn correlations in heavier nuclei. The tensor asymmetry measurements, in addition to probing the T_{20} form factor at elastic kinematics, gives access to the deuteron wave function at quasielastic and DIS kinematics, unlike measurements based on deuteron recoil polarization which are restricted to the elastic point. The proposed measurements in quasi-elastic kinematics will study the A_{zz} asymmetry in the region where it is most directly related to the short-range NN interaction. At large recoil momenta it also provides a sensitive test of relativistic effects in the treatment of deuteron structure as well as final-state interactions (FSI) in the outgoing pn pair.

2.4 Longitudinal Spin Structure of the Nucleon

I have assisted in the research and development of the horizontal longitudinally polarized target needed for the CLAS12 detector in Hall B (E12-06-109) [14]. This work is part of a comprehensive program to map out the x- and Q^2-dependence of the helicity structure of the nucleon in the region of moderate to very large x where presently the experimental uncertainties are still large. The experiment will use the upgraded CLAS12 detector, 11 GeV highly polarized electron beam, and longitudinally polarized solid ammonia targets (NH_3 and ND_3). Thanks to the large acceptance of CLAS12, it is possible to cover a large kinematical region simultaneously. Detection of both the scattered electrons and leading hadrons from the hadronization of the struck quark can be achieved, allowing access to information on its flavor. Using both inclusive and semi-inclusive data, it is possible to separate the contribution from up and down valence and sea quarks in the region $0.1 \leq x \leq 0.8$. These results will unambiguously test various models of the helicity structure of the nucleon as $x \to 1$. A combined Next-to-Leading Order (NLO) pQCD analysis of our expected data together with the existing world data will significantly improve our knowledge of all polarized parton distribution functions, including for the gluons (through

Q^2evolution). High statistics data on the deuteron in the region of moderate x and with a fairly large range in Q^2 are crucial for this purpose. Finally, this experiment will improve significantly the precision of various moments of spin structure functions at moderate Q^2, which will allow us to study duality and higher-twist contributions.

The design and construction of the new target system is a collaborative effort between JLab, UVA, ODU, and CNU. This experiment is part of a group of polarized target experiments in Hall B that have motivated our work in the simultaneously polarized two cell configuration. Much of the UVA effort on this project has come from our undergraduate work force under my supervision resulting in technotes [22, 23, 24] with undergraduates as lead authors. This work has to do with simulation of microwaves to polarize each cell equally with maximum irradiation as well as the specialized superconducting coils needed to hold two different simultaneous target helicity state in beam. This system is novel in the sense that a single microwave source will be used with two different hold coils to hold separate target cells at resonance in the beam-line.

2.5 Wide-Angle Compton Scattering from a Polarized Target

The observation of scaling in Deep Inelastic Scattering (DIS) at relatively low momentum transfers, successfully understood within the framework of pQCD, suggested that the same interpretation would be fruitful when applied to exclusive reactions: elastic electron scattering, photo- and electroproduction of mesons, and Compton scattering. This prospect was further supported by the fact that constituent counting rules, which govern reactions that conform to the pQCD picture, could describe, approximately, certain exclusive reactions. There is little doubt that the pQCD mechanism dominates at high energies. What has been lacking is a general agreement as to how high the energy must be for pQCD to be thoroughly applicable. The argument on this point is driven by more than a difference of (theoretical) opinion. The unavoidable fact is that cross sections calculated in a pQCD framework have invariably been low, sometimes by an order of magnitude or more.

Results of experiments at Jefferson Lab on the proton contradict the predictions of pQCD: the recoil polarization measurements of G_E^p E93-027, E04-108 and E99-007, and the Real Compton Scattering (RCS) experiment E99-114. The G_E^p measurements found that the ratio of F_2 and F_1, scaled by Q^2 demands a revision of one of the precepts of pQCD, namely hadron helicity conservation. Results from the RCS measurement are that the longitudinal polarization transfer K_{LL} is large and positive, also contrary to the pQCD predictions which find K_{LL} to be small and negative. These two experiments provide a compelling argument that pQCD should not be applied to exclusive processes at energy scales of 5-10 GeV.

There is an alternative approach which asserts the dominance of the handbag diagram in which the reaction amplitude factorizes into a sub-process involving a hard interaction with a single quark. The coupling of the struck quark to the spectator system is described by the Generalized Parton Distributions (GPD's). Because of the factorization the GPD formalism allows unified description of hard exclusive reactions, independent of the details of the hard scattering. Additionally motivating is the fact that the relationship between GPD's and the usual parton distribution functions provides a workable framework for relating inclusive and exclusive reactions.

Experiment C12-17-008 [10] was proposed with a novel target system and high intensity beam (1×10^{12}) configuration to create the best overall figure of merit for the run time as possible. This project has lead to the formation of a high intensity photon source collaboration of which UVA is now a central player [27, 28]. This extraordinary opportunity is expected to lead to many other projects with physics that can only be accessed with a high intensity photon beam. I developed as new style of target rastering for the experiment so that the bremsstrahlung photon beam can stay on a fixed 2 mm spot location on the target so that improved reconstruction can be achieved. In addition the collaboration has developed a Compact Photon Source (CPS) which consists of a bending magnet and locate beam dump all self contained. This novel target work and research and development on the CPS will create an avenue for an entirely new physics program at Jefferson Lab.

As mentioned there are many other projects that can be proposed with the use of our CPS and polarized target system. Some topics I am particularly interested in pursuing are listed here.

- **Asymmetry for J/ψ photoproduction and Open Charm**: It is possible to determine the gluon spin density within the nucleon by measuring the asymmetry of polarized photoproduction of charmed quarks using the longitudinal target spin correlations

- **Time Reversal and a deeper study of the TPE contributions**: It is possible using a electron-positron converter in the pure photon beam to study the QED processes for T-reversal as well as TPE (see below for more details)

- **SRC in the deuteron from $\gamma D \to \pi^- p(p)$**: T_{10} and T_{20} can be used in this photodisintegration process to under stand the short range correlation to a much better resolution. It is possible to map out some nuclear effects at the partonic level with such an experiment

- **Unnatural Parity exchange in tensor polarized D target**: The asymmetry in $K^+ + K^-$ of the photoproduction from the proton, leading to unique solutions to the exotic channels with unnatural parity exchange (ss-knockout) in the photo-reaction with a neutron.

- **Timelike Compton Scattering**: This pure photon source offers the best likelihood of see statistical and systematic precision to be able to see gluon spin contribution from dynamic twist-3.

- **Target polarization observables in π^0 photoproduction**: Kroll has recently publish prediction of the A_{LL} and K_{LL} helicity correlations which for can be extracted with a longitudinally polarized target. For a transversely polarized target it maybe possible to measure the quantum numbers of the previously LHCb detected P_c^+ states.

2.6 Tensor Analyzing Power in Deuteron Photodisintegration

One of the most fundamental processes that can be studied is the two-body photodisintegration of the deuteron. There are many essential observables that have been well studied in the past several decades leading to significant advancement both theoretically and experimentally. However, there are several measurements that show significant deviations from the best available calculations. There are also several observables for which no measurements over critical kinematic ranges are available. Tensor analyzing powers have been measured for photon energies above 40 MeV, but no measurements exist in the important low energy region below 20 MeV, the range accessible using the High Intensity Gamma-Ray Source (HIγS). The tensor analyzing powers can be accessed using an asymmetry measurement between a tensor polarized target and an unpolarized target. The tensor analyzing powers are unique in that they not only complement the vector asymmetry measurements as additional distinct observables but they give direct information about the correlations between spatial orientation of the nucleons and the scattering mechanism. For example, spatial alignment of the target deuterons can lead to large asymmetries from final state interactions. Building an understanding of the tensor analyzing powers in the HIγS energy range will also help to interpret effects from short-range correlations at higher energies. High Tensor polarization in the target increases the probability of the D-state contribution and increasing photodisgration of the compressed deuterons, making the system more sensitive to short-range QCD effects. Understanding the nucleon-nucleon potential of the deuteron is essential for understanding short-range correlations as they are largely dependent on the tensor force. A deeper understanding of the deuterons tensor structure will help to clarify how the gross properties of the nucleus arise from underlying constituents. Our proposal to measure the tensor analyzing power in deuteron photodisintegration was recently approved (HIGS-P-12-16) [15].

The TUNL HIγS producing photon energy of $1-100$ MeV provides a unique opportunity to provide a measurement of the photodisintegration tensor analyzing power T_{20} in the unmeasured energy range of $4 - 20$ MeV but also provides the perfect testing ground for tensor polarization enhancement studies closer to 100 MeV. There is much world data on the tensor analyzing powers near 100 MeV which allow calibration studies to check the measurement theory and enhancement techniques recently developed in our group for projects such at the Quasi-Elastic A_{zz} measurement (E12-15-005) and the b_1 structure function measurement (E12-13-011) as well as future possibilities in the tensor polarized asymmetries in Drell-Yan and tensor polarized DVCS. Measurements are planned with this proposal of various kinematics with well known T_{20}. This allows for a very thorough test of the optimized tensor polarization and measurement technique previously discussed. This project provides a direct overlap with cutting edge polarized spin-1 solid-state targets theory and experiment. In addition the measurement of T_20 in this kinematic range will can be used to explore possible exotic states of the deuteron. Enhancement near a dibaryon resonance cups would give direct evidence of a new state and give the information needed to measure its quantum numbers.

This project along with the HIγS experiment to measurement the Drell-Hearn-Gerasimov integrand for the Deuteron requires a dilution refrigerator system to hold the target in a frozen spin state. The UVA polarized target group along with the B. Norum group have work to refurbished and prepared the dilution refrigerator and target for this experiment. We are presently in the process of rebuilding the dilution unit for this frozen spin system.

2.7 Polarized Target Drell-Yan Single Spin Asymmetry Measurement

The polarized target Drell-Yan experiment will measure the Sivers transverse momentum dependent parton distribution (TMD) $f_{1T}^{\perp}(x, k_T)$ of unpolarized quarks in a transversely polarized proton, to probe for a possible contribution of the orbital angular momentum (OAM) component of sea quarks to the proton spin At the same time, this experiment will test a fundamental prediction of QCD about the opposite sign of the Sivers distribution as measured in DIS and DY processes.

It's well known that the sum over all active flavors of the spins of the quarks as measured from the first moment of the g_1 SSF does not saturate the spin of the nucleon, and that the contributions of the gluons' helicity is insufficient to account for the missing part. The expectation is that OAM makes up the remainder. OAM is implied by the fact that partons have transverse momentum k_T. One avenue to describe the transverse momentum structure of the nucleon is the use of TMD's, which depend on both the longitudinal momentum fraction x and on k_T. Among the eight leading twist TMD's, the Sivers distribution is most interesting for tests of OAM because it represents a correlation between the quark momentum transverse to the beam and the polarization of the target.

The connection between OAM and the sea quarks is motivated by the excess of $\bar{d}$ over $\bar{u}$ quarks at Bjorken $x < 0.3$ which, in pion cloud models, can be related to the OAM of the cloud contributing to the proton spin.

The E1039 [13] experiment requires the FNAL 120 GeV unpolarized proton beam in addition to the polarized target, to study the reaction $\vec{p}(p, \mu^+\mu^-)X$. The final muons will be detected in the previously existing FNAL E906 - SeaQuest spectrometer. Events at $0 < x_2 < 0.5$ are mainly from target anti-quarks, probing the desired $\bar{u}_t$ distributions. The difference over the sum of yields for opposite orientations of the target spins is the measured asymmetry $A_N = fP_tA_N^{DY}$, where f is the usual target dilution factor, and P_t the target polarization. A non zero A_N is a definite signature of OAM.

The experiment will use a LANL/UVA polarized target system prepared with a vertically pointing field transverse to the beamline. This target system has been designed to handle the highest instantaneous beam intensity ever attempted at 3×10^{12} protons for a 4 seconds spill. This is possible due to the high pumping power available through the

14,000 m^3/hour Oerlikon pumping system. This system also has the longest target cell for an evaporation system at 8 cm long compared to systems used at JLab at 2.5 cm long or at BNL at 4 cm long.

2.8 Near-Future Projects and Proposal Development

I have also recently submitted a few letters of intent to the JLab PAC and continue to explore other possibilities at Fermilab and other facilities.

GPDs and Imaging

One project will explore Timelike Compton Scattering (TCS) spin asymmetries with a transversely polarized NH_3 target using the Hall A large acceptance solenoid spectrometer (SoLID). There is also interest in Hall C using our high intensity photon source and polarized target combination. Such an experiment would measure exclusive e^+-e^- production using an 11 GeV polarized beam and the UVA solid polarized target to study the reaction $\gamma p \to \gamma^* p' \to e^+ e^- p'$, which is the timelike equivalent of (spacelike) DVCS. The differential cross section and moments of the weighted cross section as well as the target spin asymmetries can all be measured as a function of the four-momentum transfer t, the outgoing photon virtuality Q'^2 (up to 9 GeV 2), and the skewness η. The latter reflects the difference between the initial and final momentum fraction carried by the struck quark, and corresponds to ξ in DVCS. To leading twist TCS is expected to give similar results in the GPDs at DVCS but accessed in a completely different process allowing for the test of universality. TCS is also sensitive to the real part of the Compton form factors and provides access to GPD components describing the distribution of matter in the nucleon (form factors of energy-momentum tensor, D-term). The high luminosity of the either SoLID or the pure photon source configurations will make it possible to perform a mapping of the Q^2 and η-dependence, allowing for a deeper study of factorization, higher-twist effects, and NLO corrections.

I am also working on the phenomenological and computational level with S. Liuti to explore higher-twist contribution in both DVCS and TCS to motive this experimental effort. Here the goal is to study the contributing helicity amplitudes and resulting observables which can only be afforded through a flexible polarized target system and polarized beam. Given the experimental data and techniques in machine learning we hope to be able to significantly improve the nucleon tomography as well and develop a much broader understanding of factorization breakdown. At APS 2017 one of the undergraduate I work with (Andrew Meyer) presented some examples from using a Multilayer Perceptron neural network to study the multivariate nature of the e^+e^-p' final state. The neuron response function maps the neural units input from the kinematic variables onto the output using the activation function. The ANN is a self-learning system and is trained rather than directly programmed. The algorithm used in neural network training which adjusts the weights in connections that optimize the discriminating power of the network. The technique employed here is a supervised learning method, where Monte Carlo simulation data containing all of the processes at leading twist and their kinematic dependence seen in this final state. These simulations are then fed in and a new network is built that is sensitive to the full phase space and gluon contributions from dynamic twist. Our next step is to expand the application using Self Organizing Maps to extract more tomographical information while mitigating model dependence. This can be done by using experimental data, numerical results for higher twist helicity amplitudes as well as the information on the complex QCD interference contributions in the background. An all encompassing Monte Carlo simulation can then be generated using this phenomenological information which can be employed with the assistance of machine intelligence to propose new experiments to improve the resolution of the image of the partonic structure inside the proton, neutron, deuteron and beyond.

Time Reversal

With our new proposed high intensity photon source and target system we can use a converter in the photon beam to produce on the order of 70 nA of a e^+-e^- pairs which can be used with a vertically pointing target to test the time reversal invariance properties of the electromagnetic interaction, improving the precision of current measurements by a factor of 100. This can be done by looking at e^+/e^- scattering on a polarized proton in the resonance region using both leptons to study the up-down asymmetry. Some processes, other than single photon exchange, can produce an up-down asymmetry that may interfere with the T violating process of interest. Only processes of order α^3 are of concern here, in addition, the terms involved in the α^3 asymmetry are of opposite signs for positrons and electrons. Thus, this asymmetry cancels when measured with a positron beam is combined with the corresponding electrons asymmetry. It is possible to have two targets in different helicity configurations at the same time by having two separate target cells in the homogeneous field with small holding coils around each cell to shift the resonance field for a given microwave frequency. I was able to demonstrate AFP on a solid ammonia target as a global first recently, allowing fast helicity flips for each target cell in this setup. Such a configuration is also ideal for studying the contributions from two photon exchange (TPE) using elastic scattering. This configuration will have significant reduction of systematics than anything prior by addressing both lepton, TPE, and time-reversal asymmetry contributions all at the same time. Thus, an overall improvement of a factor of at least 100 and possibly 250 or higher than anything previously done is achievable in a reasonably long run. A major improvement in our knowledge of the invariant properties of the electromagnetic interactions of hadrons can be achieved thanks to the advances in polarized target technologies. It is likely that a null result will be found. On the other hand, we should not forget that P and even CP turned out to be non-invariant when examined at the right level of precision. The more than two orders of magnitude improvement that we propose will test T in an entirely new regime.

Hall-D Frozen Spin Target

I also submitted at letter of intent [8] on the development of a polarized target for GlueX in order to study a broad range of polarized observables in the photon beam energy range between 5 GeV and 9 GeV. We consider using a polarized proton and a polarized deuteron target with both linear and circularly polarized photon beams. A frozen spin target capable of longitudinal and transverse polarization can be constructed for the Hall-D configuration of GlueX so that a complete set of polarization observables will be determined in a single experiment, including single-polarization and beam-target, target-recoil, and beam-recoil double-polarization asymmetries, as well as tensor polarized observables, and initial state helicity correlations in possible exotic state hadrons. This experiment is complementary to previously proposed GlueX experiments, providing additional information to be used to determine complete isospin amplitudes and assist the search for exotic state mesons. Investigation into these possibilities could potentially lead to a series of polarized target experiments enhancing the on-going investigation into spin structure as well as the exotic state contributions.

Polarized observables exhibit very rich structure, reflecting the degree of complexity in dynamics adding considerable sensitivity and information in each measurement. This additional information on the various contributions leading to the final state is crucial and will need to be fully exploited in attempts to understand exotic contributions.

Photo-excitation of the nucleon as seen in the hadronic spectrum provides the quintessential tool for probing the quark and gluonic degrees of freedom, the nature of the confinement mechanism, possible gluon-gluon interactions, and the missing resonances. Exotic hybrid mesons manifest gluonic degrees of freedom, and their detailed spectroscopy will provide the precision data necessary to test assumptions in lattice QCD and the specific phenomenology leading to confinement. The use of polarized photon beams with polarized targets provides the most information and comprehensive set of constraints to assist in the search of exotic mesons as well as an understanding of their backgrounds.

In general, higher mass resonances can overlap with significant interfering backgrounds from u-channel processes. Multivariate extraction techniques and detailed partial-wave analyses are invaluable, as are the constraints provided by the polarization of the target nucleons. The ideal frame-work would account for the coupling between the various meson-decay channels using as many polarized observables as can be achieved. A comprehensive investigation of amplitudes and phase transitions is required for both the meson and baryon spectrum, which is chiefly determined from πN reactions to assist in the deconvolution of the spectrum in the search for and study of the pattern of gluonic excitation in the meson spectrum. Using polarized target data with unpolarized target data is the most thorough way to explore the spectrum for exotic states. The measurement of double spin polarization asymmetries can reveal information on the nucleon hidden structure, hadron photoproduction dynamics, and exotic hadron property. Exploring the asymmetries of Compton scattering over broad angular coverage is now much more realistic with the Hall-D optimized trigger using Boosted Decision Tree pattern recognition. It is likely to see a very strong signal in A_{NN} at the charm threshold in polarized $\gamma p \to \gamma p$ at large angles when both beam and target are polarized transverse to the beam direction. This could signify an exotic state in even the simplest of reactions. There are many channels to explore with polarized observables.

Enhanced dynamics have been seen near the heavy-quark thresholds where a large 4:1 transverse-transverse spin correlation A_{NN} is observed in large-angle elastic proton-proton scattering at $\sqrt{3}$ GeV and $\sqrt{5}$ GeV. These energies correspond to the strange and charm thresholds in the two-baryon system. The observed strong spin correlations are consistent with the formation of $J = L = S = 1$ octoquark resonances near the heavy quark pair thresholds. In photoproduction, the production energy can not be wasted at threshold, so all three valence quarks of the target nucleon must interact coherently within the small interaction volume of the heavy quark production subprocess. The same strong spin correlations can be studied with polarized photons and a polarized proton target for the Hall-D photon energy. In the case of threshold charm photoproduction on a deuteron, all color configurations of the six valence quarks will be involved at the short-distance scale $1/m_c$. Thus the exchanged gluons can couple to a color-octet quark cluster and reveal the "hidden-color" part of the nuclear wave function.

Polarization observables can be instrumental for separating of the exotic waves. The expected dominance of the one-pion-exchange which fixes naturality in the t-channel for some typologies can enable, by means of polarization observables, discrimination between naturalities of the resonances produced. If there are limitations in the partial wave analysis (PWA) it is sometimes possible to find maxima in the angular distributions of the decay products which are dominated by a single resonance of interest.

The enhancement of the hadronic interactions at threshold implies that new types of charm-based resonances may form in photoproduction in the available energy range. Some of the possibilities are the J/ψ-nucleon resonances at threshold in reactions such as $\gamma p \to [J/\psi p]$, $\gamma p \to [J/\psi p]\gamma$, $\gamma p \to [J/\psi]\pi^+$, and with the deuteron target $\gamma d \to \bar{D}^0 + [\Lambda_c n]$ and $\gamma d \to [\Lambda_c] + [\bar{D}^0 n]$ reactions. Another possibility is the octoquark $|uuduudc\bar{c}>$ in γd. In each case, resonance formation implies strong spin correlations.

There are many polarized observables that can be acquired with the combination of a polarized photon and a polarized nucleon target. These observables are important for the development of a complete understanding of the production mechanisms of the various resonances. As an example, the $\Lambda(uds)$ caries its polarization in the strange quark, with a small contribution from the (ud) diquark, where the polarization mechanism of the $\Xi((u/d)ss)$ may come from the valence quark (u/d) instead of the (ss) diquark. The $\Xi(1320)$ can be photoproduced on a polarized nucleon target which can then be used to study the different contributions of the valence quarks to the nucleon polarization. Polarized beam/target data can be compared to other GlueX experiments without beam/target polarization. Measurements of the in-plane polarization of the $\Xi^-(1320)$ can be used to differentiate between polarization and production mechanisms.

Investigations of the multi-strange hyperons are still laking. There are still far fewer Ξ resonances than Δ resonances, which under the flavor SU(3) symmetry leads to the notion that there is still much to discover. This would likely take an anti-kaon beam or a long running photoproduction experiment in combination with multivariate analysis techniques and trigger, all of which may be feasible in Hall-D.

Considering the photoproduction reaction $\gamma N \to KK\Xi$, a measure of the transverse spin-transfer can be determined by measuring both the double-polarization observable K_{yy} and the photon-beam asymmetry Σ. These observables are related to the parity of the Ξ resonance by

$$\pi_\Xi = \frac{K_{yy}}{\Sigma}.$$

This same technique can be used to study the parity of the Ω hyperon in the reaction $\gamma N \to KKK\Omega$. This can also be generalized to the Ξ of higher spin and to the polarization observables in Ξ photoproduction.

2.9 Polarized Target Research

Target Material Research

We are not just producing target material of future experiments but also doing material research to try to improve the over all figure of merit for the scattering experiments by maximizing the polarization and radiation resistance of the material as well as improving the target materials dilution factor and packing fraction. We are also working on NMR improvements and polarization uncertainty [29, 30]. Recent work on packing fraction and material geometry improvements will be published here [23]. This work will continue along with material production for most solid polarized target experiments in the country. I am also involved in theoretical research of the polarization mechanisms in solid materials at low temperature. This work requires modeling different aspects of dynamic nuclear polarization and nuclear magnetic resonance for the purpose of optimizing and measuring bulk spin alignment in a variety of materials. We are also developing simulations of these mechanisms which can be used to better understand spin dynamics in a variety of field and temperature conditions. Much of the testing and material irradiation is carried out at the MIRF facility at NIST in Gaithersburg. Some of this work is on studying the temperature dependence of the paramagnetic complex produced in ND_3. I am also investigating deuterated ethane (CD_3) and methane (CD_4) as target materials. In addition I have also recently joined in the HD-ice research at JLab and am working with A. Sandorfi and X. Wei on an NMR system that can take absorption and dispersion data on HD-Ice at the same time.

Fridge and Target Design

Besides construction and setting up of the target infrastructure for experiments I am involved in novel target systems to use in our test lab at UVA as well as other facilities for use in scattering experiments. This work also provides our graduate and undergrad students the opportunity to be intimately involved with innovative projects that can lead to real science contributions.

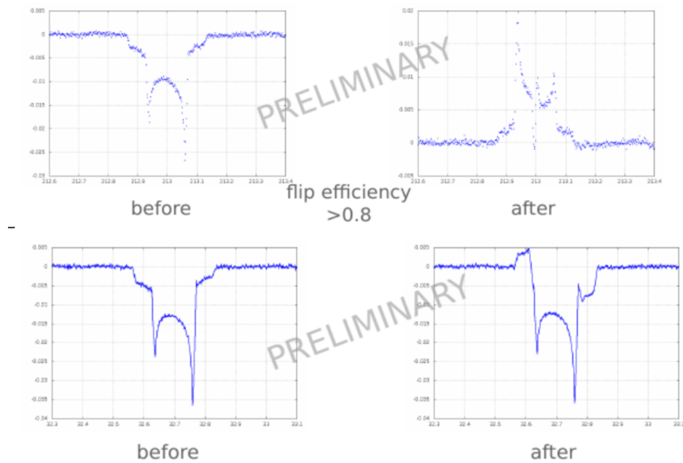

Figure 1: The d-butanol NMR signal before and after an AFP flip showing over 80% effienciency.

Solid polarized targets tend to take some time to polarize to their optimum. Research into fast target helicity flips using adiabatic fast passage historically has been very challenging for solid target materials. Recently we have been able to set some records with some new results for ammonia and butanol. Ammonia is a very important target due to its high polarization and radiation resistance as well as dilution factor. We have conducted the first AFPs on this material but there is still much work to do on optimizing the AFP efficiency. Figure 1 shows our AFP results for d-butanol. Here there is also include a new type of AFP known as a selective domain AFP where only the pedestal has been flipped to enhance the tensor polarization of the target.

Tensor polarization enhancement and measurement have also been a primary focus of my target research recently. Both negative and positive tensor polarization has many application for many different types of spin-1 target experiments. There are different polarization mechanisms that can strictly enhance negative tensor polarization while keeping vector polarization at zero in a frozen spin target. There has been very little research on this. This transfer mechanism is an enhancement technique that works together with DNP so that continuous re-polarization is possible. The RF transfer from the DNP nuclear spin

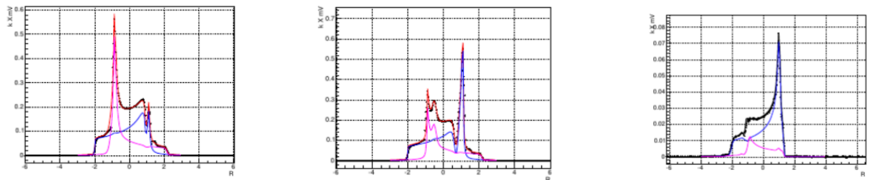

Figure 2: The d-butanol NMR signal Using RF irradiation to manipulate the tensor polarization of the deuteron.

reservoir to pump the spin-1 tensor polarization uses selective semi-saturation which is also a 1 K dynamic process. It was also necessary to develop the measuring technology and phenomenological interpretation of the spin dynamics to use in practical applications. These tools will are expected to make lasting contributions to spin-1 polarized target scattering experiments for years to come, allowing otherwise non-accessible observables to be probed. These tools can also mitigate the tensor polarization when studying the vector contributions alone. Examples of the deuteron NMR signal, shown in Figure 2 showing various degrees of manipulation of the tensor polarization which is directly proportional to the area difference in the two transition lines.

In other work, myself and undergrad J. Higgins have designed a dilution insert that will fit into our main evaporation fridge and Oxford magnet test setup [25]. This will provide a method of studying frozen spin dynamics and allow us to preform low temperature ($\sim$30 mK) solid-state NMR experiments needed for specialized low temperaure target material research. This system was design to be small and inexpensive and something that can be built right here in the physics department. Figure 3 shows the Solidworks drawing of the design. This system is a design that hold material in a glass mixing chamber which can be directly irradiated with microwave during the DNP processes. The system can then be cooled to a frozen spin mode for specialized target testing and RF transfer techniques.

I have also recently been working on a new type of fridge to be used in experiments that can run at high beam intensity ($\sim$ 100 nA) but that runs at a lower temperature to hold higher overall polarization [26]. I have been working with undergrad K. Lee to generate the mock-up shown in Figure 4. The operating principle here is to run a high-powered dilution fridge that can super-cool liquid helium-4 where the target material sits. This helium-4 reservoir is connected to a pumping system as well. The theoretical low temperature bound for 100 nA and a target cell of ammonia with geometry normally used at JLab is just below 0.6 K. The limiting factor is the kapitza resistance on the surface of the target bead. Helium-3 alone can not be used in the target bath as it has poor material cooling qualities. The target insert and material needs to be cooled fast so there is not additional overhead time in replacing material. The inner part of this system is an evaporation fridge that takes the target material and insert down to 1 K. From that point the super-cool helium-4 can be bled in gradually to keep the target bath full. This target

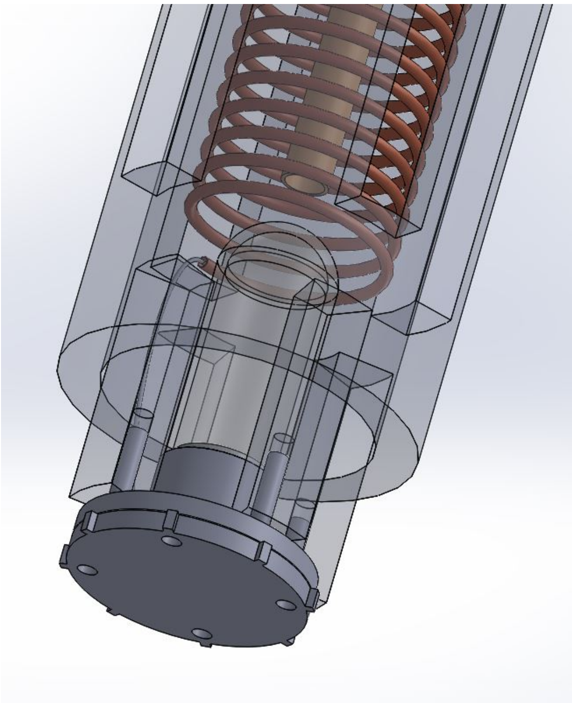

Figure 3: The dilution insert showing the inner layer with the glass mixing chamber and lower tube-in-tube heat exchanger.

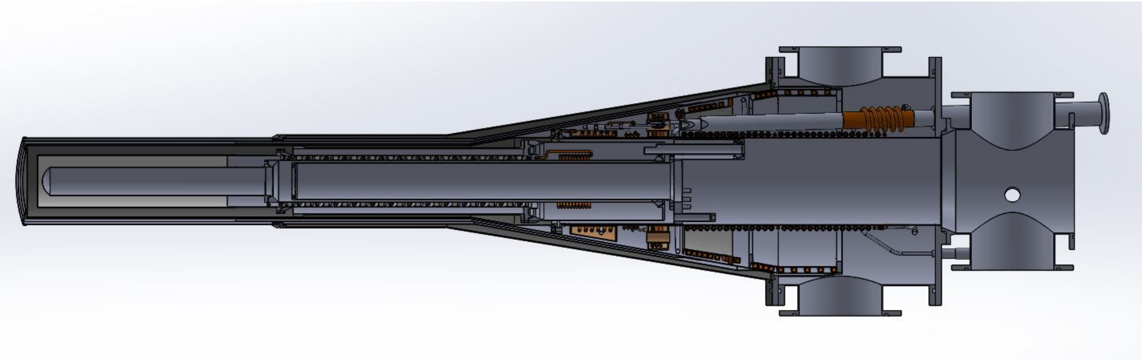

Figure 4: New design for super-cooled Helium-4 fridge

bath area is surrounded by the mixing chamber of the dilution part of the system. This system can cool off the surrounding metal and various layers of the inner insert area (He4 space) and the outer fridge with very very cold vapor. The notion here would be that you can use these extra low temperatures (300 mK) for over-cooling parts of the fridge infrastructure both surrounding and on the way up towards the insert access. It would also allow very high super-cooling of the helium-4 to use once the insert is loaded. Letting really cold LHe4 in to fill the nose will make it possible to get colder quicker. This system will be versatile in the sense that it can be use as a high cooling power system by use of a valve that allows the liquid helium-3 to bypass the lower heat exchanger. It could also run as a much lower temperature system for lower beam current by controlling the flow to be slower in the lower heat exchanger. The super-cooled helium-4 is still used in the target bath even though there is very little helium vapor pressure due to film creep. This film creep craws up the sides of the wall and warms up and then is pumped out the evaporation end of the fridge. This also creates convention in the nose area so that there is no cryo-pumping from the insert access to the fridge. This system has many application but can significantly improve the polarization of the spin-1 and neutron targets for beam intensities 100 nA and below.

I also look forward to exploring the design and construction of a new active target to use at TUNL and other facilities. The concept here was first explored by collaborators at PSI [31] for the purpose of having the polarized target be part of the detector system. Polarized scintillating targets are possible to construct with blocks of scintillating organic polymer, doped with the free radical TEMPO. This material can be polarized dynamically and then held in a frozen spin state for use in a polarized target experiment. This allows for the unique situation of being able to detect the trajectory of the low energy particle that would otherwise terminate in the target before detection. This style of target-detector is especially useful for experiments involving the coherent scattering of the deuteron. It is necessary to design and construct a dilution fridge that will facilitate the geometry needed for an active target for the next generation of polarized target experiments to run at TUNL. This project is an integral part of that plan.

Transition-edge Sensors

There are many applications for superconducting transition-edge sensor (TES) that remain largely unexplored. B. Norum and I plan to explore using a low temperature dilution fridge how to optimized TES for photon detection. X-ray spectroscopy experiments at next-generation synchrotron light sources need to successfully capture very large fluxes of photons, while detectors at free-electron laser facilities need pulse response fast enough to match repetition rates of the source. The need for greater statistical precision can limit the possibility of implementation of such detector systems. TES detectors can be extremely sensitive to pile-up effects that can distort spectra. These issues can best be handled with fast rising and falling edges. Having the infrastructure already in place at UVA affords us the opportunity to explore the low temperature characterization of specialized TES. This research could result in a significant improvement in photon resolution with the use of optimized edge control in TES mirocalorimeters.

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