

# The Solid Polarized Target Group at the University of Virginia

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## 1 Summary

The solid polarized target group began in 1990 with the preparation of a solid polarized proton target, intended for Jefferson Lab, first used at SLAC in E143 and ultimately in a

set of 3 spin structure experiments which generated, collectively, more than 2800 citations. At Jefferson Lab we have led five polarized target experiments. The first two have both earned the 100+ top citation designation at HEP-inspire ([inspirehep.net/](http://inspirehep.net/)). Both Day and Crabb have impressive h-indices, according to hep-inspires and World of Science.

Until 2015 years the principles have been Donal Day, Donald Crabb and Oscar Rondon. Rondon retired in June of 2015. Crabb is retiring at the end of the 2018 Spring semester. It is unlikely that Day will be active in this area much past the start of the next decade.

The group concentrates on experiments that use spin degrees of freedom (i.e. using polarized targets and beams) in electron-nucleon/nucleus interactions to extract new information about the properties of these fundamental building blocks of nature and lend new insights into their structure. We are **alone** among domestic university-based research groups that have the capability of developing, building and maintaining the cryogenic polarized targets critical for this research.

Since 2000 the group has produced 16 Ph.Ds and 3 M.S. graduates and there are 3 more students in training. See Table 1. Among our graduates, four have tenured or tenure track positions (Renee Fatemi, Dustin McNulty, Nadia Fomin and Jonathan Mellor) and two are staff scientists at national labs (Josh Pierce and James Maxwell). Our lab has been a very attractive place for undergraduates and we have engaged very many. A significant fraction of these students have gone on to graduate or professional school.

Former postdocs have also done well, often remaining in the field. These include Karl Slifer, now a tenured professor at the University of New Hampshire and a trailblazer in spin structure measurements, a research associate with us from 2004-2008. Dr. Benedict Zilhman was a member of our group for 4 years as a research associate in the late 1990's and is now a leading staff scientist in Hall D at Jefferson Lab. Stephen Bueltmann, a tenured professor at Old Dominion University, was our research associate in the mid-1990s.

Our funding from the DOE has been very steady in good times and bad, a total of \$12.4M since 2000. Our most recent renewal proposal with a 3-year budget (Dec. 01, 2016 - Nov. 31 2019) was awarded \$2.16M. See Figure 1 for our funding profile since 2000.

Our program manager at DOE, Gulshan Rai, and the Associate Director for Physics at Jefferson Lab, Rolf Ent, have expressed their willingness to discuss support for our group's future. We also have strong support for our succession plan from LANL and TUNL.

**Our success has arisen, to a large part, because the University had the wisdom to allow faculty to be fully dedicated to research with minimal teaching and service responsibilities. This contribution and the results of these special circumstances have not gone noticed or unrewarded by the funding agencies. Our contribution to the department's reputation has been substantial and can continue. The dismantling of the group would be a material mistake; not only would it result in the loss of substantial external research funds but also opportunities for graduate and undergraduate students alike. It would immediately diminish the standing of the department.**

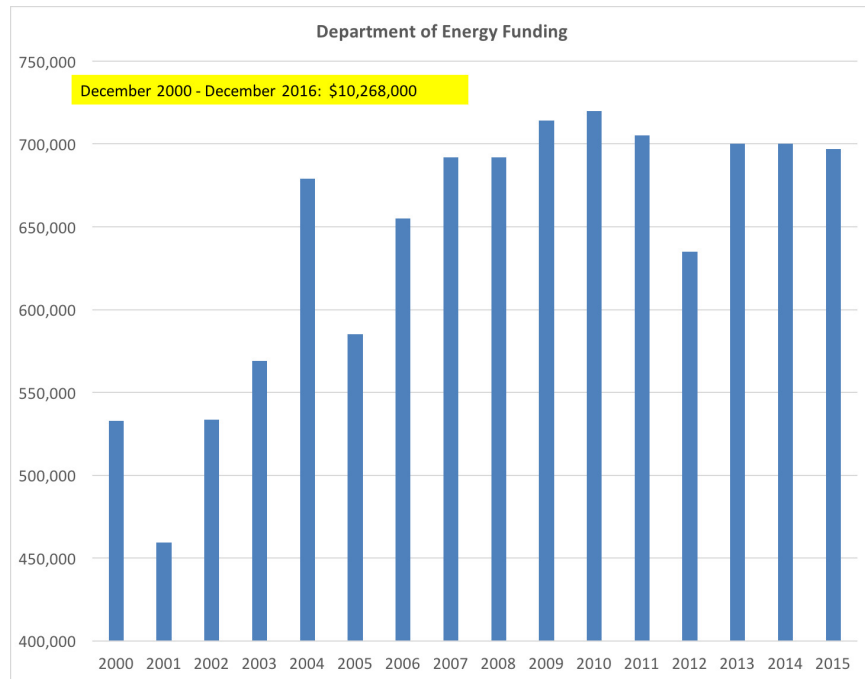


Figure 1: Since 2000 we have been awarded a total of \$12.4M. Year 2017 (in purple) is for the period Dec 01, 2017 - Nov. 30, 2018 and 2018 (in blue) is for the period Dec 01, 2018 - Nov. 30, 2019. Note the suppressed zero. The funds represented by colored bars have not yet been spent.

## 2 General Focus

Our laboratory work, since the formation of the group in 1990 has largely been focused on the polarized targets used world-wide. We intend to continue exploring the technology to deliver the best figure of merit for polarized fixed target experiments. We are among the leadership of several approved polarized target experiments at Jefferson Lab which rely on developments from our target lab. Two of these are: “Measurements of the Quasi-Elastic and Elastic Deuteron Tensor Asymmetries”, PR12-15-005, and “The Deuteron Tensor Structure Function  $b_1^d$ ”, E12-13-011. Both require a robust tensor polarized deuteron target and pioneering methods to improve both the magnitude and the precise determination of the tensor polarization have come from our lab. The third, Wide Angle Compton Scattering (E12-17-008) is conditionally approved for 45 days and has as its goal to measure the initial state helicity asymmetry in Compton scattering from a proton polarized target.  $A_{LL}$  provides access to the  $E$  and  $H$  Generalize Parton Distributions (GPDs), with a different weighting than one obtains from other exclusive processes, eg. elastic proton scattering. This latest success was made possible by our efforts designing a pure real photon source making it feasible to increase the photon flux intensity by more than a factor of 30.

Our group is deeply engaged at the TUNL facility (Duke) and two polarized target experiments have been approved - the target itself is being developed here.

We are responsible for the polarized target for the polarized SeaQuest at Fermilab (E1039) where the measurement of polarized Drell-Yan interactions is a major milestone in the hadronic physics community, motivated by a fundamental prediction of QCD that postulates that a naively time-reversal-odd distribution function, such as the Sivers function, measured in Drell-Yan production, must change sign if measured in semi-inclusive deep inelastic scattering (SIDIS). This experiment is expected to run in early 2019. A measure of the community and agency support for this experiment is made concrete by the DOE’s commitment of \$2M, largely to support the polarized target infrastructure at FermiLab.

## 3 Education

We commit a tremendous amount of time teaching and training undergraduate and graduate students enrolled at UVA as well as at other institutions. Our facility is the only fully functioning educational laboratory in the country serving solid polarized target experiments. Because our research and development in polarized targets is pivotal to the experimental effort in nuclear physics we are in the unique position to offer students opportunities in research, leading to critical work in which they have played a major role<sup>1</sup>

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<sup>1</sup>We employ high vacuum and low temperature techniques as well as millimeter microwaves and RF NMR.

Over a calendar year we will have 5-10 different undergraduates working with us. Some stay for a semester, some stay for 3 years. They all work assisting essential research projects. Table 1 provide listings of our graduate students - their current positions are included.

Our group is dedicated to the education and training of young scientists and at the same time we are committed to the training and assistance of seasoned researchers. Our relationship with UNH, TUNL, LANL, ORNL, Fermilab, and JLab have allowed us to introduce and prime scientists to construct/operate specialized cryogenic refrigerators, DNP microwave systems, superconducting magnets, and NMR systems. We are promised a continuing relationship with the national labs as only we can provide the facilities to test materials and specialize instrumentation.

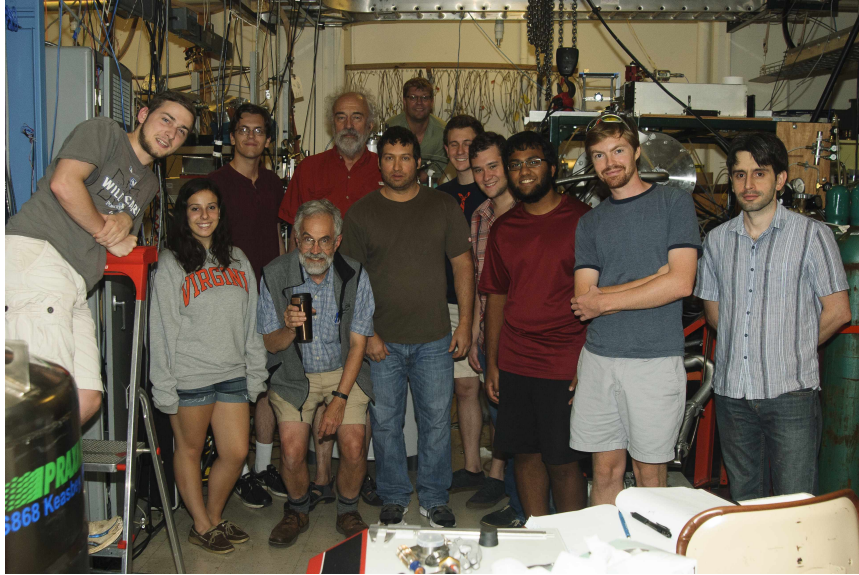


Figure 2: The Drell-Yan magnet and cryostat obscured by the UVA polarized target group and LANL staff in our lab in July 2015 where the new magnet rotation was tested successfully. Left to right: Jack Beatty, Brianna Biessecker, Ian Johnson, Richard Raymond (UMich), Donald Crabb, Dustin Keller, David Kleinjan (LANL), Jacob Higgins, Matt Biondi, Senthil Kannan, Ethan Scott and Mikhail Yurov. Photo by Andi Klein (LANL).

Much of our lab research is in low temperature physics and solid-state spin dynamics for nuclear experiment applications. UVA is the only domestic university conducting research and development in this field. Jefferson Lab has an excellent target group with an international reputation. However their group is dedicated to service and not research and development or the training of students. It is not a surprise that the JLAB target group staff has included our graduates - Josh Pierce (2008 Ph.D) left Jefferson Lab for ORNL in 2013 and James Maxwell (2012 Ph.D.) was subsequently hired as his replacement.

Name	Advisor	Graduated	Degree	Pres. Inst.	Pres. Position
Paul McKee	Day	2000	Ph.D	QIM LLC	Chief Technical Officer
Chris Cothran	Day	2000	Ph.D	Georgetown University	Director of Instr. Labs
Al Tobias	Crabb	2001	Ph.D	Univ. Virginia	Physics Staff
Hongguo Zhu	Day	2001	Ph.D	Defense Threat Reduction Agency (DTRA)	Physical Scientist
Chris Harris	Day	2002	Ph.D	Vanderbilt University	Director of Licensing
Rene Fatemi	Crabb	2002	Ph.D	U. Kentucky	Associate Professor
Dustin McNulty	Crabb	2002	Ph.D	U. Idaho	Associate Professor
Yelena Prok	Crabb	2004	Ph.D	VCU	Assistant Professor
Svyatoslav Tkachenko	Crabb	2004	M.S.	NA	NA
Jonathan Mellor	Crabb	2006	M.S.	Univ. Conn.	Assistant Professor, CE & ME
Justin Wright	Day	2006	M.S.	US Army Night Vision Lab	Staff Scientist
Nadia Fomin	Day	2008	Ph.D	Univ. Tenn.	Assistant Professor
Josh Pierce	Crabb	2008	Ph.D	ORNL	Staff Scientist
Vahe Mamyan	Day	2011	Ph.D	UCLA	Medical Physics Certification
K. Kovacs	Crabb	2010	Ph.D	UCSB	Instructor
James Maxwell	Day	2012	Ph.D	Jefferson Lab	Staff Scientist
J. Mulholland	Day	2012	Ph.D	Booz Allen	Staff Scientist
Nicholas Kvaltine	Crabb	2013	Ph.D	MHKKG (Austin)	Patent Technical Advisor
Zhihong Ye	Day	2014	Ph.D	Argonne Natl. Lab.	Research Associate
Mikhail Yurov	Day	2017	Ph.D	Los Alamos National Lab (Jan. 2018)	Research Associate
Dien Nguyen	Day	2018	Ph.D		
Dan Abrams	Day	2020	Ph.D.		

Table 1: Listing of graduate students since 2000 along with current positions.

## 4 Nuclear and Particle Physics Research - the next decade

We believe the future holds more than 10 years of work at accelerator facilities both providing, improving and exploiting solid polarized targets. We have a unique facility and unequalled experience in spin physics that has been accumulated over almost 3 decades. Our facilities and our knowledge should be fully exploited.

It is useful to have a sense of how the community views our program. Here are some selected (and highlighted) comments taken from the reviews of our 2013 and 2016 DOE renewals.

Comments from Reviewer #1 (2013):

The target group .... has an outstanding record in building and maintaining polarized targets and is internationally highly recognized. ... The group has a long-term expertise, a sound foundation of technical equipment and local facilities and is, to my knowledge the only one in the US to develop solid polarized targets on a systematic and academic level.

Comments from Reviewer #2 (2013):

... the group has a unique facility in their target lab and they take full advantage of having this technology. Their past performance is excellent. The only concern might be that this group is run by three senior PIs who are at, or close to, retirement age and may not be able to continue this work for another decade. The group has provided important and unique contributions to polarized target

development, and it would be good to see such work continue well into the next (few) decades.

Comments from Reviewer #1 (2016):

Two world experts are guiding the work. They have a long experience in polarized target developments and have largely proven to be highly qualified for the work proposed. They have provided polarized targets for many physics experiments with great success.

The PI has already endorsed several responsibilities proving wide interest in physics experiments and accelerators. He has been involved in the research and development of polarized target since long, and thus has the full expertise to lead the research program.

Another physicist is already anticipated as future Principal Scientist and co-PI. He is presently in charge of planning and day to day activity for the target research development labs, oriented towards the plans at JLab, Fermilab and Duke, in full coherence with the proposed research.

The team has access to the full hardware highly specialized resources needed thanks to extensive work in this domain in the past. Several relevant hardware installations have been successively and wisely refurbished and upgraded, and so will be with within the present grant.

Finally, it must be noted that the research is essential for unique large facilities in US. Indeed within the experimental physics program of the newly available 12 GeV electron beam of JLab, many experiments based on polarized targets have been approved by the scientific committee. To make use of such a unique beam, high performance targets are mandatory.

Comments from Reviewer #2 (2016):

The innovation in this proposal is, for the most part, leveraged on the development of solid, polarized targets. This is the leading group in the US, and probably the world, for the development of these types of targets. As a reminder, laser optical pumping cannot provide a competitive polarized gaseous hydrogen or deuterium target, and frozen spin butanol targets cannot survive beam heating from the incident electron beam. For the JLab experimental program, the target technology being developed at UVa is the main (only?) path forward. The impact of this research is deeply woven through the JLab spin-physics program.

To my knowledge, there are no other university groups in the US so heavily involved in polarized target development, and the running of target-spin-dependent electron scattering experiments. The UVa group operates within a unique niche.

## 5 Succession Plan

Don Crabb is retiring in May of this year and it is unlikely that Donal Day will be engaged in this work past the turn of the decade. Oscar Rondon has already retired. We are unique among domestic university groups with regard to building and developing these targets and training other researchers and students, however we are not a service group and our focus is most generally on spin physics research. Our infrastructure has been built up over a very long time and will hardly be reproduced elsewhere in the short term. We were able to come into existence largely because of state support for both Donal Day's and Donald Crabb's positions as full-time research faculty for more than a quarter of century. This, along with direct state and DOE support over many years, has made our success possible. Without faculty fully dedicated to research it is unlikely our success would have happened - nor is it likely to happen elsewhere without the same.

Dustin Keller's transition from principal scientist to the research professor track is a necessary step that both our group and the DOE agree to in order to keep this grant and research activities alive. Once formalized with the assistance of Donal Day he will become lead PI on our grant and be able to recruit students for the many future projects he has proposed. He has for the last 5 years taken the largest role in the lab and nearly all the progress in our novel target developments of late are due to his leadership. He has spokesperson positions on several polarized target experiments and indeed has generated several proposals at different facilities listed below. Both Donal Day and Donald Crabb are completely in support of him becoming the PI and taking over our research and strongly encourage this transition to the research professor track. The DOE has also shown considerable support for this transition and gave strict permission to promote him to principal scientist until Crabb's retirement at which point we are committed to make the transition to the research professor track. We have already received support from our reviewers of our previous renewal on this succession with regard to the DOE's support. We have had preliminary discussions with our chair, and the chair with our dean, and with the DOE about our future and we are optimistic that all parties are on the same page with our succession plan. Below we present some of Dustin Kellers research in his own words.

### 5.1 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.

## 5.2 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.

### 5.2.1 Current Polarized Target Experiments and Proposals

The present direction of the groups research focus can be seen in the polarized target proposals listed below for experiments to run in the near future at Jefferson 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  $b_1$  (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 Correlations 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

### 5.2.2 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.

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.

### 5.2.3 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 proposed so that the elastic 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  $k > 300 \text{ MeV}$  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.

#### 5.2.4 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 ( $\text{NH}_3$  and  $\text{ND}_3$ ). 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  $x \rightarrow 1$ . 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  $Q^2$  evolution). 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.

#### 5.2.5 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 ( $1 \times 10^{12}$ ) configuration to create the best overall figure of merit for the run time as possible. This project has led 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 a 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  $J/\psi$  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  $\gamma D \rightarrow \pi^- p(p)$ :** T10 and T20 can be used in this photodisintegration process to understand 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  $\pi^0$  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.

### 5.2.6 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 (HI $\gamma$ S). 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 HI $\gamma$ S 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 photodisintegration 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 HI $\gamma$ S 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 as 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.

This project along with the HI $\gamma$ S 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.

### 5.2.7 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  $A_N = f P_t A_N^{DY}$ , 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  $3 \times 10^{12}$  protons for a 4 seconds spill. This is possible due to the high pumping power available through the 14,000 m<sup>3</sup>/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.

### 5.2.8 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<sub>3</sub> 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  $\gamma p \rightarrow \gamma^* p' \rightarrow e^+ e^- p'$ , 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<sup>2</sup>), and the skewness  $\eta$ . The latter reflects the difference between the initial and final momentum fraction carried by the struck quark, and corresponds to  $\xi$  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  $\eta$ -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 motivate 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  $\alpha^3$  are of concern here, in addition, the terms involved in the  $\alpha^3$  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 a 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 quintessen-

tial 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 framework 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  $\pi N$  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  $\gamma p \rightarrow \gamma p$  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  $J/\psi$ -nucleon resonances at threshold in reactions such as  $\gamma p \rightarrow [J/\psi p]$ ,  $\gamma p \rightarrow [J/\psi p]\gamma$ ,  $\gamma p \rightarrow [J/\psi]\pi^+$ , and with the deuteron target  $\gamma d \rightarrow \bar{D}^0 + [\Lambda_c n]$  and  $\gamma d \rightarrow [\Lambda_c] + [\bar{D}^0 n]$  reactions. Another possibility is the octoquark  $|uuduudc\bar{c}\rangle$  in  $\gamma d$ . 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  $\Lambda(uds)$  carries 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 lacking. There are still far fewer  $\Xi$  resonances than  $\Delta$  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  $\gamma N \rightarrow KK\Xi$ , a measure of the transverse spin-transfer can be determined by measuring both the double-polarization observable  $K_{yy}$  and the photon-beam asymmetry  $\Sigma$ . These observables are related to the parity of the  $\Xi$  resonance by

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

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

### 5.3 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  $\text{ND}_3$ . I am also investigating deuterated ethane ( $\text{CD}_3$ ) and methane ( $\text{CD}_4$ ) 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.

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 3 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

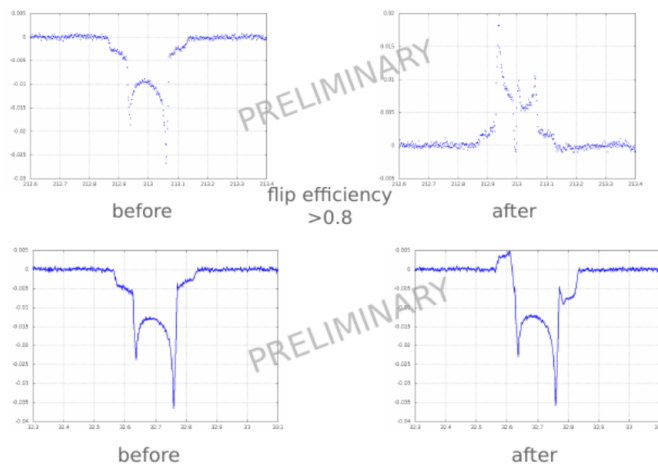


Figure 3: The d-butanol NMR signal before and after an AFP flip showing over 80% efficiency.

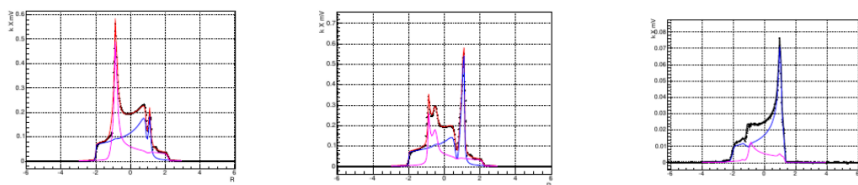


Figure 4: The d-butanol NMR signal Using RF irradiation to manipulate the tensor polarization of the deuteron.

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 be 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 4 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 perform low temperature ( $\sim 30$  mK) solid-state NMR experiments needed for specialized low temperature target material research. This system was designed to be small and inexpensive and something that can be built right here in the physics department. Figure 5 shows the Solidworks drawing of the design. This system is a design that holds 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 6. 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 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 ( $\sim 300$  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 used 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



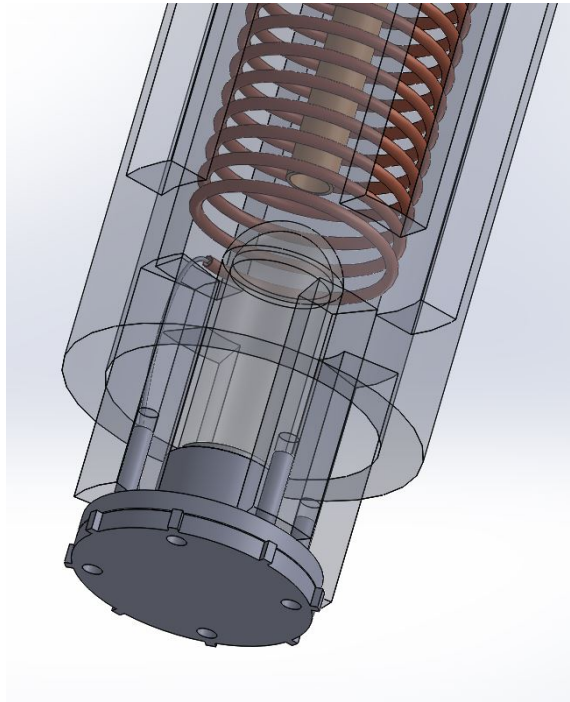


Figure 5: The dilution insert showing the inner layer with the glass mixing chamber and lower tube-in-tube heat exchanger.

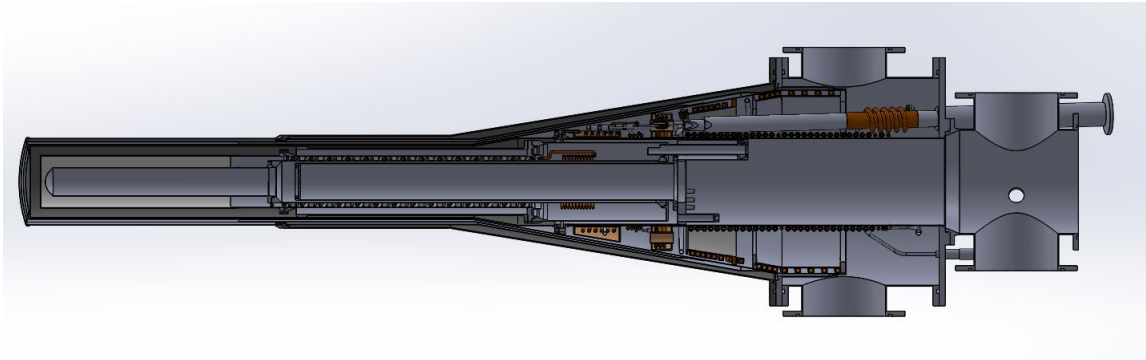


Figure 6: New design for super-cooled Helium-4 fridge

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 crawls up the sides of the wall and warms up and then is pumped out the evaporation end of the fridge. This also creates convection 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.

## A Facilities and Resources

Over the last 25 years we have built up a tremendous laboratory infrastructure some of which is listed below. These have been purchased through our previous grants, state support, have been acquired from other laboratories, or are on loan. Recently we acquired many items from the polarized target groups at Argonne National Lab and the University of Michigan Spin Physics Group. Reproduction of this laboratory will not happen elsewhere - the cost is prohibitive.

We have equipment on loan which is helping other groups, e.g a  $^4\text{He}$  fridge, 2 NMR Q-meters and a 7 T super magnet (obtained from our NMR spectroscopy colleague in the Department of Chemistry) at UNH; a set of Roots pumps (12000  $\text{m}^3/\text{hr}$ ) at JLab (for which we provide back up with our local equipment during experiments there) and a set of Roots pumps (4000  $\text{m}^3/\text{hr}$ ), operating at TUNL at Duke University.

The advantages of an in-house facility are many: students and post-docs and others can be trained in the operation of the polarized target obviating the need for on-the-job training during the particle physics experiment. It is also a facility where our undergraduates have conducted their own research projects. As mentioned above, we use the refrigerator(s) to investigate procedures (e.g. deuteron tensor polarization) which has already lead to new Jefferson Lab proposals and certainly more in the future.

We occupy 1800  $\text{ft}^2$  fully equipped lab space with the following:

- A cold bore superconducting solenoid operating up to 8 T and which has a 1 K  $^4\text{He}$  evaporation refrigerator integrated into it.
- A warm bore superconducting magnet operating up to 7 T into which our several refrigerators can be inserted.
- Two horizontal  $^4\text{He}$  refrigerators; one has been loaned to UNH.
- Two horizontal  $^3\text{He}$  refrigerators.
- Two horizontal  $^3\text{He}/^4\text{He}$  dilution refrigerators, one high power, one very low temperature for frozen spin operation, obtained from HZG Germany and to be used at HIGS.

- Four high power EIO microwave tubes, operating around 140 GHz and two matching power supplies, plus matching waveguides and instrumentation for measuring power and frequency.
- Two high power 183 GHz EIO microwave tubes (for 6.55 T) which operate with above power supplies including power and frequency measurement systems, plus appropriate wave guide components.
- Three 70 GHz carcinotron microwave tubes and 1 power supply and four 70 GHz klystrons and matching 70 GHz hardware and one power supply.
- NMR polarization measurement. Have 11 Liverpool Q-meters and matching hardware. Recently acquired 4 more plus components to make two more. Instrumentation plus spares to operate up to 6 Q-meters at a time. One of these has been lent to UNH and one to ODU.
- National Instruments DAQ hardware and robust Labview program to operate or monitor all of the above instruments.
- A chiller for for liquifying gases such as  $CD_4$  and  $CD_3$  and dripping into  $LN_2$  to make beads for our polarized targets.
- Two complete sealed Roots pump sets and pumping lines. One other set is used in our experiments at JLab. Finally a fourth set will be used in polarized target experiments at the HI $\gamma$ S facility at Duke University.
- Infrastructure (other pumps, temperature and pressure monitoring instruments, cryogenic hardware etc.) to support two separate installations.

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