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DOE Award Number	DE-SC0003885
Project Title	Recovery Act – Measurement of Parity Violation in Deep Inelastic Scattering and Studies of the Nucleon Spin Structure at JLab 6 and 11 GeV
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Recipient ID /Account Number	54-6001796
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Reporting Period End Date	May 31st, 2014
Final Report?	Yes
Submission Date	March 10th, 2016

1 Introduction and Overview

1.1 Major Goals

The objectives of Prof. Zheng’s research program supported by this award is divided into the following three topics:

1. Play a primary role in the data analysis of the 6 GeV Parity Violation in Deep Inelastic Scattering (PVDIS) experiment at Jefferson Lab (JLab) and publish the results. This topic produced the main accomplishment of this award.
2. Study and simulate the performance of a novel “Shashlyk” electromagnetic calorimeter (Ecal) and other detectors and the feasibility of using them for the JLab 11 GeV PVDIS program, testing prototypes for the calorimeter, and possibly start constructing the Solenoid Large Intensity Device (SoLID) spectrometer. The SoLID collaboration consists of 4-5 University groups. During the period of this award, Prof. Zheng’s group has led the design and simulation work of the SoLID’s Ecal and the Scintillator-Pad Detector (SPD), and have produced and tested prototypes for both Ecal’s preshower modules and the SPD.
3. Assist the polarized ^3He target R&D at JLab in preparation for the neutron spin asymmetry A_1^n experiments at 11 GeV. During the period of this award, Prof. Zheng’s group has provided the only long-term personnel for the polarized ^3He target work at JLab. The group has also carried out updated simulation work for the rate and the uncertainty estimation for the 11 GeV A_1^n measurements in experimental Hall C.

1.2 Group and Personnel Overview

At the beginning of the awarded period, Prof. Zheng’s group consisted of two (Mr. Diancheng Wang and Ms. Xiaoyan Deng) and one-half (Mr. Jie Liu) graduate students focusing on objectives 1 and 3, respectively. During the first year of the awarded period, Dr. Zhiwen Zhao joined the group as a postdoc and focused on objective 2, and Ms. Xiaoyan Deng finished with a M.A. degree. Mr. Diancheng Wang obtained his Ph.D. in November 2013. In the same year, two new students, Ms. Nguyen Ton and Mr. Kai Jin, joined Prof. Zheng’s group and their original focus was R&D on the polarized ^3He target at JLab (objective 3) while assisting with testing SoLID detector prototypes (objective #2). On the other hand, the work on the SoLID detectors and the polarized ^3He target can only provide the hardware training for Ph.D. students Jie Liu, Nguyen Ton and Kai Jin. The 11 GeV A_1^n experiment for which the R&D on the polarized ^3He target is carried out, has not been scheduled and thus cannot be expected to provide data for their thesis. Therefore Prof. Zheng has added data analysis tasks focusing on various completed JLab 6 GeV experiments towards the end of this award. More specifically, Mr. Jie Liu is focusing on analysis of the 6 GeV g_2^p experiment, “A Measurement of g_2^p and the Longitudinal Transverse Spin Polarizability”; Ms. Nguyen Ton is working on analysis of the first-period data from the 6 GeV SmallAngle GDH (SAGDH) experiment, “The GDH Sum Rule, the Spin Structure of ^3He and the Neutron using Nearly Real Photons”; and Mr. Kai Jin is focusing on analysis of

the 6 GeV Coulomb Sum Rule (CSR) experiment, “Precision Measurement on Longitudinal and Transverse Response Functions of QuasiElastic Scattering in the Momentum Transfer Range 0.55 (GeV/c)^2 to 0.9 (GeV/c)^2 ”. Dr. Zhiwen Zhao left the group in March 2014 and Dr. Vincent Sulkosky joined the group in August 2014. Dr. Sulkosky has been focusing on detector R&D and prototyping for objective #2. An overview of the group’s personnel and its evolution is provided in the table below, with graduate students’ tracking information provided in the next section.

Personnel	Time with Group	Tasks Type	Task
Diancheng Wang	6/2008	hardware	JLab 6 GeV PVDIS DAQ system and running the experiment
Ph.D.	11/2013	data analysis	JLab 6 GeV PVDIS
Xiaoyan Deng	6/2008	hardware	JLab 6 GeV PVDIS DAQ system and running the experiment
M.A.	8/2010	data analysis	JLab 6 GeV PVDIS
Jie Liu	6/2011	hardware	(until 2015) JLab Polarized ^3He target work for the 12 GeV A_1^n experiment
Ph.D. student	present	data analysis	6 GeV g_2^p experiment
Nguyen Ton	6/2013	hardware	JLab Polarized ^3He target work for the 12 GeV A_1^n experiment: pulsed NMR and NMR systems, cell characterization
Ph.D. student	present	data analysis	6 GeV SAGDH, first period data
Kai Jin	6/2013	hardware	JLab Polarized ^3He target work for the 12 GeV A_1^n experiment: EPR system, cell characterization, density measurements
Ph.D. student	present	data analysis	6 GeV CSR E05-110, ^4He target data
Zhiwen Zhao	10/2010	hardware	
postdoc	3/2014	analysis/other	JLab 12 GeV SoLID, general and Ecal simulation; proposal development; supervising students;
Vincent Sulkosky	8/2014	hardware	JLab 12 GeV SoLID Ecal R&D, prototyping and testing
postdoc	present	analysis/other	proposal development; supervising students; publishing results from SAGDH, second period data

1.3 Graduate Student Tracking Information

Table 1: Graduate students tracking information for the period from June 2010 to May 2015.

Student Name	Date Entered Grad. School	Date Joined Group	Degree Program	Date Degree Awarded/Expected	Advisor
Xiaoyan Deng	Aug.2007	June 2008	M.A.	August. 2010	Zheng
Diancheng Wang	Aug.2007	June 2008	Ph.D. ^a	Nov. 2013	Zheng
Jie Liu	Aug.2010	June 2011	Ph.D.	2016-2017	Zheng
Nguyen Ton	Aug. 2012	June 2013	Ph.D.	2018-2019	Zheng
Kai Jin	Aug. 2012	June 2013	Ph.D.	2018-2019	Zheng

^a Dr. Diancheng Wang has left the field of nuclear physics research and is now working for an industrial company in Texas.

2 Accomplishment

2.1 Accomplishments from the JLab 6 GeV PVDIS Experiment

The JLab 6 GeV Parity Violation in Deep Inelastic Scattering (PVDIS) experiment, or JLab E08-011, was carried out from October to December 2009. Prof. Zheng is the leading spokesperson of this experiment. Its data analysis, interpreting and finally publishing the results were one of the major goals of this award. After the completion of the experiment, the analysis was unblinded in April 2012 and the results were published from 2013 to 2014. A total of four publications have been produced and are reported below.

2.1.1 Report on the Fast-Counting Data Acquisition System

The first publication from JLab PVDIS is an instrumentational paper on the customized data acquisition (DAQ) and electronic system specifically built for this experiment [?]. Previous parity violation experiments at JLab detected the parity violating asymmetry from the integrated detector signals of opposite electron helicity states. While this would work for elastic scattering, it would not work for DIS scattering because of the high pion background in the scattered particles. The SLAC E122, while also carried out in the DIS regime, used the same integrating technique on the calorimeter signal. While the calorimeter does not respond to pions as much as to electrons, E122 did have large uncertainties due to pion contamination in the signal. For the JLab 6 GeV PVDIS experiment, a customized DAQ system was built utilizing signals from a double-layered scintillator detector, a gas Cherenkov counter as well as a double-layered leadglass detector. Partical identification was done by passing the Cherenkov and the leadglass detector signals through discriminators and a set of logic units. Both electron and pion triggers were formed. The PID efficiency was

determined at the hardware level and thus required examination during the run on a daily basis. In this publication, it was shown that the DAQ system could count scattered electrons up to 1 MHz with a $< 10^{-4}$ pion contamination in the electron trigger, an accomplishment of its own right. The uncertainty on the measured electron asymmetry due to the pion background was found to be negligible.

2.1.2 Results on the Nucleon Resonance PV Asymmetry

While the majority of the data of the PVDIS experiment was done in the deep inelastic scattering region, a small fraction of the beam time was used to take data on the parity-violating (PV) asymmetry in the nucleon resonance region. The original purpose of the resonance data were for providing inputs to radiative corrections of the DIS results. On the other hand, our resonance results did show that quark-hadron duality is valid for PV asymmetries at the measured precision, and thus had values on their own. The resonance results were published in Phys. Rev. Lett. [?]. For the main PVDIS asymmetry results, we combining our PVDIS asymmetries with the most recent data [?] on C_{1q} and extracted results on the C_{2q} couplings. Here $C_{1q,2q}$ are the effective electron-quark coupling constants. The coupling C_{1q} is axialvector-vector (AV) in nature, which means it probes how electrons violate parity symmetry; while the C_{2q} is vector-axialvector (VA) in nature and probes how quarks violate parity symmetry. In the tree-level diagram of the Standard Model of particle physics, these are given by the vector and the axial-vector couplings of the electron and the quark:

$$C_{1u} = 2g_A^e g_V^u = -\frac{1}{2} + \frac{4}{3} \sin^2 \theta_W, \quad C_{1d} = 2g_A^e g_V^d = \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W, \quad (1)$$

$$C_{2u} = 2g_V^e g_A^u = -\frac{1}{2} + 2 \sin^2 \theta_W, \quad C_{2d} = 2g_V^e g_A^d = \frac{1}{2} - 2 \sin^2 \theta_W, \quad (2)$$

with θ_W the weak mixing or the Weinberg angle. The first and the only PVDIS measurement before JLab E08-011 was the SLAC E122 [?, ?] in the late 1970's. It provided the first data on $\sin^2 \theta_W$, a key ingredient for the establishment of the electroweak Standard Model. At present time, data on C_{1q} and C_{2q} are used to set constraints on the electron-quark AV and VA contact interactions respectively, in beyond-the-Standard-Model (BSM) physics. Here the expression “contact interaction” is used to include BSM interactions that cannot be factorized into an electron and a quark vertex.

Our results on the combination $2C_{2u} - C_{2d}$ are five times more precise than what can be determined from SLAC E122, and provided for the first time evidence that this combination is non-zero at the more than 95% confidence level, see left panel of Fig. 1. Based on these results, mass limits on physics beyond the Standard Model have been extracted, see right panel of Fig. 1. Compare to data from high-energy colliders such as the ATLAS experiment at the Large Hadron Collider, the advantage of PVDIS is that we can isolate the electron-quark AV and VA couplings from other chiral structures. On the contrary, collider data are always sensitive to a sum of different chiral combinations, and their mass limits on the electron-quark VA or AV couplings can only be extracted based on the assumption that all other chiral terms are zero. Our results were published in *Nature* in early 2014 [?].

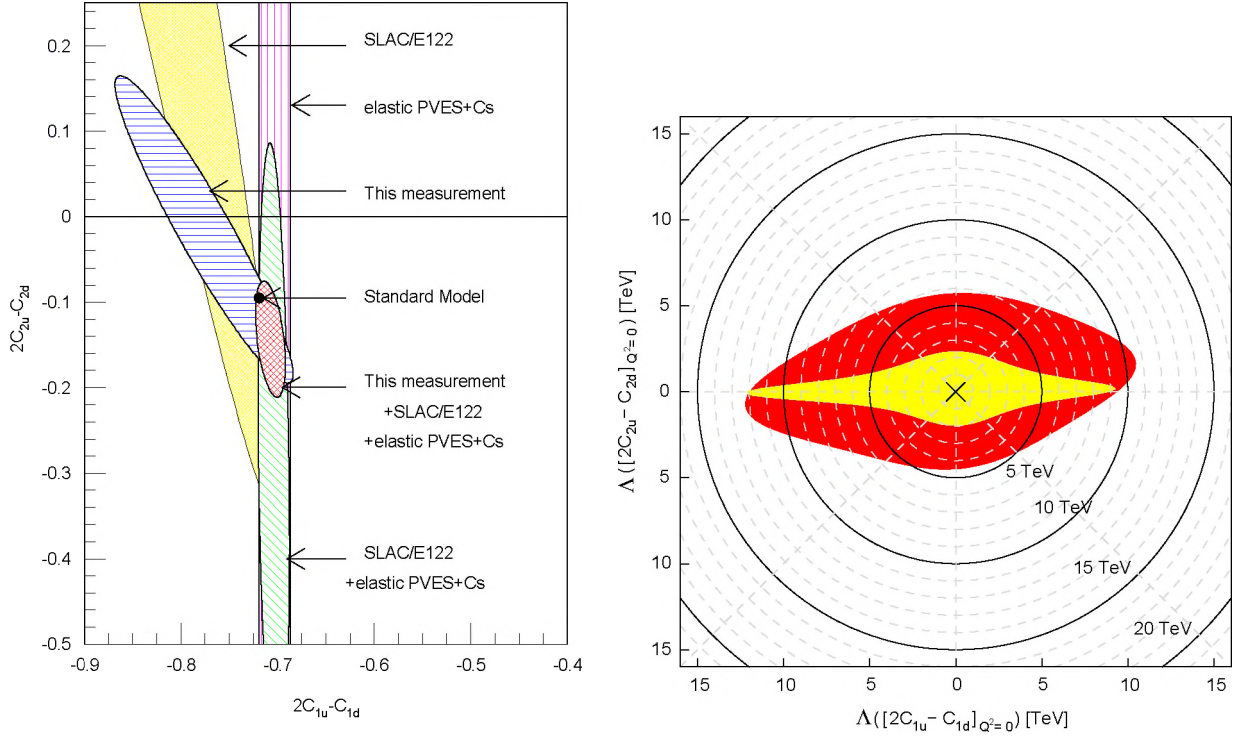


Figure 1: From Ref. [?]: *Left*: Comparison of the present results with those of earlier experiments and predictions of the Standard Model. Values of $2C_{1u} - C_{1d}$ and $2C_{2u} - C_{2d}$ from the JLab PVDIS experiment (ellipse with blue horizontal hatching) are compared with those of SLAC E122 (yellow ellipse) [?, ?]. The latest data on C_{1q} [?] are shown as the band with magenta vertical hatching. The ellipse with diagonal green hatching shows the combined result of SLAC E122 and the latest C_{1q} , while the ellipse with red cross-hatching shows the combined result of SLAC E122, this experiment, and the latest C_{1q} . The standard model value (with negligible uncertainty) is shown as the black dot, where the size of the dot is for visibility. *Right*: Mass exclusion limits Λ on the electron and quark compositeness and contact interactions. These limits are obtained from the zero- Q^2 values of $2C_{1u} - C_{1d}$ and $2C_{2u} - C_{2d}$ at the 95% confidence level. The outside of the yellow shape (inner contour) shows the limit obtained from SLAC E122 asymmetry results [?, ?] combined with the best C_{1q} [?]. The outside of the red shape (outer contour) shows the limit with our new results added. For visual guidance, mass limit scales in TeVs are shown as solid and dashed circles.

The fact that C_{2q} is non-zero implies that we have observed for the first time the parity-violating asymmetry component in electron-quark scattering that originates from the quark's axial-vector weak charge, *i.e.*, direct evidence in electron scattering that “quarks are not ambidextrous” (*Nature News and Views*) [?]. Our PVDIS results have been featured in several news releases including those from JLab, DOE, NSF, INFN, Science News, and in more than five languages.

The fourth paper on the JLab E08-011 is an “long archival” paper recording details of the experiment, including the experimental setup, data analysis, and interpretation of the

asymmetry results. It was published in Phys. Rev. C. [?].

What were the major goals of the project

What was accomplished under these goals

What opportunities for training and professional development has the project provided?

How were the results disseminated to communities of interest?

What do you plan to do during the next reporting period to accomplish the goals?

Nothing to report since this is the final report. Products: publications, conference papers, and presentations

3 Participants and Other Collaboration Organizations

3.1 Participants

Name: Project Role: Nearest person month worked: Contribution to Project: Funding Support: Country of residence: Collaborated with individual in foreign country: Country of foreign collaborator: Travelled to foreign country: If traveled to foreign countries, duration of stay:

3.2 Other Collaboration Organizations

None to report

4 Impact

4.1 Impact on the development of the principal discipline(s) of the project

4.2 Impact on other aspects

None to report

4.3 Changes, Problems

None to report