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Experimental Tests of the Standard Model for Particles and Nuclei

FINAL REPORT

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1. Introduction

This report summarizes the research carried out by the faculty, staff and students of Valparaiso University (VU) during the 30-year period from 1986 to 2015 using funds provided by the Medium Energy Nuclear Physics program of the Department of Energy (DOE). Three faculty members led the VU research group during the lifetime of the research grant. The three principal investigators responsible for the research were: Dr. Donald Koetke (1986 – 2007), Dr. Robert Manweiler (2008 – 2010), and Dr. Shirvel Stanislaus (2011 – 2015). During this period we participated and contributed to the progress of the following experiments:

1. The MEGA Experiment at Los Alamos National Laboratory (LAMPF E969).
2. The Crystal Ball Experiment at Brookhaven National Laboratory (BNL/AGS E906, E913).
3. The NuSea Experiment at Fermilab (FNAL E866).
4. The TWIST Experiment at TRIUMF (TRIUMF E614).
5. The STAR Experiment at RHIC.
6. The nEDM Experiment at Oak Ridge National Laboratory.

In the following sections we briefly describe the goals of the above experiments and the contributions made by the Valparaiso University personnel towards the progress of each project.

1. The MEGA Experiment at Los Alamos National Laboratory

1.1 Introduction

The MEGA experiment was a high-sensitivity search for the lepton family number violating decay, $\mu \rightarrow e\gamma$. Searches for this decay date back to 1945. Prior to the MEGA experiment, the most recent reported measurement was done at LAMPF by the Crystal Box collaboration, which reported a null result with a 90% confidence limit in the branching ratio $\frac{\mu \rightarrow e\gamma}{\mu \rightarrow e\nu_e\nu_\mu} < 4.9 \times 10^{-11}$ [1]. The Valparaiso University group joined this experiment in 1986 and worked on the design and construction of the detector. Data acquisition was begun in 1992 with an engineering run and concluded three years later with the final data run in 1995. In May 1999, the small group of physicists that had worked on the MEGA experiment, concluded the analysis and submitted the results in a paper to the *Physical Review Letters* wherein we reported a $< 1.2 \times 10^{-11}$ at the 90% confidence level. The paper was published in *PRL* in August 1999 [2]. Soon after the *PRL* paper was published, we wrote a comprehensive description of the experiment, including the experimental setup, the detector, the analysis, and the results. This was published in *Physical Review D* in June 2002. [3].

It is worth noting that Keith Stantz was a Ph.D. student from Indiana University who completed his Ph.D. dissertation based on a comprehensive analysis of the final large data sets that concluded the experiment and that resulted in the branching ratio limit noted above. Dr. Stantz was a Valparaiso University graduate.

1.2 Physics

The standard SU(3)XSU(2)XU(1) model of the strong and electroweak interactions has proved to be remarkably successful in describing current experimental results, with only the evidence for neutrino oscillations [4] and the measurement of the muon anomalous magnetic moment [5] falling outside its expectations. The standard model is nonetheless believed to be an effective low-energy approximation of a more fundamental theory as it contains many free parameters and unexplained symmetries. Many extensions to the standard model have been proposed. Often these are motivated by attempts to justify features, like parity violation or lepton-family-number conservation, which are put in ''by hand'' to explain experimental data.

Essentially every extension of the standard model includes new heavy particles that mediate rare decays that are otherwise forbidden. The most sensitive decay mode varies by model, so it is important to study a range of rare decays in the search for new physics. The rare decay $\mu \rightarrow e\gamma$ is the classic example of a reaction that would be allowed except for the separate conservation of muon and electron numbers within the standard model; in fact, $\mu \rightarrow e\gamma$ is predicted to occur in most proposed extensions. For example, it has been shown that a broad range of grand unified supersymmetric theories predict that $\mu \rightarrow e\gamma$ should occur with a branching ratio in the range of $10^{-10} - 10^{-14}$ [6], and the current world limits on $\mu \rightarrow e\gamma$ and other lepton-family-number violating decays including $\mu \rightarrow e\gamma\gamma$, $\mu \rightarrow eee$ and $\mu \rightarrow e$ conversion in a muonic atom have been used to set limits on many proposed extensions to the standard model.

1.3 Faculty and Staff

During the course of the 16 years that we worked on the MEGA experiment the following personnel participated in the project at different times and made significant contributions.

Dr. Donald Koetke
Dr. Robert Manweiler
Dr. Randall Fisk
Dr. Shirvel Stanislaus
Mr. Paul Nord

1.4 Undergraduate Students

Four Valparaiso University undergraduate students participated in the MEGA experiment by carrying out research during the summer. All four students went on to graduate school, and have completed their degrees. The following are the students who helped with the research on the MEGA experiment. The summer they worked and the graduate schools they entered at the completion of their undergraduate studies are also shown.

Hope Concannon	1991	Duke University
Jay Dittman	1991	Duke University
Laura Nickerson	1995	Northern Indiana University
Jon Thoms	1998	MIT

1.5 Contributions from Valparaiso University

In the course of the preparations to bring this experiment from its conceptual stages to its completion, the Valparaiso University group, including scientific staff, technical specialist, and undergraduate students have assumed numerous responsibilities. Some of the many contributions, which our group made, are described below.

- Designed, tested, and implemented a Labview-based controlling program on a Macintosh computer for the LeCroy 1445 high voltage system used for the positron detector MWPC's through our three years of data collection. The controller managed and monitored the voltages and currents simultaneously on all positron wire chambers. It also recorded all chamber over-current trips and all voltage changes chronologically, setting up alarms when necessary.
- Designed, tested, and fabricated all of the muon stopping targets for the MEGA experiment. The unique planar elliptical design, which required precise positioning with minimal mass support, prompted the development of a special fabrication technique. The design was established along with several colleagues at Los Alamos National Laboratory and all of the fabrication and testing was done at Valparaiso University.
- Made major contributions to the research, development, and fabrication of the unique low-mass high-rate MWPC positron detectors. Research and construction of these state-of-the-art detectors was the most challenging part of this experiment. One of us (Dr. Stanislaus) was a central figure in the successful completion of this work. A Valparaiso University undergraduate student was instrumental in the unique design and testing of glass anode wire restraints which were implemented to ensure electro-mechanical stability of the positron detector MWPC's.
- Took full responsibility for the development of an online filter pattern recognition algorithm and wrote all of the requisite software, tested it extensively with the Monte Carlo code and installed and maintained it throughout our data collection in 1993-1995.
- Participated (took shifts) in the acquisition of data at Los Alamos.
- Wrote all of the codes for the analysis of all cosmic ray data used for positron detector performance studies and analyzed all of these cosmic ray data taken over the course of the experiment. These data have resulted in MWPC wire-by-wire efficiency measurements, high voltage plateau curves for each

MWPC, delay curves for MWPC gates relative to the trigger time, threshold settings, and precision chamber alignment studies and delay line calibrations for the photon spectrometer.

- Carried out extensive data analyses using cosmic rays and Michel positrons to achieve precision intra-detector and inter-detector alignment, essential for obtaining good position and energy resolutions.
- Were responsible for the systematic determination of the denominator in the branching ratio, i.e., the number of useful muons, which stopped and decayed in our target for our entire data sample.
- Carried out most of the Monte Carlo studies required for our estimation of the detector acceptances and resolutions.
- Developed a track reconstruction code, which is based on "swimming" the positron through the non-uniform magnetic field of the MEGA magnet. This resulted in substantially better resolutions for the positron momentum and position at the muon decay point in the target.

1.6 Publications

1. V. Armijo et al.; "A fast MWPC with cathode strips and utilizing CF_4-Isobutane". Nuclear Instruments and Methods A303 (1991) 298.

2. S. Stanislaus et al.; "Results from beam tests of MEGA's low-mass, high-rate MWPCs". Nuclear Instruments and Methods A323 (1992) 198.

3. V. Armijo et al.; "Construction and performance of MEGA's low mass high rate cylindrical MWPCs". Nuclear Instruments and Methods A417 (1998) 24.

4. M.L. Brooks et al., "New limit for lepton-family-number non-conserving decay $\mu \rightarrow e\gamma$", Physical Review Letters 83 (1999) 1521.

5. M. Ahmed et al., "Search for the lepton-family-number non-conserving decay $\mu^+ \rightarrow e^+\gamma$", Physical Review D65 (2002) 11202.

2. The Crystal Ball Experiment at Brookhaven National Laboratory

2.1 Introduction

In 1996 we joined the Crystal Ball collaboration to study the spectroscopy of baryonic states through their neutral decay channels. This was a collaboration of 14 national and international institutions with 40 collaborators. The physics goals focused on studies of charge-neutral final states originating with $\pi^- p$ and $K^- p$ interactions. The physics studied in this experiment are of value to other experimental programs such as at the Jefferson Laboratory.

The Crystal Ball was moved from Stanford Linear Accelerator Center (SLAC) to Brookhaven National Laboratory (BNL) in November 1995. Over the next 1.5 years, the detector was positioned in line C at the Alternating Gradient Synchrotron (AGS), the detector and all of the electronics were assembled and tested, and a data acquisition system was developed and implemented. After some initial testing the collaboration collected data during the years 1997 and 1998 with π^- and K^- beams over a wide range of momentum settings up to 750 MeV/c. During the analysis phase of the experiment we collaborated very closely with colleagues at the Argonne National Laboratory, specifically with Dr. Hal Spinka. A large number of publications came out of the experiment.

2.2 Physics

The crystal ball detector possessed several valuable features that favorably lent themselves to experiments with photons in the final state. In this experiment, a 10 cm long liquid hydrogen target was positioned at the geometric center of the crystal ball. Interactions on the proton target were initiated with either a negative pion beam ($\pi^- p$) or a negative kaon beam ($K^- p$) where the pions and kaons from the external target at the AGS were separated electrostatically. The experiment focused exclusively on charge-neutral final states consisting primarily of photons from the decay of hadrons and neutrons. The trigger for these events required that the beam particle vanishes in the target and that the final state has no charged particles (charged particles were vetoed by thin scintillation counters around the hydrogen target). The crystal ball was, for these energies, a hermetic electromagnetic detector with nearly 4π steradian coverage provided by 720 NaI crystals. Outgoing photons produced electromagnetic showers in the NaI crystals providing exceptional angular and energy resolution. As such, the crystal ball detector was a remarkable multi-photon spectrometer that was used in these experiments to study $\pi^- p$ and $K^- p$ interactions in which the final states contained multiple photons

A perusal of the list of publications will give evidence of the wide array of physics that was studied in E906 ($\pi^- p$) and E913 ($K^- p$). The experiments included a search for fundamental symmetry-violating (CP) final states, a test of charge conjugation, searches for forbidden decays, and measurements of differential and total cross sections and branching ratios, all of which require a detector with the unique features of the crystal ball. The collaboration together produced a rich set of publications before the experiment was concluded and the collaboration disbanded after approximately 13 years of effort.

2.3 Faculty and Staff

Valparaiso University was a collaborator of the Crystal Ball experiment from its inception until the final publication. The following personnel from Valparaiso University contributed to the success of the experiment during the 13-year life of the experiment and made significant contributions to its success.

Dr. Donald Koetke
Dr. Robert Manweiler
Dr. Shirvel Stanislaus
Dr. David Grosnick
Mr. Paul Nord

2.4 Undergraduate Students

Over course of our work on the Crystal Ball experiment, eleven Valparaiso University undergraduate students participated in this experiment, some for more than one summer. Nine went on to graduate school, and have completed their degree. The following are the students who helped with the research on the Crystal Ball experiment. The summer they worked and the graduate schools they entered at the completion of their undergraduate studies are also shown.

Adam Gibson	1998	University of California, Berkeley
Jon Thoms	1999	MIT
Daniel Allen	2000	University of Wyoming
Robert Green	2000	Ball State University
Christopher Hoffman	2000	Northern Indiana University
Steven Wolf	2000, 2001	Dartmouth College
Tyler Parkison	2001	University of Michigan, Ann Arbor
Sarah Schlobohm	2001, 2002	University of Notre Dame
Ross Corliss	2002	MIT
Brian Bucher	2003	University of San Diego
Jason Summerlott	2004	Indiana University

2.5 Contributions from Valparaiso University

The Valparaiso University group, including scientific staff, technical specialist, and undergraduate students assumed numerous responsibilities. Some of the many contributions, which our group made, are described below.

- Carried out Monte Carlo simulations on several reaction channels in preparation for the data acquisition runs. This was very important to estimate the yields and resolutions expected from the data in preparation for decisions involving beam time allocations and scheduling.

- Wrote the initial online monitoring and histograming software. These were very important during the initial testing stages of the experiment as well as during data acquisition to understand the data that is being taken.
- Took a very active role in the data acquisition by taking shifts during the run.
- Wrote the 'Single Event Display (SED)' software to visualize individual events during data acquisition as well as during the analysis of the data. This piece of software was very widely used by the collaborators when writing data analysis software to understand the structure of the events and the behavior of the detector. The SED was also widely used to look at problematic events and understand their origin.
- Carried out an extensive study of the interaction of neutrons in NaI, specifically the neutron detection efficiency in NaI in the Crystal Ball. The measurements showed a disagreement with the GEANT Monte Carlo codes for neutron interactions in NaI. This result was especially important for certain reactions studied in the experiment wherein $\pi^- p$ and $K^- p$ interactions always resulted in a neutron final state.
- Energy calibrated the 720 NaI crystals of the Crystal Ball detector. The calibration of the detector was a very crucial part of the analysis of the data and was used by all of the collaborators. The calibration was done by using photons from the decay of neutral pions and etas produced in $\pi^- p$ and $K^- p$ reactions.
- Carried out the complete branching ratio analysis of the following two reaction channels: $K^- p \rightarrow \Sigma^o \pi^o$ and $K^- p \rightarrow \Sigma^o \gamma$

2.6 Publications

1. S. Prakhov et al., "Search for the CP forbidden decay $\eta \rightarrow 4\pi^\circ$", Physical Review Letters 84 (2000) 4802.

2. A. Starostin et al., "Measurement of $\pi^\circ\pi^\circ$ production in nuclear medium by π- at 0.408 GeV/c, Physical Review Letters 85 (2000) 5539.

3. A. Starostin et al., "Measurement of $k^- p \rightarrow \eta\Lambda$ near threshold", Physical Review C64 (2001) 055205.

4. W.B. Tippens et al., "Determination of the quadratic slope parameter in $\eta \rightarrow 3\pi^o$ decay", Physical Review Letters 87 (2001) 192001

5. T.D.S. Stanislaus et al.,"Measurement of the neutron detection efficiencies in NaI using the Crystal Ball detector", Nuclear Instruments and Methods in Physics Research A462 (2001) 463.

6. D.M. Manley et al., " Properties of the $\Lambda(1670)\frac{1}{2}^-$ resonance", Physical Review Letters 88 (2002) 12002.

7. A. Starostin et al., "Measurement of the $\pi^- p \rightarrow 3\pi^o n$ total cross sections from threshold to 0.75 GeV/c Physical Review C67 (2003) 68201

8. M. Borgh et al., "Search for $k^{-}p \rightarrow \pi^{o}\pi^{o}\pi^{o}\Lambda$ from threshold to $p_{k} = 750\ MeV/c$", Physical Review C68 (2003) 15206

9. K. Craig et al.," Dynamics of the $\pi^{-}p \rightarrow \pi^{o}\pi^{o}n$ reaction for $p\pi^{-} < 750$ MeV/c", Physical Review Letters 91 (2003) 102301

10. N. Kozlenko et al., "Measurement of the total and differential cross sections for the reaction $\pi^{-}p \rightarrow \eta n$ with the Crystal Ball Detector", Physics of Atomic Nuclei 66(2003).

11. S. Prakhov et al., "Measurement of the $\pi^{-}p \rightarrow \pi^{o}\pi^{o}n$ reaction from threshold to 750 MeV/c", Physical Review C69 (2004) 45202

12. S Prakhov et al., "Reaction $K^{-}p \rightarrow \pi^{o}\pi^{o}\Lambda$ from p_{K^-}=514-750 MeV/c ", Physical Review C69 (2004) 42202.

13. M. Saddler et al." Differential cross section of the charge-exchange reaction $\pi^- p \rightarrow \pi^0 n$ in the momentum range from 148 to 323 MeV/c", Physical Review C69 (2004) 55206.

14. R. J. Peterson et al., "y scaling in quasifree pion-single-charge exchange", Physical Review C69 (2004) 64612

15. A. Shafi et al., "Measurement of inverse pion photoproduction at energies spanning the N (1440) resonance", Physical Review C70 (2004) 35204.

16. S Prakhov et al., "$K^{-}p \rightarrow \pi^{o}\pi^{o}\Sigma^{o}$ at p_{K^-}=514-750 MeV/c and comparison with other $\pi^{o}\pi^{o}$ production", Physical Review C70 (2004) 34605

17. N., Knecht et al., "Relative branching ratio of the $\eta \rightarrow \pi^{o}\gamma\gamma$ decay channel", Physics Letters B589 (2004)

18. J. Olmsted et al., "Does the Σ(1580) 3/2- resonance exist?" Physics Letters B588(2004)

19. B.M.K. Nefkens et al., "Test of Charge Conjugation Invariance", Physical Review Letters 94 (2005) 41601

20. S Prakhov et al., "Measurement of $\pi^{-}p \rightarrow \eta n$ from threshold to $p_{\pi} = 747\ MeV/c$", Physical Review C72 (2005) 15203.

21. A. Starostin et al.," Measurement of $\pi^{-}p \rightarrow \pi^{0}n$ in the vicinity of the η threshold", Physical Review C72 (2005) 15205.

22. S Prakhov et al., "Measurement of the branching ratio for $\eta \rightarrow \pi\gamma\gamma$ decay", Physical Review C72 (2005) 25201.

23. B.M.K. Nefkens et al., "Search for the forbidden decays $\eta \rightarrow 3\gamma$ and $\eta \rightarrow \pi^{0}\gamma$ and the rare decay $\eta \rightarrow \pi^{0}\pi^{0}\gamma\gamma$", Physical Review C72 (2005) 35212.

24. R. Manweiler et al., "Measurement of the $K^{-}p \rightarrow \Sigma^{o}\pi^{o}$ reaction between 514 and 750 MeV/c", Physical Review C79 (2008) 015205.

25. S Prakhov et al., "Measurement of the invariant mass spectrum for the two photons from the $\eta \to \pi^o\gamma\gamma$ decay", Physical Review C78 (2008) 015206.

26. T.D.S. Stanislaus et al., "Measurement of the total cross section for the reaction $K^- p \to \Sigma^o\gamma$ between 514 and 750 MeV/c", Physical Review C79 (2009) 015203.

27. D. Mekterovic et al., "Differential cross sections for the charge-exchange reaction $\pi^- p \to \pi^o n$ in the momentum range from 103 to 178 MeV/c", Physical Review C80 (2009) 055207.

3. The NuSea Experiment at Fermilab

3.1 Introduction

The NuSea experiment (FNAL E866) was a complimentary approach to the study of the antiquark distributions in the nucleon. The experiment was carried with extracted beams of 800 GeV/c protons that were incident on a fixed target consisting of either hydrogen or deuterium. A blank target was also used to remove contributions from the target enclosure. The interaction of the incident proton with the neutron in the weakly bound deuteron was obtained by subtracting the proton-proton response from the proton-deuteron data.

While the central motivation for the experiment was to measure the sea antiquark distributions in the nucleon, the experiment evolved to include studies of the production of J/ψ and upsilon states. We point out that one Ph.D. student, Jason Webb, from New Mexico State University, concluded his Ph.D. dissertation based on the analysis of data collected in this experiment. Dr. Webb was a Valparaiso University graduate, and was later a postdoctoral fellow at Valparaiso University working on the STAR experiment at RHIC as described in section 6.

3.2 Physics

The principal physics goal of the NuSea experiment was to make the most definitive measurement of the sea antiquark densities inside the nucleon as a function of Bjorken x. The motivation for doing this was a published measurement of the Gottfried sum rule (GSR) by the New Muon Collaboration (NMC) that indicated that the GSR appeared to be violated. These measurements were carried out via Deep Inelastic Scattering (DIS) of muons from hydrogen and deuterium targets. One can write the Gottfried integral as

$$I_G = \int_0^1 \frac{\left[F_2^p(x,Q^2) - F_2^n(x,Q^2)\right]}{x}\, dx$$

where $F_2^p(x,Q^2)$ and $F_2^n(x,Q^2)$ are the proton and neutron inelastic structure functions obtained from DIS experiments. We can also write I_G in terms of the valence (v) and sea quark distributions of the proton as

$$I_G = \frac{1}{3}\int_0^1 [u_v(x,Q^2) - d_v(x,Q^2)]dx + \frac{2}{3}\int_0^1 [\bar{u}(x,Q^2) - \bar{d}(x,Q^2)]dx\,.$$

Here u_v and d_v are the up and down valence quark distributions in the proton and $\bar{u}$ and $\bar{d}$ are the anti-up and anti-down distributions in the proton sea. If we assume charge symmetry between the proton and neutron holds, the first integral is unity. Thus, if the nucleon sea is flavor symmetric in the light quarks, the value of the second integral is zero and $I_G = {}^1/_3$, which result is known as the Gottfried sum rule. The NMC result for the second integral was 0.147 +/- 0.0398 implying a considerable excess of $\bar{d}$ relative to $\bar{u}$ in the proton. Moreover, this result was adopted in by most parton parameterizations at the time.

The NuSea experiment employed the Drell-Yan process to study the nucleon sea antiquarks. In the Drell-Yan process, a quark from the incoming proton collides with an antiquark in the target nucleon producing a virtual photon that then results in a muon pair (μ^+ and μ^-) that traverses the NuSea spectrometer. It is thus possible to probe the sea antiquark kinematics inside the target nucleon by measuring the kinematics of the outgoing muons. The details of the methodology can be found in the initial paper published in Hawker, et al. [7]. Shown therein are the striking and surprising results displayed as the ratio d-bar/u-bar where the data at $x < 0.15$ follow the parton parameterizations (CTEQ4M) but for $x > 0.15$ the ratio diverges dramatically showing a large asymmetry in the distributions of anti-up and anti-down quarks in the nucleon sea. This remarkable result has formed the basis for all present day nucleon sea antiquark distributions. Because there is no known symmetry that would require $\bar{u} = \bar{d}$ this large observed asymmetry was not expected. From these results one can conclude that (a) the formation of sea quarks and sea antiquarks inside the nucleon is not limited to gluon interactions, and (b) that large non-perturbative processes are required to account for this asymmetry. The fundamental physics that might give rise to this observed asymmetry is explored in the paper by J.C. Peng, et al. [8].

The NuSea experiment was ideally suited to study other physics besides the antiquark distributions in nucleons. The possible suppression of J/ψ production due to heavy nuclei medium effects was explored using targets extending light (Be) to heavy (W) and the muons from the J/ψ production were studied in the NuSea spectrometer. Upsilon production from hydrogen and deuterium targets was studied to study the gluon-gluon fusion process, comparing this production in the proton vs. the neutron. Finally, a novel measurement of the polarization upsilon states (1S) and (2S + 3S), the latter being unresolved resulted in measured large transverse production polarization that was not seen previously nor expected in the NRQCD calculations.

3.3 Faculty and Staff

Only one faculty member (Prof. Donald Koetke) and a Technical Specialist (Mr. Paul Nord) from the Valparaiso University research group carried out research on the NuSea experiment.

3.4 Contributions from Valparaiso University

The collision rates in this experiment were extraordinarily high, in fact, too high to record all of the detector information for all of the collisions. To manage these high rates, a unique programmable hardware trigger was developed by collaborators at Texas A & M University and the Valparaiso University collaborators that, in principle, allowed for the implementation of a very trigger response. The individual elements in the chip were set based on the outputs from the hodoscopes in the large E866 spectrometer.

Programming this 16 x 16 array in this chip was the task taken by the Valparaiso University collaborators noted above. This was accomplished by developing an innovative lexical process whereby the physicist could enter the allowed combinations of hit elements that would satisfy the physics trigger. This information was then processed in code written explicitly for this purpose and implemented in

VxWorks software. All of the interface software required to communicate with the hardware trigger chip was also developed, implemented and tested by the Valparaiso University collaborators. Only those events that passed the trigger requirements in this trigger chip were kept for subsequent physics analysis. The rest were ignored.

To confirm that the hardware decisions were being made as intended, a parallel Fortran computer code was written to simulate the actions taken in hardware given various sets of inputs. These predictions were then compared with the output of the hardware trigger chip when the programmed code was downloaded into the chip. The authentication process was successful in confirming the actions taken by the trigger chip.

It is hard to overstate the important role that this hardware trigger and the associated programming played in this experiment. If it had been wrongly done, the experiment would fail completely! In the end, these contributions by the Valparaiso University collaborators were deemed to be a complete success.

3.5 Publications

1. E. A. Hawker, et al., (FNAL E866/NuSea Collaboration), "Measurement of the Light Antiquark Flavor Asymmetry in the Nucleon Sea", Phys. Rev. Lett. **80**, 3715 (1998).

2. J. C. Peng, et al., (FNAL E866/NuSea Collaboration), "d-bar/u-bar Asymmetry and the Origin of the Nucleon Sea", Phys. Rev. D **58**, 092004 (1998).

3. M. A. Vasiliev, et al., (FNAL E866/NuSea Collaboration), "Parton Energy Loss Limits and Shadowing in Drell-Yan Dimuon Production", Phys, Rev. Lett. **83**, 2304 (1999).

4. M. J. Leitch, et al., (FNAL E866/NuSea Collaboration), "Measurement of Differences between J/ψ and ψ' Suppression in p-A Collisions", Phys, Rev. Lett. **84**, 3256 (2000).

5. C. N. Brown, et al., (FNAL E866/NuSea Collaboration), "Observation of Polarization in Bottomonium Production at $\sqrt{s}$ = 38.8 GeV", Phys, Rev. Lett. **86**, 2529 (2001).

6. R. S. Towell, et al., (FNAL E866/NuSea Collaboration), "Improved Measurement of the d-bar/u-bar Asymmetry in the Nucleon Sea", Phys. Rev. D **64**, 052002 (2001).

7. T. H. Chang, et al., (FNAL E866/NuSea Collaboration), "J/ψ Polarization in 800 GeV p-Cu Interactions", Phys, Rev. Lett. **91**, 211801 (2003).

8. L. Y. Zhu, et al., (FNAL E866/NuSea Collaboration), "Measurement of Angular Distributions of Drell-Yan Dimuons in p+d Interactions at 800 GeV/c", Phys, Rev. Lett. **99**, 082301 (2007).

9. L. Y. Zhu, et al., (FNAL E866/NuSea Collaboration), "Measurement of Upsilon Production for p+p and p+d Interactions at 800 GeV/c", Phys, Rev. Lett. **100**, 062301 (2008).

10. L. Y. Zhu, et al., (FNAL E866/NuSea Collaboration), "Measurement of Angular Distributions of Drell-Yan Dimuons in p+p Interactions at 800 GeV/c", Phys, Rev. Lett. **102**, 182001 (2009).

4. The TWIST Experiment at TRIUMF

4.1 Introduction

In 1996 we were among a small group of Canadian, US, and Russian physicists, which formed the E614 -*TWIST* - collaboration to carry out a high precision measurement of the Michel parameters for muon decay. As the experiment gained support and endorsement from NSERC (the Canadian equivalent of NSF), more Canadian groups joined the experiment. The US contingent for TWIST experiment included Texas A&M University (TAMU) and Valparaiso University. The entire collaboration consisted of 30 physicists from 10 international institutions. The experiment was designed to search for physics beyond the Standard Model by making high precision and highly accurate measurements of the decay distributions of positrons from polarized muons stopped in a target. It was carried out at the Tri University Meson Facility (TRIUMF) at the campus of University of British Columbia in Vancouver, Canada.

The first five years from 1996 to 2000 were spent on the design and construction of the apparatus and the data taking commenced with a very successful engineering run in 2001. Physics data runs started in 2002 and continued till the summer of 2007. Since 2007 graduate students were involved with the analysis of the high precision data mostly on trying to understand the different backgrounds and biases involved. The experiment produced several publications with the last one being published during the spring of 2015.

4.2 Physics

The energy angular distribution of the positrons emitted from normal decay ($\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$) of polarized muons, is an excellent can be described in terms of four parameters ρ, η, ξ, and δ commonly referred to as the Michel parameters. Neglecting the electron and neutrino masses and radiative corrections, the differential decay rate for positive muon decay is given in terms of ρ, η, ξ, and δ by [9]

$$\frac{d^2\Gamma}{x^2 dx d(\cos\theta)} \propto (3-3x) + \frac{2}{3}\rho(4x-3) + P_\mu \xi \cos\theta \left[(1-x) + \frac{2}{3}\delta(4x-3)\right],$$

where P_μ is the polarization of the muon, $x = E_e / E_{e,\max}$, and θ is the angle between the muon polarization axis and the positron decay direction. The fourth decay parameter, η, contributes to the angle-independent part of the distribution if one includes the finite electron mass. These four Michel parameters can be directly related to the fundamental coupling constants in the generalized weak interaction. The Standard Model, thereby, makes definitive predictions for all four Michel parameters so that, in measuring them with very high precision, one can test the validity of the Standard Model for weak interactions. It is well known that the Standard Model contains an artificially incorporated left-right asymmetry. If the Michel parameters deviate from those used in the Standard Model based on pure V-A coupling, it will signal new physics beyond the Standard Model. If the Michel parameters are found to agree with the Standard Model values then extensions to the Standard Model will be considerably constrained beyond present knowledge.

4.3 Faculty and Staff

During the course of the 18 years (from the inception to completion) that we were part of the TWIST experiment the following personnel participated in the project and made significant contributions.

Dr. Donald Koetke
Dr. Shirvel Stanislaus
Mr. Paul Nord

4.4 Undergraduate Students

Two Valparaiso University undergraduate students participated in this experiment. Both of them went on to graduate school, and have completed their degrees. The following are the students who helped with the research on the TWIST experiment. The summers they worked and the graduate schools they entered at the completion of their undergraduate studies are also shown.

Daniel Allen	2000	University of Wyoming
Christopher Hoffman	2000	Northern Indiana University

4.5 Contributions from Valparaiso University

In the course of the preparations to bring this experiment from its conceptual stages to its completion, the Valparaiso University group, including scientific staff, technical specialist, and undergraduate students have assumed numerous responsibilities. Some of the many contributions, which our group made, are described below.

- During the construction phase of the experiment we worked on the fabrication of the high precision planar wire chambers at TRIUMF. VU students were stationed at TRIUMF for long periods to work on the construction. Their contributions were gratefully acknowledged by the collaboration.
- During the data acquisition phase of the experiment we took a significant role in running shifts for the experiment.
- During the analysis phase we carried out the physical alignment of the entire spectrometer with high precision. The alignment involved the translational and rotational alignment of 11 planes with each other in each half (upstream and downstream) of the detector and the alignment the two halves to each other. An iterative procedure was used for this alignment.
- Just as we had done for the Crystal Ball experiment, the ‘Event Display’ code for visualizing events for the TWIST experiment was also written at VU. This was used by all who were involved in the analysis of the data.
- We provided a large number of power supplies to power the wire chambers. These were burrowed from the Fermilab and returned at the conclusion of the experiment.

4.6 Publications

1. J. R. Musser et al., “Measurement of the Michel Parameter ρ in Muon Decay”, Physical Review Letters 94 (2005) 101805

2. A. Gaponenko et al., “Measurement of the Michel Parameter δ in Muon Decay”, Physical D71 (2005) 71101(R).

3. B. Jamieson et. al., “Measurement of $P_\mu \xi$ in polarized muon decay”, Physical Review D74 (2006) 72007.

4. R.P. McDonald et al., “Precision measurement of the muon decay parameters ρ and δ”, Physical Review D78 (2008) 032010.

5. A. Grossheim et al., “Decay of negative muons bound in 27Al”, Physical Review D80 (2009) 052012.

6. A.Grossheim et al., Calibration of the TWIST high-precision drift chambers, NIM A **623** (2010) pp. 954-959

7. R.Bayes et al., New Experimental Constraints for the Standard Model from Muon Decay, Phys. Rev. Lett. **106** (2011) 041804.

8. Precision muon decay measurements and improved constraints on the weak interaction, A. Hillairet et al. (TWIST Collaboration), Phys. Rev. D 85 (2012) 092013.

5. The STAR Experiment at RHIC

5.1 Introduction

In 2002 we were accepted to the STAR (Solenoidal Tracker at RHIC) collaboration at the Relativistic Heavy Ion Collider (RHIC) located at the Brookhaven National Laboratory (BNL). This is a collaboration of about 500 physicists from 52 international institutions. During the past 13 years we have been working in collaboration with our colleagues at Argonne National Laboratory, University of Kentucky and Indiana University on the STAR-spin physics program. The goal is to better understand the fundamental origin of the spin of the proton. We joined the collaboration at a time when the Endcap Electromagnetic Calorimeter (EEMC) was under construction. Our faculty and students participated in the construction, installation and testing of the detector. Once installed, we have participated in the acquisition and in the analysis of these data. The first data from the EEMC was taken in 2005. Since then, large amounts of data have been acquired every year and we are in the process of analyzing them and publishing the results. Over the past 13 years we had three postdoctoral fellows working in our group. They have now moved on to permanent positions.

5.2 Physics

Polarized deep-inelastic lepton-nucleon scattering (DIS) experiments performed during the last three decades have demonstrated that only about 30% of the proton's spin can be attributed to the intrinsic spin of its constituent quarks and antiquarks. These DIS experiments provide only very weak constraints on the gluon spin contribution to the proton spin and essentially nothing is known experimentally about the orbital angular momentum contribution. This surprising result has motivated worldwide experimental and theoretical efforts to determine the spin structure of the nucleons and to explain how the nucleons obtain precisely $\frac{1}{2}\hbar$ of intrinsic angular momentum from their partonic constituents. The proton spin (in units of $\hbar$) can be represented in terms of the contributions of the quarks and gluons within the proton as follows:

$$S_z = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^G,$$

where $\Delta\Sigma$ is the net helicity of all quarks and antiquarks, ΔG is the net helicity of the gluons, and L_z^q and L_z^G are the net orbital angular momentum of the quarks (and antiquarks) and the gluons, respectively.

The ability of polarized proton collisions to probe gluon polarization, ΔG, was a primary motivation for establishing the spin-physics program at RHIC. At RHIC, the STAR collaboration has developed a varied and inclusive spin-physics program that is concentrated on measurements of ΔG through several complementary measurements, and on a determination of the sea-quark explicit contribution to $\Delta\Sigma$. Measurements of ΔG are carried out with colliding beams of polarized proton at RHIC at $\sqrt{s}$ = 200 GeV and 500 GeV center of mass energies. The study of spin asymmetries associated with the production of jets in the STAR detector is used to extract measurements of the gluon helicity as a function of the gluon kinematics in the proton. The most recent publication [10] shows for the first time experimental evidence for positive gluon polarization in the Bjorken-x region x > 0.05. The paper presents a measurement of the double- spin asymmetry, A_{LL}, for mid-rapidity inclusive jet production in 200 GeV *pp* collisions. When these results are included in the global analyses it is found that the gluon polarization differs from zero by over 3σ and contributes approximately 40% of the total proton spin! This is a truly revealing result.

The study of sea quarks began when RHIC began p+p collisions at $\sqrt{s}$ = 500 GeV, where $W^{\pm}$ production is possible. Several insightful publications (below) have emerged from these analyses that show a clear asymmetric behavior for the helicity of the W^+ vs the W^-, which, in turn, gives information about the polarization of the up antiquark and the down antiquark. It is surprising that the results differ from what the models had predicted and thus, these results will have a significant impact on the global analyses relative to the of the proton's antiquark distributions.

Finally, for a complete picture of nucleon spin structure at leading twist, one must consider not only helicity distributions but also those contributions to the spin structure of the nucleon involving transverse polarization, such as the transversity distribution. The transversity distribution can be interpreted as the net *transverse* polarization of quarks within a *transversely polarized proton*. These effects are studied by observing the collisions of protons whose spin is polarized transverse to their direction of motion. From these collisions one measures the transverse single-spin asymmetries to infer the size of the transversity effect. There are two canonical mechanisms that are deemed to play a role in the transverse asymmetries: the Sivers effect and the Collins effect. In simple terms, they are initial state and final state effects, respectively. It has been suggested that the observation of a nonzero Sivers effect would require the presence of nonzero parton orbital angular momentum. In order for there to exist a nonzero Collins effect, there must exist some net quark transverse spin polarization, i.e. nonzero transversity. Thus, a nonzero Collins effect provides a path through which one may constrain transversity. While the Sivers effect exists both for quarks and gluons, the Collins effect is quark-specific.

Much work has been done to gain insights into these effects and their implications. Most recently the work of Valparaiso University postdoctoral fellow, Dr. James Drachenberg, has shown the existence of a non-zero Collins-like asymmetries as evidence of gluon linear polarization. This work will be published soon. These studies of transversity offer a rich body of information to complement and the studies of ΔG described above and help to complete the models needed to describe the proton spin in terms of its partonic constituents.

5.3 Faculty and Staff

Since joining the STAR collaboration in 2002, during the past 13 years the following personnel participated in the project at different times and made significant contributions.

Dr. Donald Koetke
Dr. Robert Manweiler
Dr. Shirvel Stanislaus
Dr. Adam Gibson
Dr. David Grosnick
Dr. Gopica Sood (postdoc)
Dr. Jason Webb (postdoc)
Dr. John Schaub (postdoc)
Dr. James Drachenberg (postdoc)
Mr. Paul Nord

5.4 Undergraduate Students

The STAR experiment saw the most number of undergraduate students from VU during our 30-year history. Twenty seven students carried out summer research in this experiment, some for more than one summer. Sixteen went on to graduate school, and have completed or are studying for their degree. Some are still at VU and will be completing their undergraduate degree prior to entering graduate school. The following are the students who carried out research on the STAR experiment. The summer they worked and the graduate schools they entered at the completion of their undergraduate studies are also shown.

Sarah Schlobohm	2003	University of Notre Dame
Ross Corliss	2003	MIT
Tim Rogers	2003	University of Minnesota
Josh Vredevoogd	2004, 2005, 2006	Michigan State University
Ted Hopkins	2005	
Noah Schroeder	2006	University of Illinois
Daniel Trubey	2006, 2007	
Ansel Hillmer	2007	University of Wisconsin
Melissa Bitters	2007	
Megan Kania	2008	University of Illinois
Nathan Kellams	2008, 2009	University of Notre Dame
Tim Olson	2008	University of Michigan
Ben Barber	2009, 2011	University of Chicago
Josh Kellams	2009	Texas A&M University
Andrew Schiller	2009	
Zach Nault	2010, 2011	Ball State University
Nathaniel Ram	2010	
Kevin Miller	2011	Vanderbilt University
Malorie Stowe	2011	University of Pennsylvania
Adam Clark	2012	University of Notre Dame
Billy Pochron	2012	
Kayla Kutz	2012	
Lauren Skiniotes	2013	
Stephen Place	2013, 2014	
Jacob Long	2013	University of Notre Dame
Erik Langholz	2014	
Sam Brandt	2014	

5.5 Contributions from Valparaiso University

The following are some of the many contributions our group has made to the STAR experiment.

- At the time we joined the STAR collaboration the Endcap Electro Magnetic Calorimeter (EEMC) was under construction. We assembled and checked approximately 75% of all of the PMT boxes for the EEMC. Assembly was mostly done by undergraduate students at Valparaiso University. Once they were shipped to RHIC, we assisted in the installation of the PMTs and cables in the EEMC. We organized and routed the fiber optic cables and maintained the database for both the PMT boxes and the fiber optic cables.
- Parts of the Shower Max detector (SMD) assembly for the EEMC was machined in Valparaiso using computer controlled milling machines.
- Completely designed the high level Graphical User Interfaces (GUI)s for the slow-controls for controlling the EEMC.
- Completely designed, wrote, installed, and tested all of the slow-controls for the EEMC using EPICS.
- Studied the shower development in the EEMC produced by electrons and hadrons. Developed an algorithm to identify electrons and reject pions using information only from the EEMC (no TPC information was used). This analysis resulted in an electron selection ratio that exceeded that anticipated in the EEMC proposal.
- Success of the analysis of the data taken with the EEMC depends heavily on the energy calibration of the detector. Calibration of the detector is carried out for data taken during each run. The EEMC consists of 720 tower detectors, 2160 pre and post shower detectors and 6912 shower max detectors. We were responsible for calibrating 9792 channels of the detector for the data taken in 2009 and 2011.
- Success of all of the physics results from the EEMC detector also relies heavily on how well one understands the detector. In order to understand this a Monte Carlo simulation of the detector has been done using the Pythia and Geant software. VU was part of the group that carried out the authentication of the simulation by comparing the simulated π° data with the real data.
- Knowing the beam line trajectory is an important constraint for finding the collision vertex particularly in polarized p+p collisions. This determination is done for each individual fill using the data acquired with minimum bias physics triggers. This calibration is used by everyone involved in the analysis of STAR data. Calibration is carried out for data taken at the end of each run. We have taken the responsibility for this service project for the last 5 years.
- Along with colleagues at Argonne National Laboratory (ANL), we investigated the π°'s in the EEMC by analyzing the longitudinally polarized proton data from 2006. This analysis resulted in the measurement of the asymmetry A_{LL} for inclusive π°'s at 200 MeV, which sheds light on the contribution of gluons to the spin of the proton.
- Analyzed the transversely polarized proton-proton data to measure the transverse single spin asymmetries in jet production in p-p collisions.

- The Forward GEM Tracker (FGT) was added to the STAR detector in 2012 in order to be able to detect the W particles to study the contribution of sea quarks to the spin of the proton. We contributed to the fabrication of the detector components. The gas system and the slow controls for the FGT was completely designed, built, installed, tested, and maintained by Valparaiso University. We also analyzed the initial cosmic ray data taken with the detector to test the detector performance while the installation was in progress.
- Prior to publication, all STAR publications are reviewed by a group of five collaborating institutions selected by the spokesperson. We have taken part in the reviews for a number of the STAR publications.
- The experiment is run each year for about five months acquiring data. Each member of the faculty and our postdoctoral fellows covered a week of shifts in running the experiment during each year we were a part of the STAR collaboration.

5.6 Publications

1. J. Adams, et al., (The STAR Collaboration), “Cross Sections and Transverse Single-Spin Asymmetries in Forward Neutral Pion Production from Proton Collisions at $\sqrt{s}$ = 200 GeV”, Phys. Rev. Lett. **92** (2004) 171801.

2. B. I. Abelev, et al., (The STAR Collaboration), “Longitudinal Double-Spin Asymmetry and Cross Section for Inclusive Jet Production I Polarized Proton Collisions at $\sqrt{s}$ = 200 GeV”, Phys. Rev. Lett. **97** (2006) 252001.

3. B. I. Abelev, et al., (The STAR Collaboration), “Measurement of Transverse Single-Spin Asymmetries for Di-Jet Production in Proton-Proton Collisions at $\sqrt{s}$ = 200 GeV”, Phys. Rev. Lett. **99** (2007) 142003.

4. B. I. Abelev, et al., (The STAR Collaboration), “Longitudinal Double-Spin Asymmetry for Inclusive Jet Production in Polarized p+p Collisions at $\sqrt{s}$ = 200 GeV”, Phys. Rev. Lett. **100** (2008) 232003.

5. B. I. Abelev, et al., (The STAR Collaboration), “Forward Neutral Pion Transverse Single Spin Asymmetries in p+p Collisions at $\sqrt{s}$ = 200 GeV”, Phys. Rev. Lett. **101** (2008) 222001.

6. B. I. Abelev, et al., (The STAR Collaboration), “Longitudinal Double-Spin Asymmetry and Cross Section for Inclusive Neutral Pion Production at Mid-rapidity in Polarized Proton Collisions at $\sqrt{s}$ = 200 GeV”, Phys. Rev. D **80** (2009) 111108.

7. M. M. Aggarwal, et al., (The STAR Collaboration), “Measurement of Parity-Violating Longitudinal Single Spin Asymmetry for W Boson Production in Polarized Proton-Proton Collisions at $\sqrt{s}$ = 500 GeV”, Phys. Rev. Lett. **106** (2011) 620002.

8. G. Agakishiev, et al., (The STAR Collaboration), “Measurement of the $W \rightarrow e\nu$ and $Z/\gamma^* \rightarrow e^+e^-$ Production Cross Sections at Mid-rapidity in Proton-Proton Collisions at $\sqrt{s}$ = 500 GeV”, Phys. Rev. D **85** (2012) 92010.

9. L. Adamczyk, et al., (The STAR Collaboration), "Longitudinal and Transverse Spin Asymmetries for Inclusive Jet Production at Mid-rapidity in Polarized p+p Collisions at $\sqrt{s}$ = 200 GeV", Phys. Rev. D **86** (2012) 32006.

10. L. Adamczyk, et al., (The STAR Collaboration), "Transverse Single-Spin Asymmetry and Cross-Section for π^0 and η Mesons at Large Feynman x in Polarized p+p Collisions at $\sqrt{s}$ = 200 GeV", Phys. Rev. D **86** (2012) 51101.

11. L. Adamczyk, et al., (The STAR Collaboration), "Single Spin Asymmetry A_N in Polarized Proton-Proton Scattering at $\sqrt{s}$ = 200 GeV", Phys. Lett. B **719** (2013) 62.

12. L. Adamczyk, et al., (The STAR Collaboration), "Neutral Pion Cross Section and Spin Asymmetries at Intermediate Pseudorapidity in Polarized Proton Collisions at $\sqrt{s}$ = 200 GeV", Phys. Rev. D **89** (2014) 12001.

13. L. Adamczyk, et al., (The STAR Collaboration), "Measurement of Longitudinal Spin Asymmetires for Weak Boson Production in Polarized Proton-Proton Collisions at RHIC", Phys. Rev. Lett. **113** (2014) 72301.

14. L. Adamczyk, et al., (The STAR Collaboration), "Precision Measurement of Longitudinal Double-spin Asymmetry for Inclusive Jet Production in Polarized Proton Collisions at $\sqrt{s}$ = 200 GeV", Phys. Rev. Lett. **115** (2015) 92002.

In addition to these publications specifically related to the STAR spin-physics program we are co-authors on *many, many papers* that report the interesting discoveries associated with the RHIC-STAR heavy ion program to which we have also contributed. A list can be provided upon request.

6. The nEDM Experiment at ORNL

6.1 Introduction

In 2008 Valparaiso University joined the nEDM collaboration whose goal is to measure the electric dipole moment of the neutron (nEDM). It is a DOE approved experiment consisting of about 60 collaborators from 16 US and international institutions including the Los Alamos National Laboratory (LANL) and the Oak Ridge National Laboratory (ORNL). The experiment will be conducted at the Oak Ridge National Laboratory Spallation Neutron Source (SNS). At present the experiment is in the R&D phase with the construction expected to begin around 2017. Data taking expected to be between the years 2018-2020. At present Prof. Stanislaus is the only Ph.D. physicist of the Valparaiso University group working on this experiment. Several undergraduate students have made very useful contributions to the experiment. Some of them have spent the entire summer at LANL helping the scientists with the R&D.

6.2 Physics

Precision measurements of the properties of the neutron present an opportunity to search for violations of fundamental symmetries and to make critical tests of the validity of the Standard Model. Measurements of the particle electric dipole moment provide some of the tightest constraints on extensions to the Standard Model. In an interim report to the US Department of Energy (DOE) Office of Science and the National Science Foundation (NSF), the Nuclear Science Advisory Committee (NSAC) Subcommittee on Fundamental Nuclear Physics with Neutrons wrote in their findings "the successful completion of an nEDM experiment, the initiative with the highest scientific priority in US neutron science, would represent an impressive scientific and technical achievement for all of nuclear physics, with ramifications well beyond the field"[11].

A search for a non-zero value of the nEDM is a search for a violation of time reversal invariance. T violation or CP violation (which are related via the CPT theorem) has played a very important role in constructing theories of modern particle physics. It shapes our understanding of the origin and evolution of the universe. Explaining the origin of the baryonic matter in the universe is an important goal for nuclear physics [12]. Up to now there has been only one measurement in which T violation has been observed. This was a comparison of neutral K and meson decay rates where the asymmetry was found to be consistent with the SM [13]. The CP violation present in the SM is sufficient to explain these observations in the kaon system. But it is not sufficient to explain the baryon asymmetry found in the present universe. Baryon asymmetry of the universe is one of the outstanding puzzles in physics. At the beginning if the universe were matter-antimatter symmetric then it can be expected that the matter and antimatter will balance out in the current universe. But the experimental observation is that the ratio $\frac{n_{Baryon} - n_{Antibaryon}}{n_{Baryon} + n_{Antibaryon}}$ at the beginning of the universe was only a few x 10^{-10}[14]. It has been suggested by Sakharov [15] that in the physics of the early universe there were reactions that changed baryon number and that these reactions must have been both C and CP violating. The currently developed nEDM experiment at ORNL has a much greater sensitivity to CP violation compared to those in the kaon sector and hence is expected to considerably broaden our understanding of the baryonic matter in the universe.

6.3 Faculty and Staff

Only one faculty member, Dr. Shirvel Stanislaus is part of the nEDM collaboration from Valparaiso University.

6.4 Undergraduate Students

Over course of our work on the nEDM experiment, four Valparaiso University undergraduate students participated in this experiment, some for more than one summer. Three went on to graduate school, and have completed or are studying for their degree. The fourth student is still at VU and will be completing his undergraduate degree in spring 2016 prior to entering graduate school. The following are the students who carried out research on the nEDM experiment. The summer they worked and the graduate schools they entered at the completion of their undergraduate studies are also shown.

Sam Schaub	2011	MIT
Ben Barber	2012	University of Chicago
Adam Clark	2013, 2014	University of Notre Dame
Matthew Libersky	2013, 2014	

6.5 Contributions from Valparaiso University

Prof. Stanislaus spent a sabbatical year (2008-2009) at Los Alamos National Laboratory working full time on the R&D of the experiment. Some of the above mentioned undergraduate students also spent the entire summer at LANL helping the scientists with the R&D. Some of the many contributions the faculty and students of Valparaiso University made to the nEDM experiment are described below.

- One of the most challenging parts of the experiment is producing an electric field of 75 kV/cm in the region of the experimental cell. At Valparaiso University we carried out electrostatic calculations using two different software packages to:
  - (a) Optimize the design parameters of the experiment so as to minimize unwanted high electric fields that could cause breakdown of the system due to sparking.
  - (b) Optimize the design and the parameters of the charging capacitor in order to be able to attain the required high electric field.
  - (c) Optimize the design of the V1-valve through which the neutrons enter the measurement cell.
- Carried out measurements of the properties of several materials in order to identify a good conductive coating for the electrodes.
- Carried out mechanical tests of material for use for the electrodes.
- Studied the compatibility of PMT operation with SQUIDs.
- Participated in in several others tests that were carried out at LANL.

Summary

Over the duration of this grant the Valparaiso University nuclear physics group has been part of, and made very significant contributions to six world-class experiments in fundamental physics. We have earned the respect of our colleagues and collaborators on these experiments by work that was well-done and often central to the success of these experiments.

In addition, perhaps one of our most lasting legacies from our participation in these experiments was the opportunity these created for our Valparaiso University undergraduate physics research students. For essentially all of these students their participation in this collaborative research was a transformative experience. It broadened their perspectives of the scope of the discipline, enriched their skill sets and developed in them a sense of rigor and discipline that is essential to success in their careers. Most of these students went on to graduate school. Many of them are practicing scientists, professors, teachers, and other professionals. We regard the opportunities that this funded research provided for these students to be a central part of the DOE Office of Science mission – to train the next generation of scientists.

Finally, we are proud of the accomplishments of our postdoctoral fellows following the completion of their postdoctoral work with the Valparaiso University group. Each has gone on to a full-time position in a college, university, or national laboratory.

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10 L. Adamczyk, et al., (The STAR Collaboration), "Precision Measurement of Longitudinal Double-spin Asymmetry for Inclusive Jet Production in Polarized Proton Collisions at $\sqrt{s}$ = 200 GeV", Phys. Rev. Lett. **115** (2015) 92002.

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