COVER PAGE

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ACCOMPLISHMENTS

1. What are the major goals of the project?

The major goals are (1) the analysis of a measurement of the neutron magnetic form factor (GMn) and (2) the continued development, testing, and validating of software for the CLAS12 data reconstruction and analysis. For goal (1) The first period of data collection for the GMn measurement was completed in 2019-2020 with the CLAS12 detector in Hall B at Jefferson Lab (JLab experiment E12-07-104). We are part of a broad program at JLab to measure the elastic, electromagnetic form factors including two to measure GMn. Both GMn experiments use methods pioneered in Hall B with the previous detector CLAS6. The PI is one of the lead authors on that work. See Part 2 for more details. For goal (2) we continue to coordinate our software work with the JLab staff. We have a joint program between the University of Richmond and the University of Surrey in the UK to support a masters students for ten months. The Surrey students are required to engage in a significant research year as part of their degree requirements. DOE funding supported these students who are stationed at JLab. In the last grant period funding was available for two students in 2019 (Michael Armstrong) and 2020 (Adrien Saina). Additional work on Mr. Saina's project continued into 2021 and is described in Part 2.

2. What was accomplished under these goals?

Goal (1)
The first stage of the data collection for the GMn measurement (JLab experiment E12-07-104) was completed. About half of the approved beam time has been run. The remaining time is not yet scheduled. The relevant CLAS12 run groups are Run Groups A, B, and K (RGA, RGB, and RGK). In RGB a liquid deuterium target was used to measure the ratio R of e-n/ep

scattering which will enable us to extract GMn. A liquid hydrogen target was used for RGA and RGK and we will use those data to measure the CLAS12 neutron detection efficiency (NDE) which is a key contributor to the systematic uncertainty of GMn.

We now summarize these data sets. RGB was run at beam energies of 10.2, 10.4, and 10.6 GeV during spring and fall 2019 and January 2020 for a total of 39 PAC days out of 90 PAC approved days. A total integrated charge of 155 mC was collected out of 510 mC approved by the PAC. The run group has completed pass1 of the analysis of the Run Group B data and we are working toward pass2. During RGB Gilfoyle served as run coordinator during spring 2019 (8 days) and January 2020 (11 days).

We are analyzing data from two run groups (RGA and RGK) to measure the CLAS12 neutron detection efficiency (NDE). The NDE is needed to correct the measured e-n yield and it is one of the largest components of the systematic uncertainty of GMn. Both run groups used a liquid hydrogen target and we are exploiting the ep->e' pi+ n reaction as a source of tagged neutrons. RGA used beam energies in the range 10.2-10.6 GeV, and collected data during spring and fall 2018 and spring 2019. A total charge of 300 mC out of 648 approved was collected. The data analysis far along is far along (pass1 is complete) and the Run Groups are working toward improvements for pass2. We are also taking advantage of RGK. It ran in fall 2018 and collected about 7% of the approved integrated charge. The beam energies were 6.5 and 7.5 GeV giving us the opportunity to study the NDE under different run conditions and with different backgrounds..

We now discuss the status of the analysis of the GMn measurement and the extraction of the CLAS12 NDE. We are part of a collaboration with Dr. Brian Raue in the nuclear physics group at Florida International University. Dr. Raue's doctoral student Lamya Baashen is analyzing the RGB data to extract GMn for her thesis. She is working exclusively on the GMn analysis and the NDE measurement. She has passed her PhD qualifying exam. As mentioned above our method is to use the reaction ep -> e' pi+ n reaction on liquid hydrogen as a source of tagged neutrons. We use the scattered electron and pi+ information to predict the location of the neutron in CLAS12. If this predicted track strikes the electromagnetic calorimeter (ECAL) fiducial volume we search for nearby hits in the CLAS12 calorimeters that are not associated with a charged particle track. We then require the predicted and found calorimeter hits to be near one another. The NDE is the ratio of the detected neutrons to the ones expected to strike the fiducial volume. We have used two versions of the code written to extract the NDE. One version was developed by a Richmond undergraduate Keegan Sherman (now a PhD student in nuclear physics at Old Dominion). The other was developed by another CLAS collaborator Cole Smith. The two codes gave consistent results. Ms. Baashen has taken up the continued development of those codes. We are now optimizing the event selection and investigating ways to reduce the neutral background we observe in the CLAS12 Forward Detector so we can extend the missing momentum range of the NDE. We are now in the midst of exploring different algorithms for fitting the data to extract the NDE from background in a consistent manner. Ms. Baashen presented preliminary results at the fall, 2020 DNP meeting and continues to present her results at weekly run group meeting (RGB) and software meetings. The PI now meets with her over zoom 1-2 times per week and is also investigating ways to improve the NDE extraction. In particular he has used the pythia event generator to simulate the NDE calibration reaction with the CLAS Collaboration physics-based code called gemc. The idea was to validate the NDE calibration codes and characterize the background that contaminates the NDE histograms at higher neutron momentum. The resolution in the code was significantly better than the current state of CLAS12 so it did not provide a realistic simulation that could be compared with the data. Work continues on this project.

The analysis of the 2H(e,e'n(p)) and 2H(e,e'p(n)) reactions to extract GMn have made significant progress. We obtain GMn by measuring the ratio of e-n/e-p scattering in quasielastic (QE) kinematics. This ratio depends on GMn, the well-known proton form factors (GMp and GEp), and a small contribution from GEn. We begin with a description of the e-n analysis. First, we detect the scattered electron e', assume elastic kinematics, and predict the direction of both the neutron and proton. The tracks for both particles through CLAS12 are calculated. We require both 'swum' tracks to strike the CLAS12 fiducial volume. If either track, proton or neutron, fails to strike the fiducial volume we drop the event. This acceptance matching ensures that when we take the ratio of e-n to e-p events the acceptances are identical. Second, we search for neutral particle candidates in an angular cone around the predicted direction of the neutron. If we find a neutron candidate we assign the missing momentum to this track (assuming there are no other missing particles) and histogram the result. Third, we do much the same thing with the charged particles, the e-p events. After acceptance matching we search the cone around the predicted proton location based on QE kinematics. We use the same CLAS12 subsystems to identify a proton candidate as used for the neutron candidate. We treat the e-n and e-p events the same as much as possible to reduce bias in the ratio. Fourth, for each nucleon we calculate the angle between the nucleon 3-momentum and the transferred 3-moment. We require this angle to be small to separate QE events from background.

We now discuss the status of the analysis above. This is one of the two central pieces of Ms. Baashen's doctorate. The other is the NDE analysis. We have a full, functioning code to calculate the e-n/e-p ratio. Significant portions were developed by undergraduates at Richmond. The event selection requires pulling the quasi-elastic signal out of a large background and much of our work over the last year has been to optimize that selection. We use the properties of elastic scattering to identify the QE events. For example, we calculate the incident beam energy in two ways from the data. We use the measured electron momentum and angle to calculate Ebeam and the electron and nucleon angles to extract Ebeam. Plotted against each other in a two-dimensional histogram reveals a large 'peninsula' of QE events separated from the inelastic background. We continue to study other ways like momentum corrections and other kinematic cuts to separate out the QE events. Ms. Baashen has made progress on the analysis for both e-p and e-n events. The e-p analysis is further along since charged particles are also measured in the CLAS12 drift chambers and provide additional tools to probe the features of the data.

To compliment Ms. Baashen's work on the NDE a Richmond undergraduate Jessie Hess spent the summer of 2021 developing the tools to extract the NDE in simulation. The goal at this stage of the project is to develop the scripts required to simulate the calibration reaction and reproduce the method used by Ms. Baashen to determine the NDE. Ms. Hess presented her work in a poster at the fall, 2021 DNP meeting.

Goal (2)
The second component of the Richmond program is to develop software for the simulation, reconstruction, and analysis of CLAS12 data.We coordinate our software work with the JLab staff. In the last year one of the University of Surrey masters students Adrien Saina completed an investigation of the reconstruction resolution of the CLAS12 software working with JLab staff scientist Dr. Veronique Ziegler. The resolution here is measured by swimming two simulated tracks through the CLAS12 Forward Detector. One track uses the known/generated vertex and initial 3-momentum from the event generator that was the input to the simulation. The second track uses the reconstructed vertex and momentum produced by the reconstruction code itself. Differences between these two tracks at different detector subsystems are used to fill histograms and the width of the histogram is a measure of the reconstruction resolution. This work was the basis for Mr. Saina's masters thesis and a draft of a CLAS12-NOTE (CLAS Collaboration technical report) has been written. In the course of this writing we discovered a surprising effect where the resolution in the azimuthal angle phi was better in the second superlayer of the drift chambers than in the first superlayer even though the tracks had passed through more material to reach the second superlayer. A Richmond undergraduate spent the summer of 2021 validating the codes used in this study including inserting his own rotation algorithms and searching for possible bugs. The original results passed all the tests we made. The Richmond student, Mr. Ryan Sanford presented his work at the fall, 2021 DNP meeting.

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

We now summarize the training benefits of the Richmond program for the last year. Since 2013 the University of Richmond and the University of Surrey in the UK have supported a joint research program for Surrey physics masters degree students at Jefferson Lab. These students must participate in a 10-month research experience at an appropriate facility. The program at Richmond has been funded by this DOE grant since its inception. The students are typically the age of US college seniors, but they have a deeper physics background than students at liberal arts institutions like Richmond. They also come with some knowledge of the linux operating system and programming experience from their course work at Surrey which is a good match for our Richmond program at JLab which has a sharp focus on software development. The Surrey students are stationed at JLab to make full use of the resources there. Before the pandemic the PI spent one day each week at JLab (during the academic semester and the summer) and holds 1-2 additional meetings via video conference. During the pandemic in 2020 the PI met more often (about twice per week) and kept up-to-date on the work of the Surrey student (Arien Saina. Five students have completed the Richmond research year and a sixth, Rocco Monteiro Nunes Pesce, recently arrived in the US. These students have made four poster presentations at APS Division of Nuclear Physics meetings and have been co-authors on three JLab technical reports (CLAS12-NOTES). A fourth report is in preparation based on the work of the most recent student, Adrien Saina, who completed his research year in December 2020. Components of the programming projects for three of the students has been incorporated into the CLAS12 Common Tools. The students have universally been impressed with the environment at JLab and attended seminars, CLAS12 Collaboration meetings, and traveled to conferences. The last two students Mr. Saina and Mr. Michael Armstrong are now in graduate school pursuing doctorates.

University of Richmond undergraduates also benefit from the training they receive in our program. Each summer 2-3 Richmond students work in my laboratory on-campus at Richmond for 10-12 weeks. This grant provides funding for two of the students and the University supplies some additional funding for summer stipends. Almost all of these student researchers present posters at the fall meeting of the APS Division of Nuclear Physics and, like the Surrey students, benefit from the breadth of talks and learning experiences at a US national lab. Before the pandemic We typically visited JLab one day per week during the summer and have 1-2 additional meetings electronically. During the pandemic our JLab meetings have been remote. In the summer of 2020 I worked with two Richmond undergraduates (Jessie Hess and Ryan

Sanford) remotely (the University of Richmond prohibited all summer student research) and again with the same two students in the summer of 2021 face-to-face at Richmond.

It's worth noting here that a recent University of Richmond physics graduate Keegan Sherman is a PhD student at Old Dominion University and has received a supplemental research award from the DOE Office of Science Graduate Student Research Program. He is one of 52 awardees nationwide to receive the award and will be working with a staff scientist on developing the formalism and numerical technology to study the structure of hadronic resonances using lattice QCD.

4. How have the results been disseminated to communities of interest?

The results have been disseminated through presentations at conferences - two Richmond undergraduates (Ryan Sanford and Jessie Hess) and presented posters at the fall, 2021 DNP meeting. Gilfoyle typically gives one invited talk each year which in 2021 meant a remote presentation to the Physics Department at Virginia Commonwealth University. Gilfoyle was co-author on nine refereed papers in 2021. Lamya Baashen is a doctoral student at Florida International working on the GMn analysis. She gives regular reports at the weekly Run Group B meeting and the Software meeting.

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

During the next reporting period we will continue our focus on the analysis of the CLAS12 GMn experiment (E12-07-104) and the software development for the CLAS12 Common Tools. The GMn analysis at this stage consists of two major parts - (1) the measurement of the neutron detection efficiency (NDE) and (2) the extraction of GMn. The NDE will be measured with the ep -> e' pi+ n reaction on liquid hydrogen. See Part 2 for more details. This procedure provides us with a sample of tagged neutrons we use to determine the NDE. The liquid hydrogen data for this measurement have already been collected in Run Groups A (RGA) and K (RGK). RGA ran at beam energies 10.2-10.6 GeV and RGK ran at 6.5 GeV and 7.5 GeV. The range of beam energies presents an opportunity to study systematic effects on the NDE and better understand the CLAS12 response. Pass1 analysis for RGA and RGK is complete. The lead analysis person for this part of the project is L.Baashen who is a PhD student at Florida International University working with Dr. B. Raue. Gilfoyle will be responsible for simulations of the NDE to test and validate our procedures. We have made significant progress on extracting the NDE. We are now studying ways to optimize extracting the signal from background events. We are investigating different fitting procedures like the Crystal Ball function, mixtures of asymmetric Gaussian and Lorentzian functions, and using interpolated functions from simulation. The goal here is to extend the range of the NDE to high neutron momentum. In the CLAS6 measurement the systematic uncertainty on the NDE was the largest single contributor to the overall systematic uncertainty of GMn. We hope to reach as high as a neutron momentum of 7 GeV which corresponds to an upper limit of 10 GeV2 in Q2.

The extraction of the neutron magnetic form factor from the deuterium data will be done using the ratio method. The ratio R of e-n to e-p events is formed, corrected for various effects (e.g. the neutron detection efficiency) and related to the expression for R in terms of the proton and neutron elastic, electromagnetic form factors (EEFFs). The ratio depends on all the EEFFs (electric and magnetic for protons and neutrons). The proton form factors are known much more precisely than the neutron ones and the neutron electric form factor GEn is small and can be estimated from systematics. These features enable us to use the measured R to solve for GMn with a much better resolution than other methods. This technique was used in the previous 6-GeV-era CLAS measurement of GMn. Pass1 results are being used now. For this part of the project L.Baashen will be lead analysis person and Gilfoyle will be responsible for simulations and testing algorithms.

We will also continue our commitment to develop software for the simulation, reconstruction, and analysis of data for CLAS12. The joint Richmond-Surrey program to support a masters student continues with funding from this grant. Past students have made significant contributions to the CLAS12 Common Tools and we plan to follow that precedent. The latest student Rocco Monteiro arrived in mid-February and is stationed at Jefferson Lab. We are training him in the CLAS12 software and will coordinate his work with Dr. V.Ziegler the JLab staff scientist who is one of the lead developers in the CLAS12 software group. Our preliminary plan is to continue the project started by the previous Surrey student Adrien Saina on the reconstruction resolution of the CLAS12 software. The reconstruction code uses a Kalman filter and we step through the tracking data updating and improving the fit with each step. The Kalman filter relies on the initial value of the state vector which contains the tracking information and the covariance matrix. We currently use the results of hit-based tracking and global estimates of the uncertainty to fill the initial covariance matrix. The goal here is to improve on that method and take advantage of recent upgrades to the CLAS12 simulation program gemc.

PRODUCTS - DETAILS

PUBLICATIONS DETAIL

Conference Paper/Presentation (New):
J. Hess, G.P. Gilfoyle, L. Baashen, "Simulation of Neutron Detection Efficiency in the CLAS12 detector", *2021 Fall Meeting of the APS Division of Nuclear Physics*, Contributed, 2021.

Conference Paper/Presentation (New):
R.J. Sanford, G.P. Gilfoyle, A. Saina, V.Ziegler, "Analysis and Validation of Reconstruction Resolution for CLAS12", *2021 Fall Meeting of the APS Division of Nuclear Physics*, Contributed poster, 2021.

Thesis/Dissertation (New):
Adrian Saina, "The Resolution of the CLAS12 Reconstruction Software", *University of Surrey*, 01/02/2021.

Journal Article (New):
N. Zachariou et al., "Double polarisation observable $\mathbb G$ for single pion photoproduction from the proton ", *Phys. Lett. B*, Volume 817, 136304, 2021.

Journal Article (New):
U.Shrestha wt al., "Differential cross sections for Lambda(1520)$using photoproduction at CLAS ", *Phys. Rev. C*, Volume 103, 025206, 2021.

Journal Article (New):
R. Dupre et al., "Measurement of deeply virtual Compton scattering off He4 with the CEBAF Large Acceptance Spectrometer at Jefferson Lab ", *Phys. Rev. C*, Volume 104, 025203, 2021.

Journal Article (New):
Chatagnon et al., "First Measurement of Timelike Compton Scattering ", *Phys. Rev. Lett.*, Volume 127, 262501, 2021.

Journal Article (New):
T.B.Hayward et al., "Observation of Beam Spin Asymmetries in the Process ep-->e' pi+ pi- X with CLAS12 ", *Phys. Rev. Lett.*, Volume 126, 152501, 2021.

Journal Article (New):
M.Mirazita et al., "Beam Spin Asymmetry in Semi-Inclusive Electroproduction of Hadron Pairs ", *Phys. Rev. Lett*, Volume 126, 062002, 2021.

Journal Article (New):
M. Carver et al., "Photoproduction of the f_2(1270) meson using the CLAS detector ", *Phys. Rev. Lett.*, Volume 126, 082002, 2021.

Journal Article (New):
M. Khachatryan et al., "Electron-beam energy reconstruction for neutrino oscillation measurements. ", *Nature,*, Volume 599, 565, 2021.

Journal Article (New):
X.Zheng et al., "Measurement of the proton spin structure at long distances ", *Nature Phys.*, Volume 17, 736, 2021.

Conference Paper/Presentation (No Change):
A. Saina, V. Ziegler, and G.P. Gilfoyle, "The CLAS12 Reconstruction Resolution", *Fall, 2020 Division of Nuclear Physics Meeting*, Published, 2020.

Conference Paper/Presentation (No Change):
L. Baashen, B. Raue, C. Smith, and G.P. Gilfoyle, "Measurement of the Neutron Magnetic Form Factor at High Q2 Using the Ratio Method on the Deuteron", *Fall, 2020 Division of Nuclear Physics Meeting*, Published, 2020.

Journal Article (No Change):
M. Armstrong , V. Ziegler , and G.P. Gilfoyle, "CLAS12 Drift Chamber Reconstruction Software Unit Test ", *CLAS12 NOTE (Technical Report)*, Volume 2020, 02, 2020.

Thesis/Dissertation (Updated):
Michael Armstrong, "CLAS12 Hough Transform Track Recognition and Drift Chamber Reconstruction Software Validation", *University of Surrey*, 01/14/2020.

Journal Article (No Change):
A. Schmidt et al., "Probing the core of the strong nuclear interaction ", *Nature*, Volume 578, 540, 2020.

Journal Article (No Change):
N. Zachariou et al., "Beam–target helicity asymmetry E in K + Σ − photoproduction on the neutron ", *Phys. Lett. B*, Volume 808, 135662, 2020.

Journal Article (No Change):
S. Diehl et al., "Extraction of beam-spin asymmetries from the hard exclusive π+ channel off protons in a wide range of kinematics ", *Phys Rev Lett*, Volume 125, 182001, 2020.

Journal Article (No Change):
V. Ziegler et al., "The CLAS12 software framework and event reconstruction ", *Nucl. Instrum. Meth*, Volume A959, 163472, 2020.

Journal Article (No Change):
M. A. Antonioli et al., "The CLAS12 Silicon Vertex Tracker ", *Nucl. Instrum. Meth*, Volume A962, 163701, 2020.

Journal Article (No Change):
V. D. Burkert et al., "The CLAS12 Spectrometer at Jefferson Laboratory ", *Nucl. Instrum. Meth*, Volume A959, 163419, 2020.

Conference Paper/Presentation (No Change):
M.Heyrich, X.Hu, and G.P.Gilfoyle, "Event Selection in Electron Scattering on Deuterium", *Fall 2019 Division of Nuclear Physics Meeting*, Published, 2019.

Conference Paper/Presentation (No Change):
M.Armstrong, V.Ziegler, and G.P.Gilfoyle, "CLAS12 Drift Chamber Reconstruction Code Validation", *Fall 2019 Division of*

Nuclear Physics Meeting, Published, 2019.

Journal Article (No Change):
B. Zhao et al., "Measurement of the beam spin asymmetry of vec e p → e' p' η in the deep-inelastic regime with CLAS ", *Phys. Lett*, Volume B789, 426, 2019.

Conference Paper/Presentation (No Change):
G.P.Gilfoyle, "Hunting for Quarks and Gluons", *Physics Department, University of Surrey Seminar*, Not published, 2018.

Journal Article (No Change):
S. Chandavar et al., "Double KS^0 Photoproduction off the Proton at CLAS ", *Phys. Rev.*, Volume C97, 025203, 2018.

Journal Article (No Change):
S. Jawalkar et al., "Semi-Inclusive π 0 target and beam-target asymmetries from 6 GeV electron scattering with CLAS ", *Phys.Lett.B*, Volume 782, 662, 2018.

Journal Article (No Change):
G.P.Gilfoyle, "Future Measurements of the Nucleon Elastic Electromagnetic Form Factors at Jefferson Lab ", *EPJ Web Conf.*, Volume 172, 02004, 2018.

Journal Article (No Change):
P. Roy et al., "Measurement of the beam asymmetry Σ and the target asymmetry T in the photoproduction of ω mesons off the proton using CLAS at Jefferson Laboratory ", *Phys. Rev.*, Volume C97, 055202, 2018.

Journal Article (No Change):
M. C. Kunkel et al., "Exclusive photoproduction of π 0 up to large values of Mandelstam variables s, t and u with CLAS ", *Phys. Rev.*, Volume C98, 015207, 2018.

Journal Article (No Change):
K. Park et al, "Hard exclusive pion electroproduction at backward angles with CLAS ", *Phys. Lett.*, Volume B780, 340, 2018.

Journal Article (No Change):
K. P. Adhikari et al., "Measurement of the Q2 Dependence of the Deuteron Spin Structure Function g1 and its Moments at Low Q2 with CLAS ", *Phys. Rev. Lett.*, Volume 120, 062501, 2018.

Conference Paper/Presentation (No Change):
A.Balsamo, K.Sherman, and G.P.Gilfoyle, "Analysis of Quasi-Elastic e-n and e-p Scattering from Deuterium", *Meeting of the Division of Nuclear Physics of the American Physical Society*, Abstract published, 2017.

Conference Paper/Presentation (No Change):
G.P. Gilfoyle, "Future Measurements of the Nucleon Elastic Electromagnetic Form Factors at Jefferson Lab", *47th International Symposium on Multiparticle Dynamics*, Published, 2017.

Journal Article (No Change):
M. Hattawy et al., "First Exclusive Measurement of Deeply Virtual Compton Scattering off 4He: Toward the 3D Tomography of

Nuclei ", *Phys. Rev. Lett.*, Volume 119, 202004, 2017.

Journal Article (No Change):

R. Fersch et al., "Determination of the proton spin structure functions for 0.05 ≤ Q 2 ≤ 5 GeV 2 using CLAS ", *Phys. Rev.*, Volume C96, 065208, 2017.

INTELLECTUAL PROPERTIES DETAIL

There are no intellectual properties to report.

TECHNOLOGIES AND TECHNIQUES DETAIL

There are no technologies or techniques to report.

OTHER PRODUCTS DETAIL

Data and Research Material (Updated):

Description: Measurement of the Neutron Magnetic Form Factor with the Ratio Method - One of Jefferson Lab's goals is to unravel the quark-gluon structure of nuclei. We will use the ratio, R, of electron-neutron to electron-proton scattering on deuterium to probe the magnetic form factor of the neutron, GMn. GMn probes the distribution of magnetization within the neutron. We have been analyzing recently collected data from CLAS12 to extract GMn. This is part of an approved experiment (E12-07-104).One of the challenges in this work is to extract quasielastic (QE) events from a large inelastic background. We focus on neutrons detected in the CLAS12 calorimeters and protons measured with the CLAS12 forward detector. In the analysis we first match the solid angle for e-n and e-p events. The electron information is used to predict the path of QE neutrons and protons through CLAS12. If both particles interact in CLAS12, the e-n and e-p events have the same solid angle. We select QE events by searching for nucleons near the predicted position based on the scattered electron information. An angular cut between the predicted 3-momentum of the nucleon and the measured value, θpq , separates QE and inelastic events. We found in our simulations the QE peak was initially overwhelmed by the inelastic background. However, when we applied the angular θpq cut we see a dramatic reduction in the inelastic background. We continue to optimize the extraction of GMn using more precise kinematic cuts, momentum corrections, artificial-intelligence (AI) assisted tracking, and corrections to the neutron pathlength. This last item is based on the recent discovery that the reconstruction code uses a neutron pathlength from the target vertex (determined from the scattered electron track) to the front face of the electromagnetic calorimeter. In many cases the neutron does not create the shower at this point, but passes through some portion of the detector before interacting. We are investigating how to correct for this effect to improve the extraction of the QE events for GMn.

Protocols (Updated):

Description: Measuring the CLAS12 Neutron Detection Efficiency (NDE) - The method to extract GMn described above to measure GMn does require precise knowledge of the neutron detection efficiency (NDE) to correct the measured e-n yield and it is one of the largest components of the systematic uncertainty of GMn. Comparison of past measurements at different laboratories reveals considerable tension among those experiments possibly due to variations in detector performance and efficiency. To measure the neutron detection efficiency we use the 1H(e,e' π+ n) reaction on a hydrogen target from Run Group A (RGA) data. This reaction is a source of tagged neutrons which can be detected in the electromagnetic calorimeter (PCAL/EC). We start with the 1H(e,e' π+ Xn) reaction where Xn is a single neutral. We infer the mass of the unobserved neutron from the measured electron and pion kinematics and swim the candidate neutron through CLAS12. This expected track is required to lie within the CLAS12 acceptance. We then search this event for neutral hits in the PCAL/EC and calculate the distance delta_R between the intersection point of the expected track with the front face of the detector and the intersection point of each measured track. We select the hit with the smallest delta_R and call it the measured track. We calculate the direction cosines of the expected and measured neutron 3-momenta and take the difference. The distribution of this difference is strongly peaked around zero. Finally, we add additional cuts in the mass squared versus neutron momentum plain to eliminate overlaps with photon events. We continue the work to optimize the extraction of the neutrons from background. We have used several methods to fit the missing mass distribution to accomplish this goal. These efforts including using a combination of asymmetric Gaussian and Lorentzian functions combined with a polynomial background which shows good promise. We have more recently studied the use of the Crystal Ball function to fit the missing mass distribution. A comparison of these different methods will enable us to understand our systematic uncertainties. This work holds the potential to push the measurement of the NDE to a neutron momentum of 7 GeV which corresponds to Q2 ~ 10 GeVs which is about a factor of two greater than the current upper limit on precise measurements of GMn.

Software or NetWare (Updated):
Description: CLAS12 Reconstruction Resolution - In this project we measure the reconstruction resolution in simulation for each of the subsystems of the CLAS12 Forward Detector (FD). This is done by swimming two simulated tracks through the CLAS12 FD. One track uses the known (or generated) vertex and the initial 3-momentum from the event generator that was the input to the simulation. The second track uses the reconstructed vertex and momentum produced by the reconstruction code itself. Differences between these two tracks are used to extract the reconstruction resolution. The effects of particle energy, particle type, torus field polarity, sector dependence, and geometry were studied using two recent versions of the CLAS12, physics-based simulation code gemc. These results can provide benchmarks for hardware and software development for the FD subsystems and guidance for setting goals and specifications. The micro-service architecture of Clara enables developers to quickly swap components of the reconstruction chain and the benchmarks established here can provide test goals. They can also illuminate the different contributions of software and hardware to the CLAS12 resolution and be employed in unit tests as a measure of the stability of new code. The reconstruction code uses a Kalman filter to extract the track parameters. The results here can be used to parameterize the dependence of the resolution on various kinematic variables and incorporate this dependence into the covariance matrix for the Kalman filter state vector. At each step in the Kalman filter a new state vector is estimated with a weighted average of the track data where the weights are contained in the covariance matrix. This matrix contains both the uncertainties and their correlations and identifies which measurements should have greater weight in the calculation. The results of this study can also be used to validate the matching criteria for the outer detector subsystems. We have generated a baseline for the reconstruction resolution for five observables and seven dependencies. Most of our results agree with expectations. This work is a starting point for further development of the Kalman filter method used in the CLAS12 reconstruction code. This work was presented at the fall 2021 DNP meeting and is the subject of a CLAS12-NOTE in preparation.

PARTICIPANTS AND OTHER COLLABORATING ORGANIZATIONS

PARTICIPANTS DETAIL

1. Participant: Lamya Baashen

Project Role: Graduate Student (Research Assistant)	**Person Months Worked**: 11	**Funding Support (if other than this award)**: Florida International University

Contribution to the Project: Florida International doctoral student Lamya Baashen will analyze the CLAS12 Run Group B data and extract GMn for her thesis. She is now working primarily on the GMn analysis and the NDE measurement which is being extracted from data from Run Groups A and K. She has passed her PhD qualifier. Her focus over the last six months has been measuring the NDE from the RGA and RGK data sets.

International Collaboration: No

International Travel: No

2. Participant: Dr. Gerard P Gilfoyle

Project Role: Principal Investigator/Project Director	**Person Months Worked**: 11	**Funding Support (if other than this award)**: University of Richmond

Contribution to the Project: Gilfoyle is the principal investigator on the project and mentors the students listed on the grant. He is also a member of the team on the track-based alignment project for the Central Vertex Tracker in CLAS12 and is leading the effort to calibrate and analyze the CLAS12 GMn data measured in 2019-2020. He is also working with a doctoral student Lamya Baashen at Florida International University (FIU) who is a student of Dr. Brian Raue (faculty member at FIU). Gilfoyle is a member of Ms. Baashen's thesis committee.

International Collaboration: No

International Travel: No

3. Participant: Jessie Hess		
Project Role: Undergraduate Student	**Person Months Worked**: 3	**Funding Support (if other than this award)**: Not Provided
Contribution to the Project: To accurately determine GMn we need to measure the neutron detection efficiency (NDE) of the CLAS12 electromagnetic calorimeters. Our method is to use the reaction 1H(e,e' π+)n on a hydrogen target as a source of tagged neutrons. We first detect the scattered electron and π+ in CLAS12. Neutrons are selected with a missing mass cut and we use the missing 3-momentum to predict the location of the neutron in CLAS12. If this predicted track strikes the ECAL fiducial volume we search for nearby hits that are not associated with a charged particle track. Last, we require the distance between the predicted and found ECAL hit to lie within a range determined by the spatial resolution of the ECAL. The NDE is the ratio of the detected neutrons to the ones expected to strike the fiducial volume. We have begun this measurement of the NDE using the CLAS12 data already collected on hydrogen for Run Groups A and K during 2018. Code to perform this analysis was originally developed by a Richmond undergraduate (Keegan Sherman and was modified for the current software framework in this project. We use a modified version of the Pythia event generator to produce the initial 4-vectors. We then go through a full, end-to-end simulation of the reaction and extract the NDE. We find the simulation agrees with preliminary measured results for NDE at high neutron momentum and diverges at low neutron momentum. This work was presented at the fall, 2021 DNP meeting.		
International Collaboration: No		
International Travel: No		

4. Participant: Prof. Brian Raue		
Project Role: Faculty	**Person Months Worked**: 11	**Funding Support (if other than this award)**: Florida International University
Contribution to the Project: Dr. Brian Raue is a faculty member in nuclear physics at Florida International University. He is a long-standing member of the CLAS Collaboration who has worked on a variety of important projects including the CLAS6 two-photon exchange measurement, the development and maintenance of the CLAS6/CLAS12 Moeller polarimeter used to measure the electron beam spin, and the construction and design of drift chambers for CLAS6.		
International Collaboration: No		
International Travel: No		

5. Participant: Ryan Sanford		
Project Role: Undergraduate Student	**Person Months Worked**: 3	**Funding Support (if other than this award)**: Not Provided
Contribution to the Project: The CLAS12 detector at Jefferson Laboratory measures electron-nucleus scattering and requires a complex reconstruction code. The reconstruction resolution is extracted from the difference between the reconstructed trajectory of a particle and a 'true' trajectory (from simulation) to understand and improve the CLAS12		

performance. Events are simulated with the physics-based code gemc and reconstructed with the CLAS12 Common Tools. We then start at the reconstructed track vertex and swim a track starting with the known momentum before the simulation. A second track is swum from the same starting point with the reconstructed momentum. We take the difference between points where the two tracks intersect CLAS12 subsystems and fit the distributions to obtain the widths/resolutions for the observables x, y, z, theta, phi, and b (b is the distance between points where the tracks intersect the front face of the detector subsystems). We plot the resolutions versus the positions of the detector subsystems. As particles go through more layers of CLAS12, the reconstruction resolution increases. We also see that after a gemc upgrade to make the code more realistic, the resolutions increased by about 50% on average and were more consistent with measured data. This work was presented at the fall, 2021 DNP meeting.

International Collaboration: No

International Travel: No

PARTNERS DETAIL

There are no partners to report.

OTHER COLLABORATORS DETAIL

There are no other collaborators to report.

IMPACT

1. What is the impact on the development of the principal discipline(s) of the project?

The elastic electromagnetic form factors (EEFFs) are fundamental observables in electron scattering that encode information about the distribution of electric charge and current in the nucleus and its constituents. We are calibrating and analyzing data from a large JLab experiment (E12-07-104) with the CLAS12 detector in Hall B at Jefferson Lab to measure the magnetic form factor (EEFF) of the neutron. We are part of a broad program at JLab to measure the four EEFFs (electric and magnetic for the proton and neutron) including two to measure GMn. Both GMn experiments use methods pioneered in Hall B with the previous detector CLAS6. The study of the EEFFs already has a long history, but new features have been revealed over the last fifteen years. This new knowledge is built on new technologies in superconducting electron accelerators, high luminosity detectors, and cryogenic and polarized targets. Their application has lead to new discoveries that overturned our previous understanding. Jefferson Lab has a program to measure all of the EEFFs precisely and over a broad kinematic range. This opens the door to extending our understanding of nuclear structure at the quark level (e.g. flavor decomposition to extract individual quark form factors) and to stringently challenge our theoretical understanding of QCD with data (e.g. distinguish between competing theoretical approaches like the Dyson-Schwinger Equation method and light-front holographic QCD). This campaign has begun and we expect much of it to play out in the next few years.

2. What is the impact on other disciplines?

3. What is the impact on the development of human resources?

Two University of Richmond undergraduates (Ryan Sanford and Jessie Hess) were trained at Richmond and JLab in 2021 and presented a poster on their work at the Fall, 2021 DNP meeting. A masters student from the University of Surrey (Rocco Monteiro) recently arrived at JLab for ten months in 2022 as part of his research requirement. We are now working with the JLab staff to identify the best area for him to contribute to the CLAS12 research program. Lamya Baashen is a PhD student from Florida International University who has worked with the PI extensively starting in 2019. Analysis of the GMn experiment will be her doctoral thesis.

4. What is the impact on physical, institutional, and information resources that form infrastructure?

The Richmond program educates young scientists for future work, attracts students into nuclear physics, and builds and maintains the research infrastructure at Richmond. We made heavy use during the summer of 2021 of the JLab computing farm. The University of Richmond recently acquired a new computing cluster which we can also benefit from using and to relieve some of the demand on the JLab farm.

5. What is the impact on technology transfer?

Undergraduates and masters students are trained in analysis of large, complex data sets. Richmond physics majors have gone on to jobs in industry using precisely the skills they learned as research assistants working on JLab projects. They have also pursued doctorates in physics. One recent graduate, Keegan Sherman, is now a post-qualifier doctoral student and my two current undergraduate researchers, Jessie Hess and Ryan Sanford, are planning to go to graduate school in physics. There is also growing interest at the University of Richmond in data science and support for high-performance computing like that used in physics and for JLab research.

6. What is the impact on society beyond science and technology?
Undergraduates and our masters students are technically trained at the leading edge of technology which prepares them for high-paying jobs that will build our future economy and standard of living.
7. Foreign Spending
Not Provided

CHANGES - PROBLEMS

1. Changes in approach and reasons for change
2. Actual or anticipated problems or delays and actions or plans to resolve them
It may be worth noting here the impact of the pandemic on the University of Richmond program in nuclear physics. During the summer of 2020 the University was closed to summer researchers. I had two students interested in working with me so I decided to work with them remotely. Remote learning to learn how to write code in a new language (Java) and to understand a complex suite of software tools (the CLAS12 Common Tools) was challenging. We typically met several times per week as a group, but progress was still slow. They did not cover as much ground as on-campus students usually do. However, both were willing to work with me again in the summer of 2021 when the University re-opened with restrictions for summer research. Both students were much more productive in that environment and both presented posters at the Conference Experience for Undergraduates (CEU) held remotely at the fall, 2021 Meeting of the APS Division of Nuclear Physics.
3. Changes that have a significant impact on expenditures
The PI will be on sabbatical during the 2022-2023 academic year. According to University of Richmond policy the PI will only receive half his salary during that time. To partially fill that gap the PI will convert the remaining travel, equipment, and supplies funds in the grant to his salary which fill cover about one-quarter of his salary. This change has been approved by the DOE program officer (Gulshan Rai). JLab has committed to support the PI's travel expenses during the academic year. Support for student travel, equipment, and supplies will now come from an endowed chair held by the PI.
4. Significant changes in use or care of human subjects, vertebrate animals, and/or biohazards
5. Change of primary performance site location from that originally proposed
6. Carryover Amount
Estimated carryover amount for the next budget period: $21,000.00