Few-Body Studies Using Electromagnetic Interactions

Final Technical Report

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Blaine Norum
Principal Investigator

Department of Physics
University of Virginia
Charlottesville, VA 22904

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Abstract:

The work discussed here is an extension of work previously funded by U.S. Department of Energy Grant DE-FG02-97ER41025.

Measurements of charged pion photoproduction from deuterium using the Laser Electron Gamma Source (LEGS) at the Brookhaven National Laboratory previously made by us, as members of the LEGS Collaboration, resulted in the most interesting result of two decades of work. By measuring the production of a charged pion $\left(\pi^{+}\right)$ in coincidence with an emitted photon we observed structures in the residual two-nucleon system. These indicated the existence of rare, long-lived states not explicable by standard nuclear theory; they suggested a set of configurations not explicable in terms of a nucleon-nucleon pair. The existence of such "exotic" structures has formed the foundation for most of the work that has ensued.

Several measurements at various laboratories have supported, but not proved, the existence of these exotic states. The rarity of these states made their existence undetectable in most previous measurements. Only by observing characteristic signatures of such states (i.e., decay photons), by using very specific kinematics which isolate certain reaction products, or by measuring polarization-dependent observables. During the period of this grant we pursued and made progress on the development of experiments to be performed at the High Intensity Gamma Source (HIGS) of the Tri Universities Nuclear Laboratory (TUNL). These include the reactions $d(\vec{\gamma},n)$, $d(\vec{\gamma},n)$, $d(\vec{\gamma},n)$, and $d(\vec{\gamma},n)$.

Our understanding of photon- and electron-induced nuclear reactions depends on understanding of the basic electron and photon interaction. Recently, the issue of two-photon contributions has arisen in the context of deeply inelastic electron scattering. One way to address this is to measure asymmetries in the Bethe-Heitler ee process. We also made progress in developing the detectors required to measure these asymmetries at HIGS.

During the last several years the apparent discrepancy between the size of the proton as measured using electrons and that as measured using muons has received a great deal of attention. Working with colleagues at the Jefferson Laboratory (JLAB) we showed that the apparent discrepancy was almost surely the result of mistakes in the statistical analysis of electron scattering data, that there is almost surely no discrepancy.

Activities and Results:

<u>HIGS:</u>

Experiments at HIGS were our principal focus during the period of this grant. We have received approval from the HIGS Program Advisory Committee to perform six experiments, three of which require the Blowfish neutron detector and three of which require the HIFROST polarized target:

1. Measurement of the GDH integrand for the deuteron up to $E_{\gamma} = 20\ MeV$;
2. Measurement of T_{20} for deuteron photodisintegration;

3. Measurement of induced polarization in $d(\vec{\gamma},\vec{n})p$;
4. Measurement of $^{4}He(\vec{\gamma},n)X$;
5. Measurement of $\vec{p}(\vec{\gamma},\gamma)p$ for the determination of spin polarizabilities;
6. Measurement of Asymmetries in the Bethe Heitler process $A(\gamma,e^{+}e^{-})$.

Two of these experiments required additional equipment development. These are the induced polarization measurement and the Bethe Heitler experiment. Work began to assemble, upgrade as necessary, and commission the equipment for the Bethe Heitler experiment. Design work began on the apparatus required for the induced polarization measurements. This experiment will require dismantling the Blowfish detector array in order to repurpose the detector cells.

We proceeded with the development of the neutron polarization analyzers and the 66-detector system required, along with the analyzers, to analyze the polarization. The polarizers consist of 6 high pressure (2800 psi), thin walled cylinders with phototubes attached at each end. The design of these analyzers were modified as a result of changing safety regulations. The basic construction was completed and the addition of reflective surfaces and wavelength shifting coatings begun.

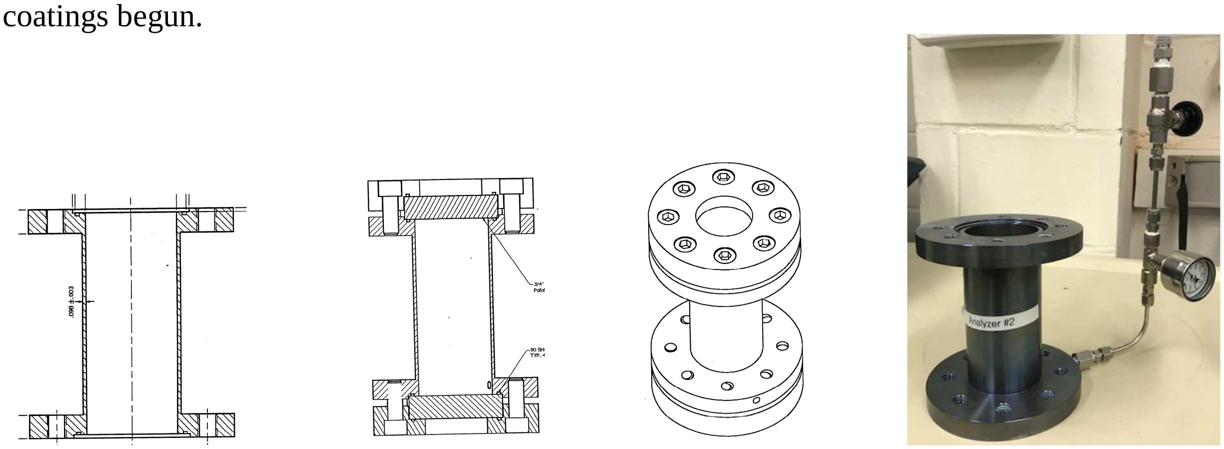

Figure 1. Neutron polarization analyzer during assembly

We worked on completing repairs to the Blowfish detector required due to accidents due to unknown sources. An additional detector was found this year to be similarly damaged and it was repaired as well. It was not clear if this last detector was damaged at the same time as the previous ones or was the result of a new event.

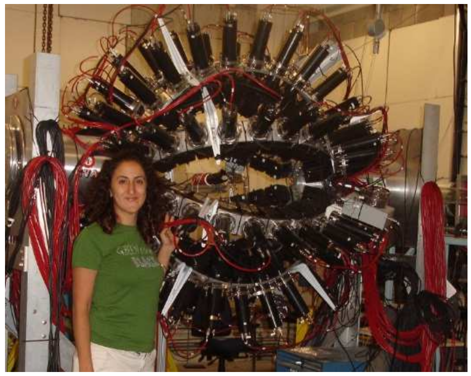

Figure 2. Blowfish neutron detector array consisting of 88 cells containing BC505 liquid scintillator, each being viewed by a 2262B PMT. Detector was constructed at the University of Virginia with cells obtained from the University of Saskatchewan.

At the beginning of our involvement at HIGS the agreed upon plan was for us to construct the Blowfish and for TUNL to construct the polarized target. TUNL subsequently found they would be unable to build the target. Rather than abandon the project I convinced Prof. D. Crabb of UVA to assist us in producing a target. We were told that directed funding for such a target was not available from DOE so we undertook the refurbishment of a 40 yr. old refrigerator from CERN. With financial assistance from TUNL and UVA we were able to obtain substantial infrastructure equipment of similar vintage as the target from the Argonne National Lab and the University of Michigan as they closed their polarized target efforts. Ultimately, we were unable to make the first target operable but were able to obtain another CERN system of the same vintage, including significant infrastructure, from Geesthacht, Germany for the price of transportation. The target, the HIgs FROzen Spin Target (HIFROST), has been cooled to the required temperature in a "cold test" at UVA. Unfortunately, like the Blowfish the target suffered two accidents involving unknown causes. First, the outer vacuum container was broken, necessitating rewelding by the target group at JLAB. Second, the superconducting coil of the holding magnet was broken, necessitating the replacement of the inner vacuum container and the rewinding of the coil (twice). The layered structure of the fridge made it difficult to effect the repairs without disturbing the extremely tight alignment tolerances. This has finally been accomplished and the target cooled to the point where the holding coil has become superconducting.

The final step before returning the target to TUNL was to optimize the $^3He/^4He$ ratio in the dilution section to achieve the lowest possible temperature. This has proved to be difficult as the aging (40^+ year old) target as well as our supporting infrastructure of the same vintage are showing the wear of many transitions from room temperature to almost absolute zero and back to room temperature. During the grant period we made several test, only to reveal new problems each time. While progress was made, it was slow and continues at what is at times a discouraging pace.

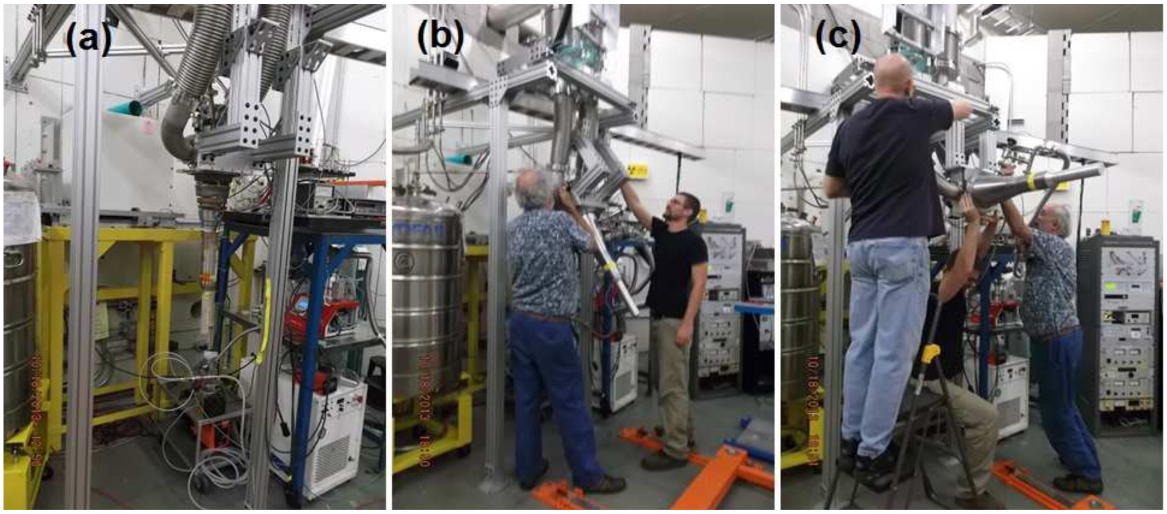

Figure 3. Preparation of the dilution refrigerator for cool down ; (a) mount and assemble the fridge in vertical position (b)swing the fridge (c) the fridge in horizontal position

Our experiment to measure the asymmetries in the Bethe-Heitler process has again required the refurbishing of old equipment. During this grant period, we made progress on re-commissioning the wire chamber and scintillator detectors and started construction of the supporting structures for the detectors.

Figure 4. One of two pairs of wire chambers on loan to us from the College of William and Mary for use in the Bethe-Heitler measurement.

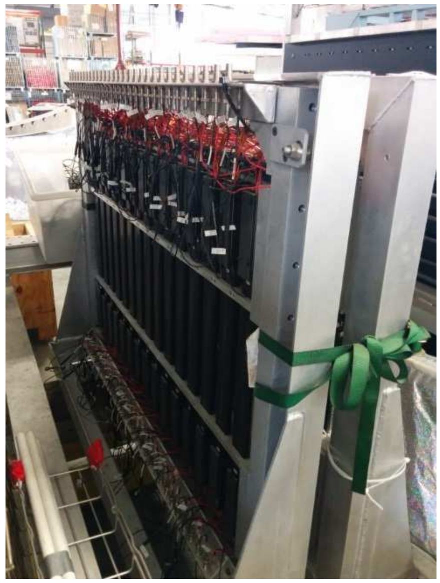

Figure 5. Trigger scintillators on loan from Tohoku University to be used in the Bethe-Heitler measurements at $\mathrm{HI}\vec{\gamma}\mathrm{S}$. They were previously used at JLAB.

It was recognized that spin-dependent interactions of particles like neutrons are not included in the simulation package used by almost everyone in the field. At the energies where we are working the associated asymmetries in the interactions between neutrons and material through which the neutrons pass on their way to a detector can be significant. We collected the available data on these interactions and contacted the SLAC GEANT4 Team for guidance on modifying the code. During this grant period we produced a modification to the relevant CLASS in GEANT that includes these effects.

MAMI:

The MAMI PAC approved measurements of $d\left(\vec{\gamma},\pi^{+}\gamma'\right)$ and $d\left(e,e'\pi^{+}\gamma'\right)$ subject to the requirement that we publish the results from LEGS. It was not until after the LEGS facility was closed and the in-house group disbanded that I resolved the questions I had about the data and became very confident that they were truly correct. Prior to publishing we want to analyze the data anew, lowering the γ' energy threshold, extracting the spectrum of the energies of γ's associated with the peaks, etc. This has proven difficult and very time consuming as a lot of files were lost during the hectic time of our final run and subsequent dismantling of the facility. In addition, my collaborator on this, Sam Hoblit, the person by far the most familiar with the LEGS data acquisition passed away in 2016. To date, we have been unable to locate the missing files but are continuing to search.

The $d\left(\vec{\gamma},\pi^{+}\gamma'\right)$ measurements are a reprise of the LEGS measurements with higher luminosity but less well defined polarization. They will involve the standard experimental configuration so no development will be required. The $d\left(e,e'\pi^{+}\gamma'\right)$ measurements will require installing 390 photon detectors at extreme backward angles to detect the decay gammas. We have received a commitment of suitable detectors in the form of the 120 NMS CsI detectors and 270 of the LEGS (Xtal Box) NaI detectors which were refurbished at JLAB.

Participation at MAMI requires a commitment from an outside group to the functioning of the overall experimental program. It is our hope that in the near term we will acquire resources to hire a Res. Associate as well as a new student to comprise this contribution.

We also began discussions with Prof. M. Petri of TH-Darmstadt regarding moving the above photon detectors from Mainz to Darmstadt to repeat of their measurements of $d(e,e'p)$ but with detection of a coincident (presumably) decay photon: $d(e,e'p\gamma')$.

While this opportunity remains open to us the difficulties we had with the HIFROST has precluded our pursuing them during this grant period.

Proton Radius:

We also worked with colleagues, former graduate students of mine, to reexamine the analysis of low energy electron scattering data to determine whether the purported proton radius puzzle was, in fact, a puzzle. The issue arose when measurement of the radius using muonic atoms yielded a radius of 0.84 fm while a recent electron scattering measurement claimed a radius 0.89 fm. It was suggested that the difference might be due to violation of lepton universality which, if it were, would be a striking discrepancy with the Standard Model. Our analysis showed that the proton radius based on electron scattering data was 0.84 fm, in agreement with the muonic atom result and that the claim of a radius of 0.89 fm from new electron scattering measurements was the result of errors in the statistical analysis of those data. Thus, we concluded, there was no discrepancy[1)]

JLAB:

Work was also done with collaborators on experiments conducted prior to the current grant period at JLAB to prepare the results for publication; see refs. 2-5.

References:

All publications listed here are ones of which the P.I. and members of our group are authors.

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4. “Electroexcitation of the $\Delta^+(1232)$ at low momentum transfer,” with A. Blomerg *et al.*, Phys. Lett. **B760**, 267 (2016).

5. “Measurements of d_n^2 and A_n^1: Probing the neutron spins structure,” with D. Flay *et al.*, Phys. Rev. **D94**, 052003 (2016).