Nuclear Studies with Intermediate Energy Probes

Final Technical Report

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Abstract:

During the almost 20 year period of this grant research was carried out on atomic nuclei and their constituents using both photons and electrons. Research was carried out at the electron accelerator facility of the Netherlands Institute for Nuclear and High Energy Physics (NIKHEF-K, Amsterdam) until the electron accelerator facility was closed in 1998. Subsequently, research was carried out at the Laser-Electron Gamma Source (LEGS) of the National Synchrotron Light Source (NSLS) located at the Brookhaven National Laboratory (BNL) until the LEGS was closed at the end of 2006. During the next several years research was carried out at both the Thomas Jefferson National Accelerator Facility (JLAB) and the High Intensity Gamma Source (HIGS) of the Tri-Universities Nuclear Laboratory (TUNL) located on the campus of Duke University. Since approximately 2010 the principal focus was on research at TUNL, although analysis of data from previous research at other facilities continued.

The principal early focus of the research was on the role of pions in nuclei. This was studied by studying the production of pions using both photons (at LEGS) and electrons (at NIKHEF-K and JLAB). Measurements of charged pion photoproduction from deuterium at LEGS resulted in the most interesting result of these 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 long-lived states not explicable by standard nuclear theory; they suggest 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.

Activities and Results:

The theme of the research has evolved over these two decades and the changes in facilities utilized has been the result not only of the closure of NIKHEF-K and LEGS, but the requirements of the new questions that arose from previous work. Nevertheless, this report will be divided into four main sections: NIKHEF-K, LEGS, JLAB, and HIGS. A fifth section will address investigations into possible experiments at Mainz Microtron (MAMI) should resources become available. There is necessarily overlaps between the efforts at multiple facilities. Nevertheless, it seems most efficient to discuss each facility separately.

NIKHEF-K:

The period covered by this grant represented the last two years of the operation of the NIKHEF-K electron accelerator. During this period work on both the analysis of previously acquired data as well as the taking of as much data as possible before the closure of the facility was pursued. One series of these measurements involved measurements of electroproduction of pions from the proton1) and ^{4}He 2). Both of these measurements confirmed the reliability of then current theoretical approaches.

The final set of measurements we were involved in at NIKHEF-K required the use of thin, gaseous targets in the electron storage ring attached to the electron accelerator; in particular, thin polarized deuteron 3) and ^{3}He targets. Some measurements also required the development and use of small detectors to observe recoiling nuclei$^{4,5)}$. We also contributed to the development and utilization of a Compton back-scattering polarimeter for the measurement of the polarization of the electron beam$^{6,7)}$. The novel experiments that were made possible by this complement of apparatus were summarized in ref. 8).

One group of experiments performed with these targets internal to the electron storage ring were directed at understanding spin effects in quasi-elastic scattering of electrons in deuterium$^{9,10)}$ and ^{3}He $^{11,12,13)}$. These were the first such measurements and provided stringent constraints on nuclear theories of light systems. A second series of measurements were of the neutron electric form factor. As the neutron has no net charge, this form factor is uniquely sensitive to the distribution of quarks in it. And, since a pure neutron target is infeasible, a good substitute is the deuteron because it consists primarily of a loosely bound proton-neutron pair. The measurements$^{14,15)}$ we collaborated on at NIKHEF-K were among the earliest precision measurements of this form factor.

Two of our students received PhD degrees based on their work at NIKHEF-K.

LEGS:

As the work at NIKHEF-K came to a close we started working with the LEGS group to perform photonuclear experiments with polarized photons$^{16,17)}$. Here again, the focus was on the production of pions from nuclei such as ^{16}O $^{18,19)}$, the purpose of which was to understand the properties of the Delta-excitation of nucleons bound in a finite-sized nucleus. The longer term goal of the work at LEGS was to measure the integrand of the Drell-Hearn-Gerasimov GDH) Sum Rule integral$^{20)}$ for the proton and neutron. Here again the deuteron serves as a neutron target where corrections must be made to account that the neutron is not free but bound in a nucleus. The dominant reactions contributing to this integral are those of pion, both $\boldsymbol{\pi}^0$ and $\boldsymbol{\pi}^{\pm}$, production. To perform these experiments with the highest completeness and precision we worked with the in-house LEGS group to develop 1) an $\vec{H}\cdot\vec{D}$ “Ice” target and 2) a cylindrical Time Projection Chamber (TPC) detector. For the $\vec{H}\cdot\vec{D}$ “Ice” target work we oversaw the construction of an In-Beam Cryostat (IBC), the cryostat which maintained the target polarization during experimental measurements. For the TPC we designed and fabricated the cylindrical detector chamber as well as the electric filed shaping electronics. Only one full set of measurements was completed using the $\vec{H}\cdot\vec{D}$ “Ice” target prior to the closure of the LEGS facility$^{21)}$. An engineering run was completed using the TPC. No publishable data were obtained but valuable experience was obtained inasmuch as this detector was one of the first applications at this scale of the then-new Gas-Electron-Multiplier (GEM) detector technology.

The results obtained for the GDH integrand for the proton suggested that the sum rule was, indeed, fulfilled for the proton. However, the results suggested that it was not for the neutron. One possible source of error in the evaluation of the GDH integrand was the knowledge of the effect of the neutron being part of a deuteron. One way to test this was to measure the GDH integrand for the deuteron at low photon energies. This measurement would be the principal focus of our work at HIGS.

A measurement of $\boldsymbol{\pi^+}$ photoproduction made shortly before the closure of the LEGS facility resulted in a possibly very significant discovery. Having heard from L. Filkov (Moscow Meson Facility) of their observation of evidence for bound, proton-neutron states with masses above that of the deuteron. Such states would be incompatible with our existing knowledge of the nucleon-nucleon interaction. As a result these observations were met with skepticism. It was posited that such states could be populated via the $\boldsymbol{\pi^+}$ photoproduction reaction. The narrow width of the states indicated that they must decay by emitting a photon. We analyzed the data from the aforementioned run looking for evidence of the production of such states via the reaction:

$$d\left(\vec{\gamma},\pi^+[n\gamma']\right)n$$

where the n and γ' in the square brackets were detected but not used in the calculation of the masses of the resonances. Following Fil'kov's arguments regarding the narrow widths of the structures, we assumed that the reaction proceeded via:

$$\vec{\gamma}+d\rightarrow D^*+\pi^+$$
$$\overbrace{n+n+\gamma'}^{\downarrow}$$

One neutron was detected to establish that it was a π^+ (the detector system used involved no magnetic field) and the photon (γ') was detected to eliminate the huge number of events coming from quasifree π^+ production from the proton in the deuteron. The middle (lower) panel of Figure1 shows the missing mass spectrum obtained when the π^+ was emitted in (perpendicular to) the plane of the incident photon polarization.

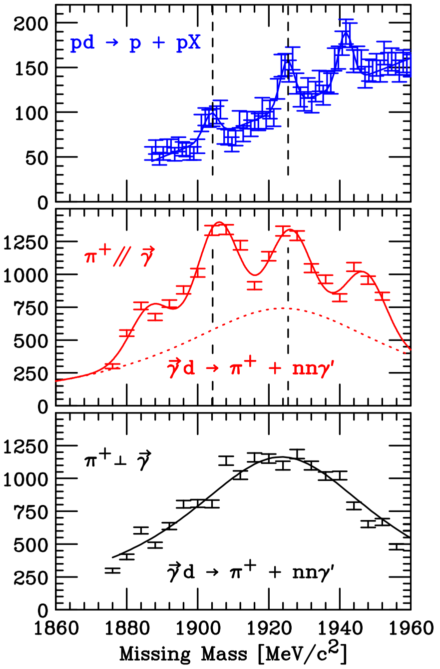

Figure 1. The top panel shows the data of Fil'kov *et al.* for the reaction $d(p,pp)X$; the middle (bottom) panel shows the data of Cichocki *et al.* for the reaction $d\left(\vec{\gamma},\pi^+[n\gamma']\right)X$ in which the π^+ is emitted parallel (perpendicular) to the plane of polarization of the incident photon. Particles in square brackets were detected to identify the reaction but were not used in computing the missing mass of the intermediate state.

It is interesting to note the sequence of energies at which peaks were observed in the missing mass spectrum:

n	State	Energy (E_n)	$E_n - E_{n-1}$
		Two neutrons	1.878 GeV
0	Peak # 1	1.887 GeV	9 MeV $(\equiv E_0)$
1	Peak # 2	1.906 GeV	19 MeV
2	Peak # 3	1.926 GeV	20 MeV
3	Peak # 4	1.947 GeV	21 MeV

This is just the spectrum of states one would expect from a harmonic oscillator $\left[E_n = \left(n+1/2\right)\hbar\omega\right]$ with $\hbar\omega \approx 20\,MeV$.

Two point about the analysis are significant. First, the fitted widths of the peak were narrower than observed in our $p\left(\boldsymbol{\gamma},\boldsymbol{\pi}^+\right)n$ and statistically just what one would expect for a heavier target such as the deuteron. Second, the smooth missing mass distributions largely describing the perpendicular spectrum and underlying the peaks in the parallel spectrum were fit with the same shape but fitted amplitude. The ratio between the different amplitudes was determined to be what one would expect from the theory of the reaction where a pion is created from a deuteron and the pion emits a Bremstrahlung photon.

The existence of such two-nucleon states could contribute to our answering several outstanding questions:

1. The ratio of deuterium to hydrogen created shortly after the Big Bang.
2. The shortage of lithium-7 in the universe.
3. The enormous magnetic fields at the poles of neutron stars.
4. The observation of “short-range correlations” between nucleons in nuclei.
5. The question of whether “exotic” six-quark, non-nucleonic states exist.

To understand the possible role of such entities in answering these and other questions will require first, further verification of their actual existence and, second, a much deeper understanding of their properties.

Anomalies observed in reactions involving the deuteron support, but do not prove, the existence of these states. Further studies of reactions that could shed light are a focus of our work at HIGS.

One of our students received her PhD based on work at LEGS.

JLAB:

We worked on a variety of experiments at JLAB in both Experimental Hall A and B while continuing to work with the $\vec{H}\cdot\vec{D}$ “Ice” polarized target group until the work at HIGS required us to focus solely on it.

The experiments at JLAB were primarily focused on the structure of nuclei as opposed to that of nucleons, although we worked on some measurements involving specifically nucleonic properties. These included the neutron and proton electric form factors, nucleon spin structure, threshold production of neutral pions from the proton.

The experiments at JLAB on which we worked produced 24 Letters (refs. 22-45) and 10 other journal articles (refs. 46-55)

In addition to our experimental work, we worked with C. Kao on two calculations of pion polarizabilities[56, 57)].

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. Thus, we concluded, there was no discrepancy58).

Five of our students received their PhD based on work at JLAB.

HIGS:

Experiments at HIGS were our principal focus for the last several years of this grant. I worked on the development of the establishment of the HIGS facility based on a novel method of using photons produced by the storage ring free electron laser of the Duke Free Electron Laser Laboratory (DFEL L) to Compton scatter from the electrons in the same storage ring59,60). We also worked on one the first experiments at the facility, Compton scattering from oxygen-16 61).

Then, we worked on establishing the capability to perform precision $(\vec{\gamma}, n)$ measurements and the aforementioned GDH measurements. For the latter we constructed a large solid angle neutron detector, the Blowfish.

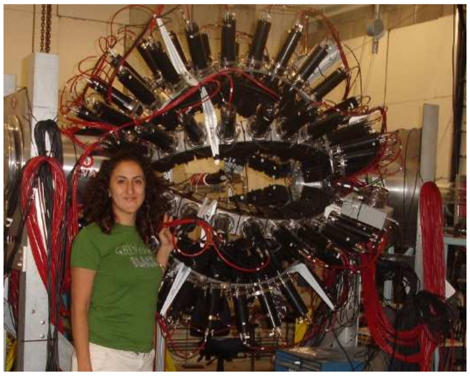

Figure 2. Blowfish neutron detector array consisting of 88 cells containing BC505 liquid scintillator, each being viewed by a 2262B PMT. Detector was constructed at the University of Virginia with cells obtained from the University of Saskatchewan.

We assembled the Blowfish array (fig. 2) from detectors provided by Prof. R. Pywell of the University of Saskatchewan who continues to collaborate with us at $\mathrm{HI}\vec{\gamma}\mathrm{S}$. The Blowfish has been used in several measurements with deuterium and lithium targets54-58). It has been upgraded from its initial configuration by the addition of a real-time gain monitoring system and has been refurbished to repair some serious accidental damage. 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 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 will be to optimize the $^{3}He/^{4}He$ ratio in the dilution section to achieve the lowest possible temperature. This has proved to be difficult as the aging (40^{+} year old) target is showing the wear of many transitions from room temperature to almost absolute zero and back to room temperature.

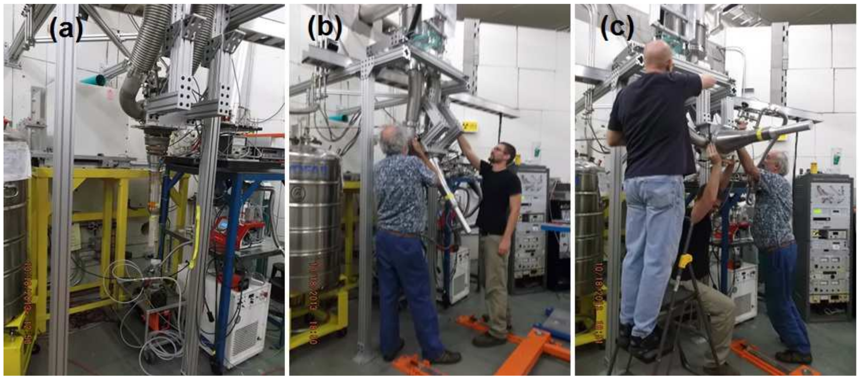

Figure 3. Preparation of the dilution refrigerator for cool down ; (a) mount and assemble the fridge in vertical position (b)swing the fridge (c) the fridge in horizontal position

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

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.

In preparation for the Bethe Heitler experiment we have refurbished and mapped the dipole magnet to be used as the spectrometer (see fig. 4); started testing and evaluating the wire chambers to be used (fig. 5); and are testing the trigger hodoscope (fig. 6). Collaborator R. Pywell is running GEANT simulations to optimize the detector positions. As in the case of the GDH measurements, we have had to reuse old equipment. In this case, the spectrometer dipole is over 40 years old and the detector systems are both about 10 years old. Refurbishing this equipment has proven to be more time intensive than we had hoped.

Figure 4. Saskatchewan Accelerator Laboratory pair spectrometer dipole to be used as a spectrometer in the Bethe-Heitler measurement.

Figure 5. 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.

Preparations for all six of these experiments are underway.

To date, three of our students received their PhD based on work at HIGS.

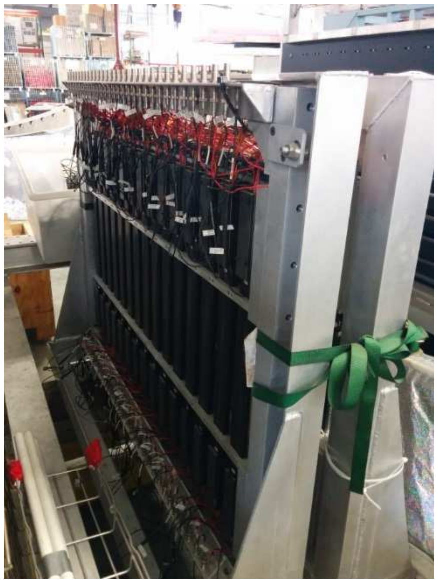

Figure 6. Trigger scintillators on loan from Tohoku University to be used in the Bethe-Heitler measurements at $\mathrm{HI}\vec{\gamma}\mathrm{S}$. They were previously used at JLAB.

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 $d\left(e,e'\,p\right)$ but with detection of a coincident (presumably) decay photon: $d\left(e,e'\,p\gamma'\right)$.

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