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Mainz Microtron MAMI

Collaboration A2: "Tagged Photons"
Spokesperson: A. Thomas

Proposal for an Experiment

"Photoproduction of Pions off Polarized Neutrons"

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Abstract of Physics:

The focus of this proposal is the production of pions and the study of their interactions with transversely and longitudinally polarized neutrons. Our program centers on the use of real polarized photons to produce short-lived mesons on polarized and unpolarized nucleon targets. With the recent upgrade of MAMI-C to 1.5 GeV, we can now produce the complete nonet of pseudoscalar mesons. The results of our program will be used to test theoretical predictions based on ChPT, which links meson-nucleon dynamics and QCD, chiral soliton model (ChSM), lattice QCD, and dynamical models. They will also be used to expand the GW SAID and MAMI MAID analyses and the SAID data base. These data will also provide coherent pi0 production off the polarized deuteron which will allow us to expand our studies of the reaction mechanism of this process.

Abstract of Equipment:

The experiment will be performed using the 4π Crystal Ball (CB) spectrometer in conjunction with the TAPS detector at MAMI. The facilities at MAMI needed for this proposal include tagged, linearly polarized photons provided by the Glasgow Tagger and transversely and longitudinally polarized (deuterated) targets as described in Appendix A.

MAMI Specifications:

beam energy	1558 MeV
beam current	< 20 nA
beam polarisation	polarised and unpolarised

Photon Beam Specifications:

tagged energy range	480 - 1480 MeV
photon beam polarisation	linearly and circularly polarised

Equipment Specifications:

detectors	Crystal Ball/TAPS
target	frozen spin butanol (transverse and longitudinal polarisation)

Beam Time Request:

set–up/tests with beam	100 hours (parallel with proposal A2/12,13)
data taking	1200 hours (parallel with proposals A2/12,13)
	1200 hours (stand alone)

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1 Introduction

1.1 The Structure of the Nucleon

“What is the structure of the nucleon?" is a key question in nuclear physics. [1, 2] In order to address this question it is essential to have a clear understanding of the spectrum of excited states of the nucleon. One measure that can be proposed to understand better the baryon spectrum is that the community perform a combined analysis of the π, η and K photo-production data and incorporate two-pion final states into a coupled-channel analysis. [3] All hadronic channels that have significant coupling strength need to be included in the analysis. The cross sections, beam asymmetry and especially target polarization measurements of meson production on the neutron are largely missing from this database as are the double polarization measurements. These measurements are essential to our understanding of the nucleon excitation spectra and thereby to our understanding of nucleon structure.
According to Quantum Chromodynamics, QCD, nucleons are complicated systems of quarks and gluons held together by strong interactions. The field theoretic approach to the problem is based on QCD. Perturbative solutions, that are applicable at high energies, fail in the resonance region. Connecting the observed properties of baryons with the underlying theoretical framework provided by QCD is one of the central challenges of modern science. Effective Field methods, such as Chiral Perturbation Theory (ChPT), have been successful at low energies, but an extension to the resonance region is difficult. The lattice technique holds promise as it is a direct solution to QCD, but extraction of resonance properties becomes progressively more difficult for higher excited states having a given set of quantum numbers [*i.e.* the nucleon, Roper, and N(1710)]. For this reason, and in order to facilitate comparisons with more phenomenological models, it is important to: a) determine to the few percent level the properties of low-lying resonances, and b) determine the set of (higher) resonances that can be unambiguously extracted from fits to experimental data. Efforts are being made to study these problems at GW, ITEP, JLab, Mainz and other nuclear theory centers. These theoretical efforts can only be tested by accurate and comprehensive measurement of the full nucleon resonance spectrum, with polarization observables from both protons and neutrons.
The focus of this proposal is the production of pions and the study of their interactions with the neutron. Other proposals concern themselves with etas and kaons. Our program centers on the use of real linearly and circularly polarized photons to produce short-lived mesons on transversely and longitudinally polarized neutron (deuterium) targets. With the upgrade of MAMI-C to 1.558 GeV, we can produce the complete nonet of pseudoscalar mesons. The results of our program and the complementary experiments submitted by other members of the collaboration will be used to test theoretical predictions based on ChPT, which links meson-nucleon dynamics and QCD, the chiral soliton model (ChSM), lattice QCD, and dynamical models. They will also be used to expand the GW SAID and MAMI MAID analyses and data bases [4, 5].
The particular measurements proposed herein are:

- $\vec{\gamma}\,\vec{d_t} \to \pi^0 n(p_s)$ & $\vec{\gamma}\,\vec{d_l} \to \pi^0 n(p_s)$;
- $\vec{\gamma}\,\vec{d_t} \to \pi^0\pi^0 n(p_s)$ & $\vec{\gamma}\,\vec{d_l} \to \pi^0\pi^0 n(p_s)$;
- $\vec{\gamma}\,\vec{d_t} \to \pi^0\eta n(p_s)$ & $\vec{\gamma}\,\vec{d_l} \to \pi^0\eta n(p_s)$.

Our program emphasizes the use of polarized beams and targets allowing us to measure independent amplitude combinations contributing to the scattering processes and thus resolve the ambiguities in partial-wave analyses.

1.2 Extracting Resonance Information

Pion photoproduction has long been analyzed in order to extract the photo-decay amplitudes associated with the N^* and Δ^* resonances. Extensive fits to elastic pion-nucleon scattering have provided mass and width values for the contributing resonances. Multipole phases are also linked to corresponding pion-nucleon phase shifts, through Watson's theorem, up to the onset of inelasticity.
Above the two-pion production threshold, multipole analysis becomes increasingly model-dependent. The GW DAC (SAID)[6] and Mainz (MAID) fits to this region attempt to describe the available data, within the constraints obtained from pion-nucleon scattering from the SAID analysis [7], employing different phenomenology. In the MAID approach, resonance parameters are varied in fitting the data. The SAID approach is to first obtain multipole amplitudes in a manner as “model-independent" as possible. The extracted multipoles are then refitted to functional forms having both resonance and background contributions.
Differences between these approaches are most evident in predictions for observables not yet measured. Each new experiment provides further constraints related to a different bi-linear combination of helicity amplitudes. We need to consider what types of data are currently available in the database, and consider which measurements are both necessary and best suited to the Crystal Ball and TAPS at MAMI.

1.3 Spin Observables

In the reaction $\gamma N \to N\pi$, three particles carry polarization: the photon beam, target nucleon, and recoil nucleon. There are three possible double-polarization experiments: beam/target, beam/recoil, and target/recoil. The total number of observables is 16, though not all are independent. The formalism and definitions of observables commonly used to describe pseudoscalar meson photoproduction is found in Ref. [8]. Without a recoil polarimeter we cannot measure recoil polarization with either the Crystal Ball or TAPS and are left with the beam/target combinations given in Table 1.

Table 1: Observables in single-pion photoproduction with polarized target and/or polarized photons. See also Ref. [8].

	Photon beam		
Target	unpolarized	circularly polarized	linearly polarized
unpolarized	$d\sigma/d\Omega$	—	Σ
longitudinally	—	E	G
transversely	T	F	H, P

With polarized targets, all the observables from Table 1 are measurable in an energy region where SAID and MAID give different predictions and no data are available for the $\gamma n \to n\pi^0$ reaction [Fig. 1]. The further possibility of nucleon polarimetry at MAMI expands the scope of this project in future years.
The differential cross section for reactions of the type $\vec{\gamma} + \vec{p} \to p + X$, where X is a pseudoscalar meson, with linearly polarized ($P_\gamma^{\rm L}$) or circularly polarized ($P_\gamma^{\rm c}$) photons and with longitudinally polarized targets [$P_T = (P_x, P_y, P_z)$], can be written

$$\begin{aligned} \frac{d\sigma}{d\Omega}(\theta,\phi) &= \frac{d\sigma}{d\Omega}(\theta)\,\big[\,1 - P_\gamma^{\rm L}\,\Sigma\,\cos 2\phi \qquad (1) \\ &+ P_x(-P_\gamma^{\rm L}\,H\,\sin 2\phi + P_\gamma^{\rm c}\,F) + P_y(T - P_\gamma^{\rm L}\,P\,\cos 2\phi) + P_z(P_\gamma^{\rm L}\,G\,\sin 2\phi - P_\gamma^{\rm c}\,E)\,\big]\,, \end{aligned}$$

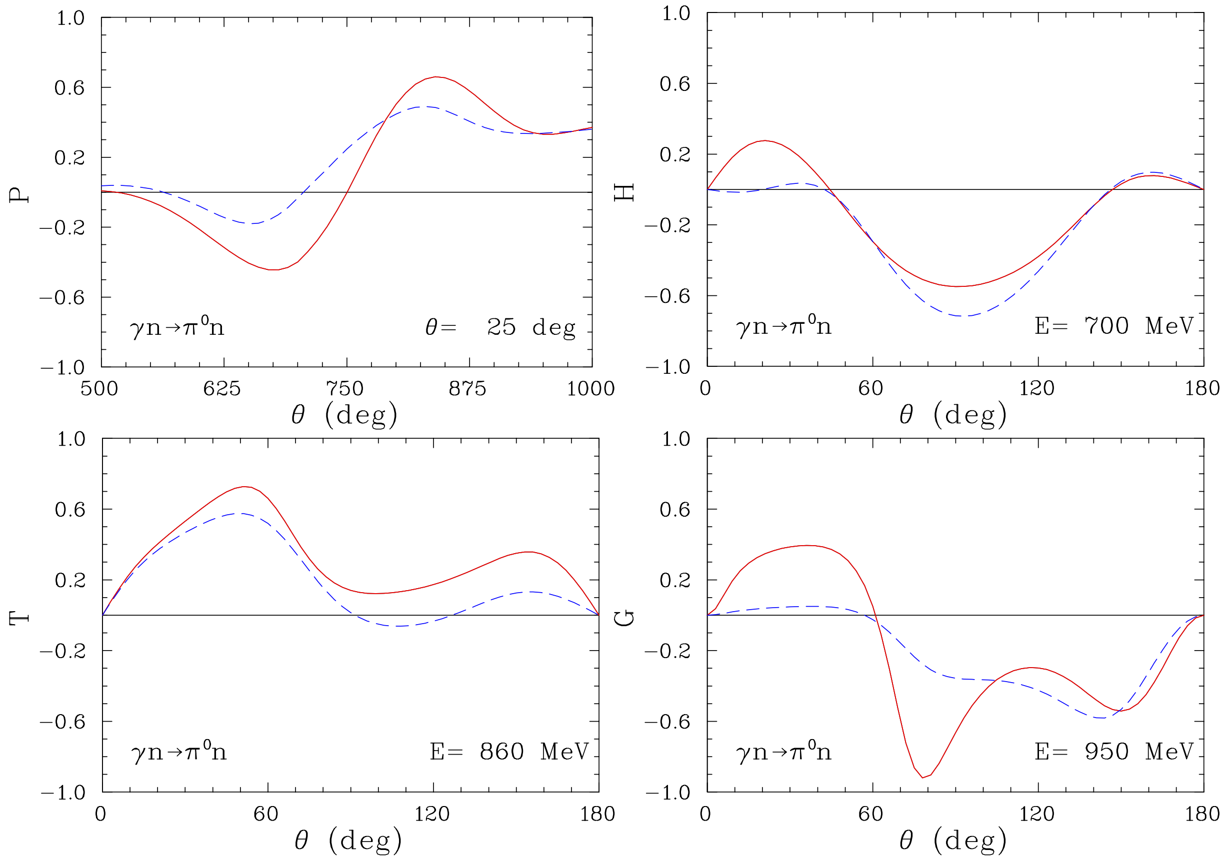

Figure 1: Plots comparing the MAID07 [5] (dashed line) and SAID-SP09 [6] (solid line) predictions for the $\gamma n \to n\pi^0$ observables P, T, H, and G.

where θ is the polar angle and ϕ is the azimuthal angle. The factors Σ (photon asymmetry), H, F, T (target asymmetry), P, G, and E are the observables. The dominant multipole amplitudes for excitation of the low-lying baryon resonances are: $M_{1+} \Leftrightarrow \Delta(1232)\frac{3}{2}^+$; $M_{1-} \Leftrightarrow N(1440)\frac{1}{2}^+$; $E_{2-} \Leftrightarrow N(1520)\frac{3}{2}^-$; and $E_{0+} \Leftrightarrow N(1535)\frac{1}{2}^-$. The above observables can be related to the interference of the multipole amplitudes as: $G \sim \Im(M_{1+}M_{1-})$; $\Sigma \sim \Re(M_{1+}E_{2-})$; and $T \sim \Im(M_{1+}E_{0+})$. We can obtain some of these measurable like G and Σ together in a single experiment with linearly polarized photons and a longitudinally polarized target. The advantage of the 4π Crystal Ball and TAPS detectors at MAMI for obtaining the ϕ dependence is clearly evident. A transversely polarized target is being built at MAMI. We proposed that, in light of the schedules at other labs, it might be important for MAMI to begin with the transverse target measurements with high priority.

2 The Photoproduction of Pions on the Neutron.

2.1 Single Pion Photoproduction off Polarized Neutrons

The photoproduction of pions has been the most important process used in the determination of baryon-resonance photo-decay amplitudes. This process is defined by three independent isospin amplitudes (the isospin 3/2 amplitude and independent isospin 1/2 amplitudes for proton and neutron targets). Of these, the isospin 3/2 and isospin 1/2 (proton) amplitudes are most reliably determined from experiments measuring polarized and unpolarized observables for $\gamma p \to p\pi^0$ and $\gamma p \to n\pi^+$. Assuming a good determination of the isospin 3/2 amplitude, measurements of $\gamma n \to p\pi^-$ are sufficient to give the remaining isospin 1/2 amplitude for neutrons. However, fits much above the $\Delta(1232)$ region are generally model-dependent and this model-dependence is greatest for the extraction of $n\gamma$ photo-decay amplitudes.
The measurement of $\gamma n \to n\pi^0$ allows a valuable check of the $n\gamma$ photo-decay amplitudes and the models used in analyzing both proton and neutron target data. Given a model for the background and photo-decay amplitudes, determined from reactions excluding $n\pi^0$ photoproduction, one should be able to predict the $n\pi^0$ observables. However, at higher energies there is little justification for the most commonly used background parameterizations. Simple Born-term (point coupling) calculations of the background give very large contributions that must either be damped with phenomenological form-factors or cancel with resonance contributions [9]. The Born-term contribution to $n\pi^0$ photoproduction is much simpler due to the lack of charged particles. This should also be an advantage for the separation of resonance and background effects. The availability of $n\pi^0$ observables would allow a determination of resonance contributions from four possible sets of the required three charge channels [($p\pi^0$, $n\pi^+$, $p\pi^-$), ($p\pi^0$, $n\pi^+$, $n\pi^0$), ($n\pi^0$, $p\pi^-$, $n\pi^+$), or ($n\pi^0$, $p\pi^-$, $p\pi^0$)], which would tightly constrain the analysis methods.
The present neutron target data are quite sparse. Only differential cross sections exist for $n\pi^0$ - with no published measurements beyond 905 MeV (corresponding to a center-of-mass energy of about 1600 MeV). Differential cross sections for $p\pi^-$ are more numerous, but few polarized measurements exist above 1 GeV, and these give almost no coverage of the backward angles [Fig. 2]. As one should expect, predictions for backward angle observables show large differences between the existing SAID and MAID analyses [Figs. 1 and 3]. However, as both SAID and MAID use similar background parametrizations, deviations could easily arise in unexpected kinematic regions. Only a precise set of neutron-target measurements can settle these issues.

2.2 The Photoproduction of $\pi^0\pi^0$ and $\pi^0\eta$ on the Neutron

In order to extract reliable N^* resonance parameters from the meson photoproduction data which are now coming out of JLab, GRAAL, ELSA, and MAMI, partial-wave analyses must be extended to include additional channels and reactions. It has become increasingly evident that

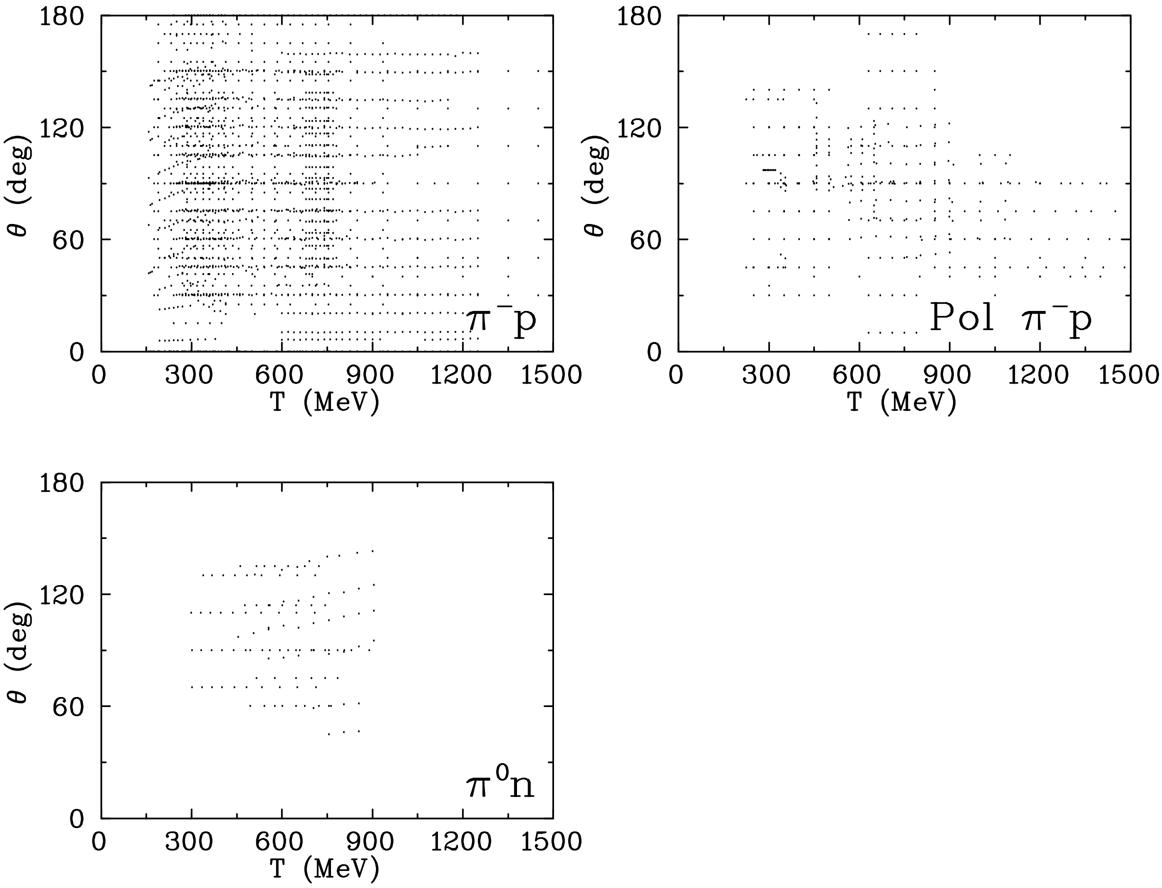

Figure 2: Energy-angle distribution of available neutron target photoproduction data: unpolarized and polarized $\pi^- p$ and unpolarized $\pi^0 n$. No polarization observable data exist for the $\gamma n \to \pi^0 n$ reaction. Data are from the SAID database [6].

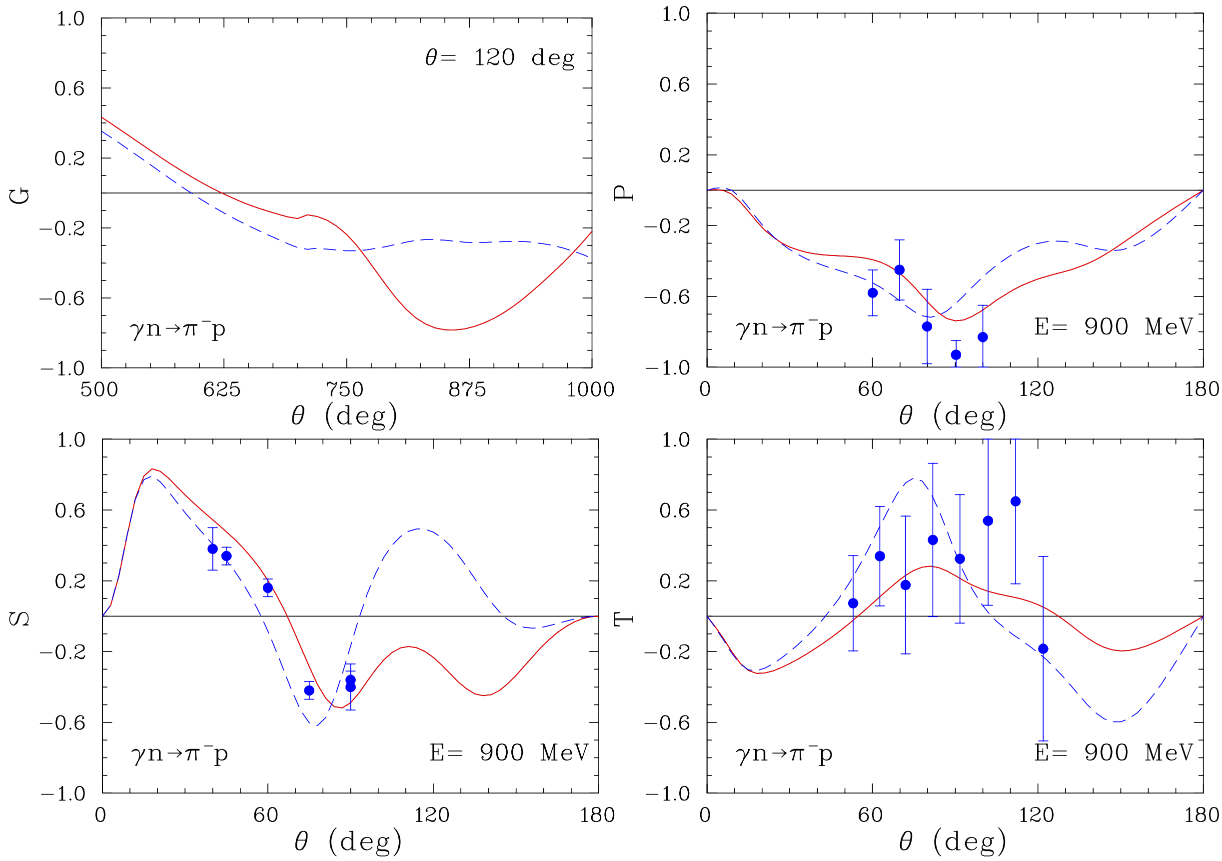

Figure 3: Polarized measurements Σ, P, and T in negative pion photoproduction on the neutron at 900 MeV. Solid (dashed) line gives the GW SAID SP09 [7] (MAID07 [5]) solution. Data are from the SAID database [6].

single-channel πN analyses alone do not provide the necessary constraints needed for a full and unambiguous determination of resonance properties. This is particularly true for resonances that have only a weak coupling to the πN state.
We will exploit the photon and neutron detection properties of the Crystal Ball and TAPS at MAMI by measuring the fundamental photoproduction reaction $\gamma n \rightarrow \pi^0 n$. (The reaction $\gamma n \rightarrow \eta n$ is treated in another proposal) from threshold to 1400 MeV. Using our proposed end-point tagger, we will extend this to above 1500 MeV. In this same energy region we shall study the production of the two-step decays $\gamma n \rightarrow \pi^0 \pi^0 n$ and $\gamma n \rightarrow \pi^0 \eta n$. In addition, from these same data, we will be able to explore the details of the electromagnetic properties of resonances by searching for the radiative decay chains that result in a $\pi^0 \gamma$ or $\eta\gamma$ final state such as $N^* \rightarrow \gamma\Delta$ or $N^* \rightarrow \gamma N(1535)$.
These measurements will be carried out using the polarized deuterium target to make double polarization measurements. These experiments are complementary to the charged final-state measurements at JLab [10, 11, 12, 13, 14]; they will further the investigation of low-lying resonances and will contribute to the search for the "missing" resonances. The longitudinal polarization measurements for these on the proton have already been accomplished. The transverse measurements and longitudinal measurements off the neutron (deuteron) are scheduled for mid to late 2010. Clearly we need to take advantage of being prepared and run these measurement while we have the opportunity to beat the competition.

3 Event rates and beamtime estimate

Our beam-time request is based on the reaction $\gamma n \rightarrow \pi^0 n$. For example, to obtain measurements of G and E of the order of 10% uncertainty, we would need approximately 600 hours of linearly polarized beam on the longitudinal deuteron target. The dominant consideration is that the beam polarization in one region of interest near the $S_{11}(1535)$ only reaches about 40% even though lower intensity and polarization maxima are higher. We would need about the same amount of time to measure T, F, H, and P with the transverse deuteron target. Of course, much of this time is in parallel with other proposed experiments.
We will obtain data with circularly polarized beam for the the two-meson final states simultaneous with the experiment of Pedroni *et al.*. The time requested by that experiment also provides sufficient beam time for us to fulfill the goals of this proposal that utilize circularly polarized beam.

4 Personnel Contributing to this Proposal

The contact spokesperson, William Briscoe of the George Washington University, and the co-spokespersons Mark Manley from Kent State University and Evangeline J. Downie of Mainz University are contributing members to the Crystal Ball and TAPS Collaboration at MAMI. They provide expertise to this program in data acquisition and analysis. The US co-spokespersons have undergraduate and/or graduate student support from the US Department of Energy Office of Science and their institutions for these experiments. The spokesperson also has funding from the National Science Foundation International Programs Division in the form of an International Research Experience for Students grant.
William Briscoe, Igor Strakovsky, Ronald Workman, and Mark Paris together with Richard A. Arndt, are members of the GW DAC (SAID) group and together with additional George Washington University collaborators Morton Taragin, Thomas Morrison, Harald Griesshammer, Helmut Haberzettl, and Baya Ousenna represent many decades of experience in phenomenological, experimental and theoretical nuclear physics at GW as well as expertise in data acquisition and monte carlo simulation. Evangeline Downie is guiding two GW students, Berhan Taddesse

and Zoe Marinedes, in analysis of the unpolarized pion-production data. This will be the basis of an honors thesis for Ms Marinedes and a masters thesis to Ms Taddesse. Ms Taddesse's PhD project will be selected from the topics presented in this proposal.
We have been consulting with Prof. Hartmuth Arenhoevel, Dr. Michael Schwamb, and Dr. Alexander Fix concerning the corrections necessary to extract pion photoproduction cross sections on the neutron using deuterium and ^3He targets. Dr. Fix visited GW three years ago to discuss with this and other topics such as the coherent photoproduction neutral pions from the deuteron of with our experimenters and theorists.
Professor Alexander Kudryatsev, Dr. V.E. Tarasov, both of ITEP, have worked very closely with us on several projects, and who are developing a code for us to calculate final-state interactions. They, with Prof Maxim Polyakov, Ruhr-Universitaet, Bochum, and Prof Yakov Azimov, PNPI, Gatchina, will provide theoretical support of the analysis and interpretation of our data.

References

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[13] Jeffeson Lab experiment E03-105: *Pion Photoproduction from a Polarized Target* N. Benmouna, W.J. Briscoe, G. O'Rielly, I. Strakovsky, and S. Strauch, spokespesons.

[14] Jefferson Lab experiment E05-012: *Measurement of Polarization Observables in eta-photoproduction with CLAS*, M. Dugger and E. Pasyuk, spokespersons.

A Experimental apparatus

A.1 Photon Beam

The A2 photon beam is derived from the production of Bremsstrahlung photons during the passage of the MAMI electron beam through a thin radiator. The resulting photons can be circularly polarised, with the application of a polarised electron beam, or linearly polarised, in the case of a crystalline radiator. The degree of polarisation achieved is dependent on the energy of the incident photon beam (E_0) and the energy range of interest, but currently peaks at ∼75% for linear polarisation (Fig. 4) and ∼85% for circular polarisation (Fig. 5). The maximum degree of linear polarisation should be further improved by 5 to 10% by the end of 2009 when the collimation and beam monitoring systems will be optimised for MAMI-C during the installation of the Frozen Spin Target. The Glasgow Photon Tagger (Fig 6) provides energy tagging of the photons by detecting the post-radiating electrons and can determine the photon energy with a resolution of 2 to 4 MeV depending on the incident beam energy, with a single-counter time resolution $\sigma_t = 0.117$ ns [2]. Each counter can operate reliably to a rate of ∼1 MHz, giving a photon flux of $2.5 \cdot 10^5$ photons per MeV. Photons can be tagged in the momentum range from 4.7 to 93.0% of E_0.

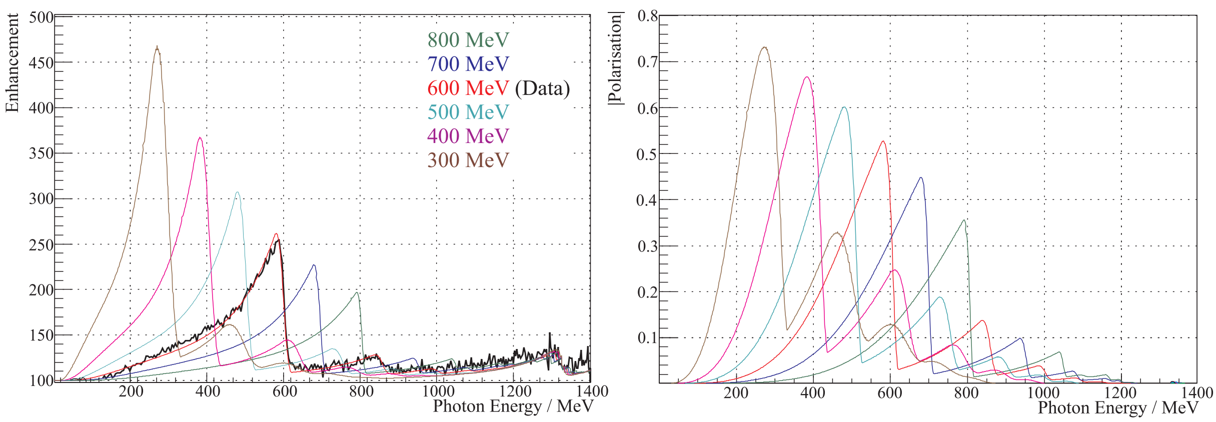

Figure 4: Linear polarisation available with the current collimation system for a variety of crystal orientations. The thin black lines are data obtained during recent MAMI-C runs.

To augment the standard focal plane detector system and make use of the Tagger's intrinsic energy resolution of 0.4 MeV (FWHM), there exists a scintillating fibre detector ('Tagger Microscope') that can improve the energy resolution by a factor of about 6 for a ∼100 MeV wide region of the focal plane (dependent on its position) [4].

A.2 Frozen-Spin Target

Polarisation experiments using high density solid-state targets in combination with tagged photon beams can reach the highest luminosities. For the double polarisation measurements planned with the Crystal Ball detector on polarised protons and deuterons a specially designed, large horizontal ^{3}He/^{4}He dilution refrigerator was built in cooperation with the Joint Institute for Nuclear Research (JINR) Dubna (see Figure 7). It has minimum limitations for the particle detection and fits into the central core of the inner Particle Identification Detector (PID2). This was achieved by using the frozen spin technique with the new concept of placing a thin superconducting holding coil inside the

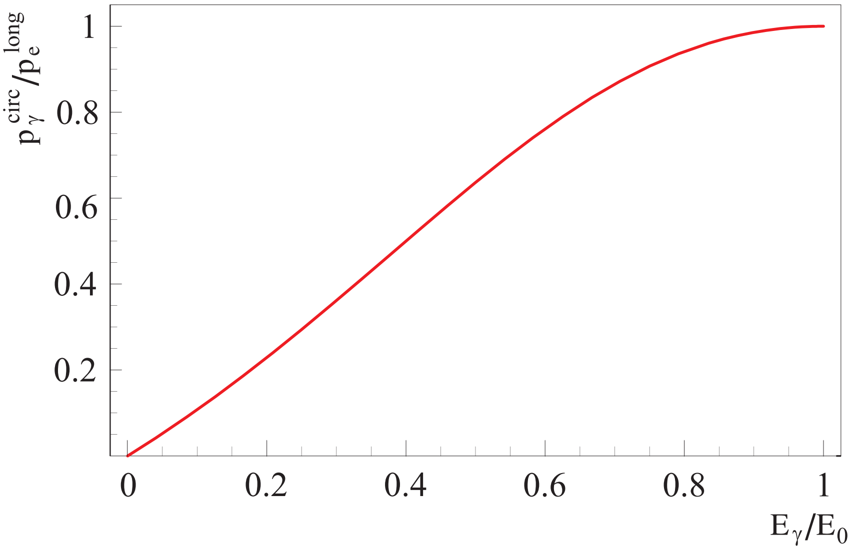

Figure 5: Helicity transfer from the electron to the photon beam as function of the energy transfer. The MAMI beam polarisation is $P_e \approx 85\%$.

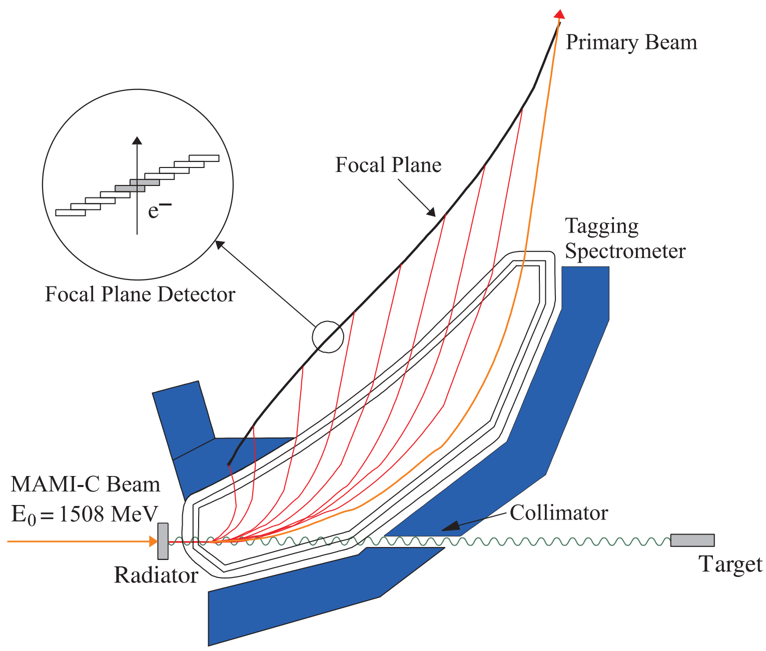

Figure 6: The Glasgow photon tagging spectrometer.

Figure 7: The new dilution refrigerator for the Crystal Ball Frozen Spin Target.

polarisation refrigerator. Longitudinal and transverse polarisations will be possible.
Highest nucleon polarisation in solid-state target materials is obtained by a microwave pumping process, known as 'Dynamic Nucleon Polarisation' (DNP). This process is applicable to any nucleus with spin and has already been used in different experiments with polarised proton and deuteron targets. The geometric configuration of the target is the same for the polarised proton and neutron setup. However, since the polarisation measurement of the deuteron is more delicate due to the small size of the polarisation signals, the modification of some basic components is needed. The reason for this is twofold: firstly the magnetic moment of the deuteron is smaller than that of the proton and, in addition, the interaction of the deuteron quadrupole moment with the electric field gradient in the sample broadens the deuteron polarisation signal. An accuracy $\delta P_p/P_p$ of 2 to 3% for the protons and $\delta P_D/P_D$ of 4 to 5% for the deuterons is expected in the polarisation measurement. It has also to be taken into account that the measured deuteron polarisation P_D is not equal to the neutron polarisation P_n. Assuming a 6 % admixture of the D-state of the deuteron, a calculation based on the Clebsch-Gordon coefficients leads to $P_n = 0.91\ P_D$. Several polarised proton and deuteron materials are available such as alcohols and deuterated alcohols (e.g. butanol C_4H_9OH), NH_3, ND_3 or ^{6}LiD. The most important criteria in the choice of material suitable for particle physics experiments are the degree of polarisation P and the ratio k of free polarisable nucleons to the total number of nucleons. Further requirements on polarised target materials are a short polarisation build-up time and a simple, reproducible target preparation. The polarisation resistance against radiation damage is not an issue for experiments with a low intensity tagged photon beam ($\dot{N}_\gamma \approx 5 \cdot 10^7\,\mathrm{s}^{-1}$) as will be used here. However, the limitations of a reduced relaxation time due to overheating of the target beads (Kapitza resistance) will

have to be investigated.
Taking all properties together, butanol and deuterated butanol are the best material for this experiment. For protons we expect a maximum polarisation of $P_p = 90\%$ and an average polarisation of $P_p = 70\%$ in the frozen spin mode. Recently, a deuteron polarisation $P_D = 80\%$ was obtained with Trityl doped butanol targets at 2.5 T magnetic field in a ^{3}He/^{4}He dilution refrigerator. At a 0.4 T holding field an average neutron polarisation P_n (see above) of 50 % will be obtained. The filling factor for the ~2 mm diameter butanol spheres into the 2 cm long, 2 cm diameter target container will be around 60%. The experience from the GDH runs in 1998 [5] shows that, with a total tagged photon flux of $5 \cdot 10^7$, relaxation times of about 200 hours can be expected. The polarisation has to be refreshed by microwave pumping every two days.
In conclusion, we estimate that we will achieve the following target parameters:

- Maximum total tagged photon flux in the energy range of 4.7 to 93% of E_0: $\dot{N}_\gamma \approx 5 \cdot 10^7\ \mathrm{s}^{-1}$, with relaxation time of 200 hours.
- Target proton density in 2 cm cell: $N_T \approx 9.1 \cdot 10^{22}\mathrm{cm}^{-2}$ (including dilution and filling factors)
- Average proton polarisation $P_p = 70\%$
- Target deuteron density in 2cm cell: $N_T \approx 9.4 \cdot 10^{22}\mathrm{cm}^{-2}$ (including dilution and filling factors)
- Average neutron polarisation $P_n = 50\%$

A.3 Crystal Ball Detector System

The central detector system consists of the Crystal Ball calorimeter combined with a barrel of scintillation counters for particle identification and two coaxial multiwire proportional counters for charged particle tracking. This central system provides position, energy and timing information for both charged and neutral particles in the region between 21° and 159° in the polar angle (θ) and over almost the full azimuthal (ϕ) range. At forward angles, less than 21°, reaction products are detected in the TAPS forward wall. The full, almost hermetic, detector system is shown schematically in Fig. 8 and the measured two-photon invariant mass spectrum is shown in Fig. 9.
The Crystal Ball detector (CB) is a highly segmented 672-element NaI(Tl), self triggering photon spectrometer constructed at SLAC in the 1970's. Each element is a truncated triangular pyramid, 41 cm (15.7 radiation lengths) long. The Crystal Ball has an energy resolution of $\Delta E/E = 0.020 \cdot E[GeV]^{0.36}$, angular resolutions of $\sigma_\theta = 2 \ldots 3^\circ$ and $\sigma_\phi = \sigma_\theta / \sin\theta$ for electromagnetic showers [1]. The readout electronics for the Crystal Ball were completely renewed in 2003, and it now is fully equipped with SADCs which allow for the full sampling of pulse-shape element by element. In normal operation, the onboard summing capacity of these ADCs is used to enable dynamic pedestal subtraction and the provision of pedestal, signal and tail values for each element event-by-event. Each CB element is also newly equipped with multi-hit CATCH TDCs. The readout of the CB is effected in such a way as to allow for flexible triggering algorithms. There is an analogue sum of all ADCs, allowing for a total energy trigger, and also an OR of groups of sixteen crystals to allow for a hit-multiplicity second-level trigger - ideal for use when searching for high multiplicity final states.
In order to distinguish between neutral and charged particles species detected by the Crystal Ball, the system is equipped with PID2, a barrel detector of twenty-four 50 mm long, 4 mm thick scintillators, arranged so that each PID2 scintillator subtends an angle

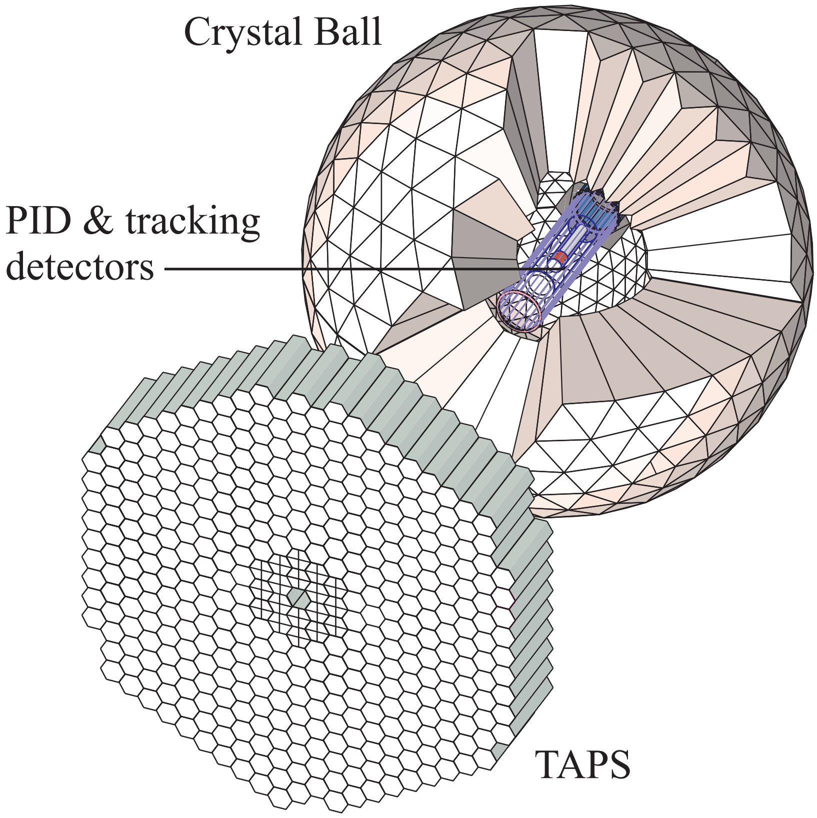

Figure 8: The A2 detector setup: The Crystal Ball calorimeter, with cut-away section showing the inner detectors, and the TAPS forward wall.

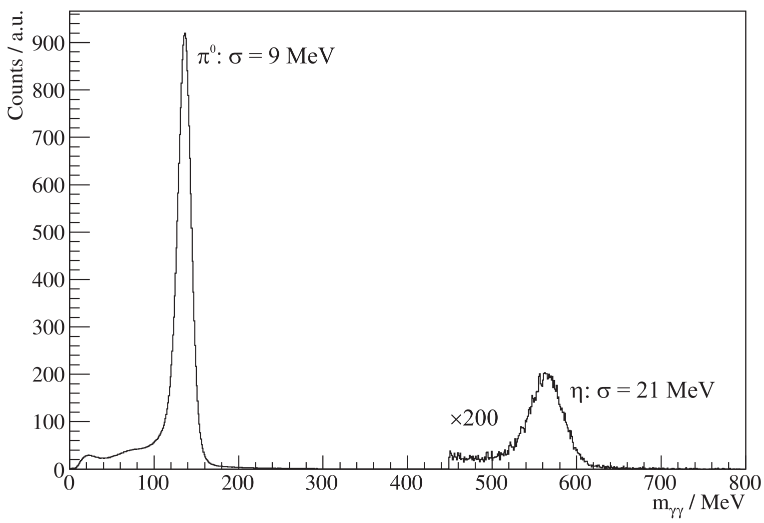

Figure 9: Two photon invariant mass spectrum for the CB/TAPS detector setup. Both η and π^0 mesons can be clearly seen.

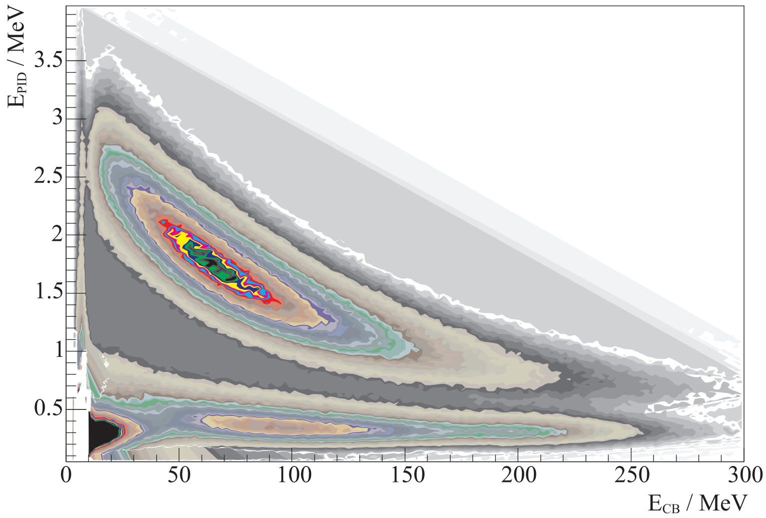

Figure 10: A typical $\Delta E/E$ plot from the Crystal Ball and the PID2 detector. The upper curved region is the proton locus, the lower region contains the pions and the peak towards the origin contains mostly electrons.

of 15° in ϕ. By matching a hit in the PID2 with a corresponding hit in the CB, it is possible to use the locus of the $\Delta E, E$ combination to identify the particle species (Fig. 10). This is primarily used for the separation of charged pions, electrons and protons. The PID2 covers from 15° to 159° in θ.

The excellent CB position resolution for photons stems from the fact that a given photon triggers several crystals and the energy-weighted mean of their positions locates the photon position to better than the crystal pitch. For charged particles which deposit their energy over only one or two crystals, this is not so precise. Here the tracks of charged particles emitted within the angular and momentum acceptance of the CB detector will be reconstructed from the coordinates of point of intersections of the tracks with two coaxial cylindrical multiwire proportional chambers (MWPCs) with cathode strip readout. These MWPCs are similar to those installed inside the CB during the first round of MAMI-B runs [3]. The most significant difference is that all detector signals are taken at the upstream end of the MWPCs, minimising the material required and facilitating particle detection in the forward polar region.

A mixture of argon (79.5%), ethane (30%) and freon-CF_4 (0.5%) is used as the filling gas. This mixture is a compromise between charge multiplication and localization requirements imposed by the ionizing particle tracks.

Within each chamber both the azimuthal and the longitudinal coordinates of the avalanche will be evaluated from the centroid of the charge distribution induced on the cathode strips. The location of the hit wires(s) will be used to resolve ambiguities which arise from the fact that each pair of inner and outer strip cross each other twice. The expected angular resolution (rms) will be ~2° in the polar emission angle θ and ~3° in the azimuthal emission angle ϕ.

The MWPCs have been recently installed inside the CB frame and their calibration using both cosmic rays and test beam data is currently underway.

A.4 TAPS Forward Wall

The TAPS forward wall is composed of 384 BaF_2 elements, each 25 cm in length (12 radiation lengths) and hexagonal in cross section, with a diameter of 59 mm. The front of every TAPS element is covered by a 5 mm thick plastic veto scintillator. The single counter time resolution is $\sigma_t = 0.2$ ns, the energy resolution can be described by $\Delta E/E = 0.018 + 0.008/E[GeV]^{0.5}$ [1]. The angular resolution in the polar angle is better than 1°, and in the azimuthal angle it improves with increasing θ, being always better than $1/R$ radian, where R is the distance in centimeters from the central point of the TAPS wall surface to the point on the surface where the particle trajectory meets the detector. The TAPS readout was custom built for the beginning of the CB@MAMI program and is effected in such a way as to allow particle identification by Pulse Shape Analysis (PSA), Time Of Flight (TOF) and $\Delta E/E$ methods (using the energy deposit in the plastic scintillator to give ΔE). TAPS can also contribute to the CB multiplicity trigger and is currrently divided into upto six sectors for this purpose. The 2 inner rings of 18 BaF_2 elements have been replaced recently by 72 $PbWO_4$ crystals each 20 cm in length (22 radiation lengths). The higher granularity improves the rate capability as well as the angular resolution. The crystals are operated at room temperature. The energy resolution for photons is similar to BaF_2 under these conditions [6].

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