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Final Report

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UCLA Intermediate Energy Nuclear and Particle Physics Research

B.M.K. Nefkens (Principal Investigator, ed.), J. Goetz, A. Lapik,
M. Korolija, S. Prakhov, A. Starostin (ed.)

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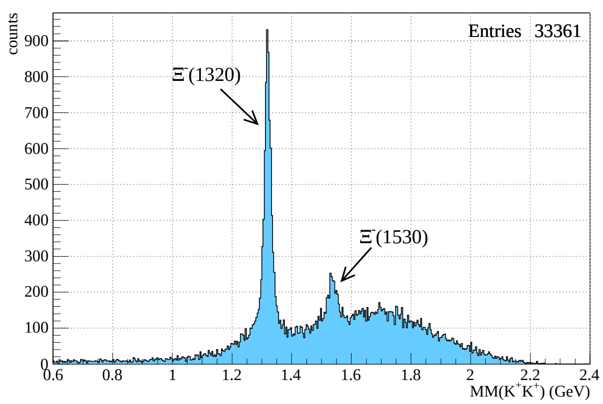
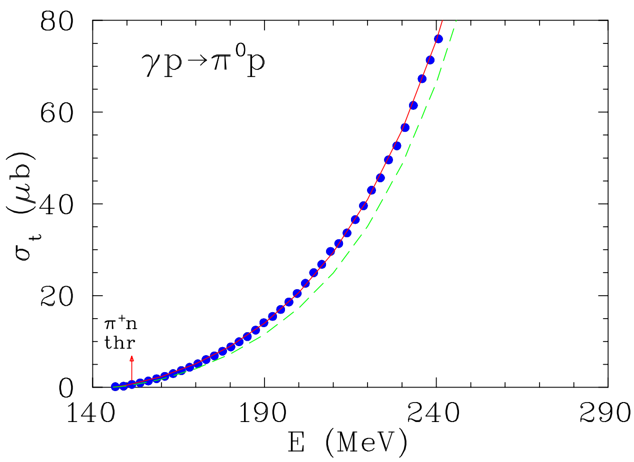
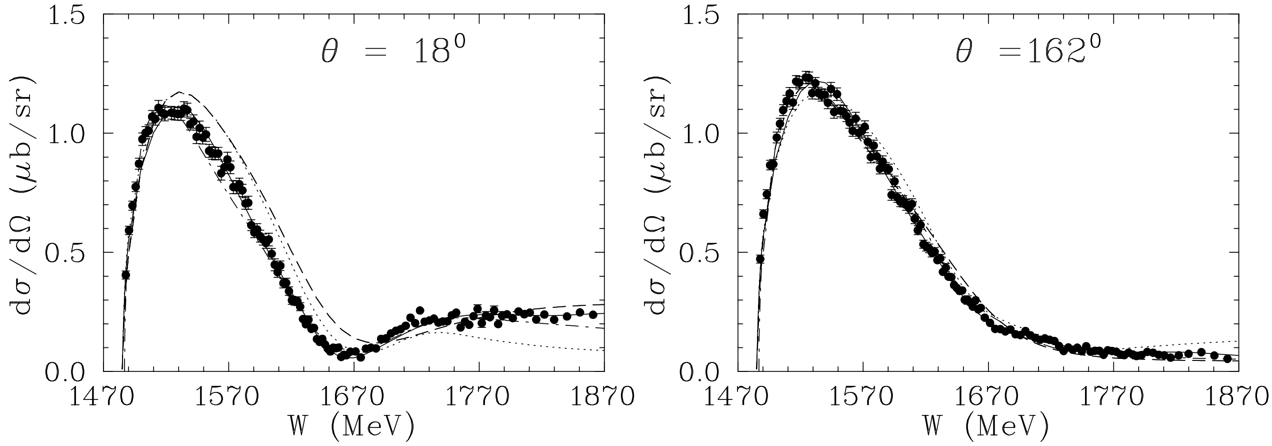
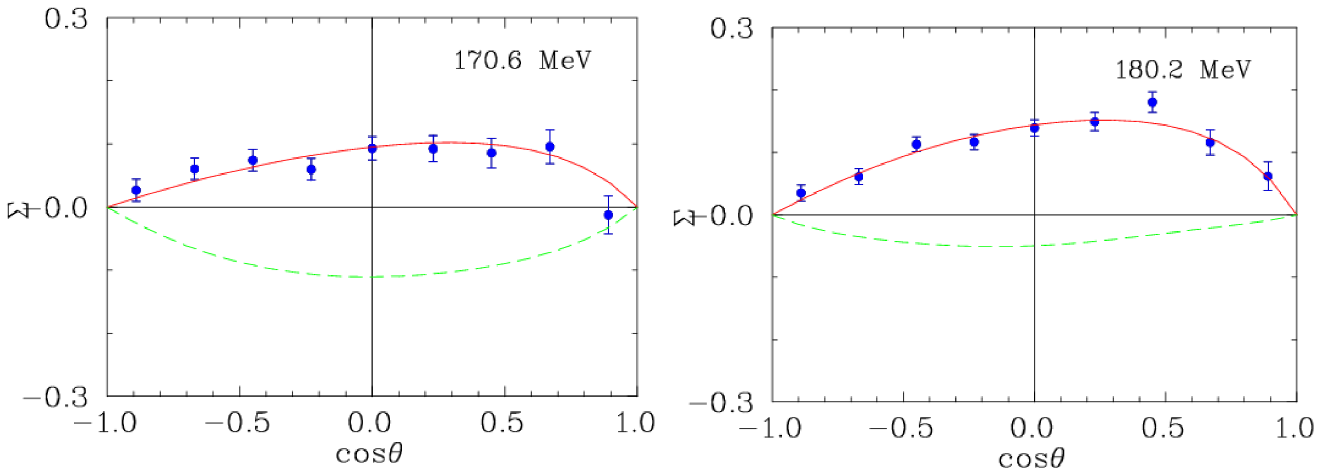




UCLA Department of Physics and Astronomy
Los Angeles, CA 90095-1547
Telephone: (310) 825-4970; FAX: (310) 206-4397
E-mail: nefkens@physics.ucla.edu
Crystal Ball websites:
http://cbmaster.physics.ucla.edu/Crystalball/crystalball.html
http://wwwa2.kph.uni-mainz.de/A2/



Fixed-angle excitation functions for $\gamma p \rightarrow \eta p$ as a function of the c.m. energy W shown for the η production angles 18 and 162 degrees. The Crystal Ball MAMI-C data are shown by solid circles. The curves denote SAID solution GE09 (solid line), SAID solution E429 (dashed line), η-MAID solution (dotted line) and Regge-MAID solution (dot-dashed line).



Beam asymmetries measured for the reaction $\vec{\gamma} p \rightarrow \pi^0 p$ with the Crystal Ball detector at the MAMI linearly polarized tagged photon beam at the beam energies of 170.6 MeV and 180.2 MeV compared to the calculations by SAID (red solid curve) and MAID (green dashed curve) PWA groups. Our data are in clear agreement with the SAID results.

Front Cover:

Left Figure – Missing mass off K^+K^+ in the reaction $\gamma p \rightarrow pK^+K^+X$ from the *g12* experiment. The large narrow peak at 1.3 GeV corresponds to the ground state cascade $\Xi^-(1320)$, while the smaller peak at 1.5 GeV corresponds to the $\Xi^{*-}(1530)$.

Right Figure – $\vec{\gamma} p \rightarrow \pi^0 p$ total cross section close to threshold obtained with the Crystal Ball detector and the MAMI polarized photon beam compared to the results from SAID (red solid line) and MAID (green dashed line) partial-wave analyses. The experimental results obtained favor the SAID predictions.

Contents

1.1 Abstract

This project covers the following research:

(a) Investigations into the structure of the proton and neutron. This is done by investigating the different resonance states of nucleons with beams of tagged, polarized photons, linearly as well as circularly, incident on polarized hydrogen/deuterium targets and measuring the production of π^0, $2\pi^0$, $3\pi^0$, η, η', ω, *etc.* The principal detector is the Crystal Ball multiphoton spectrometer which has an acceptance of nearly 4π. It has been moved to the MAMI accelerator facility of the University of Mainz, Germany. We investigate the conversion of electromagnetic energy into mesonic matter and conversely.

(b) We investigate the consequences of applying the "standard" symmetries of isospin, G–parity, charge conjugation, C, P, T, and chirality using rare and forbidden decays of light mesons such as the η, η' and ω. We also investigate the consequences of these symmetries being slightly broken symmetries. We do this by studying selected meson decays using the Crystal Ball detector.

(c) We determine the mass, or more precisely the mass difference of the three light quarks (which are inputs to Quantum Chromodynamics) by measuring the decay rate of specially selected η and η' decay modes, again we use the Crystal Ball.

(d) We have started a new program to search for the 33 missing cascade baryons using the CLAS detector at the Thomas Jefferson Laboratory. Cascade resonances are very special: they have double strangeness and are quite narrow. This implies that they can be discovered by the missing mass technique in photoproduction reactions such as in $\gamma p \to \Xi^- K^+ K^+$. The cascade program is of particular importance for the upgrade to 12 GeV of the CLAS detector and for design of the Hall D at JLab.

(e) Finally, we are getting more involved in a new program to measure the hadronic matter form factor of complex nuclei, in particular the "neutron skin" of ^{208}Pb, which is of great interest to astroparticle physics for determining the properties of neutron stars. Processes of study are coherent and non–coherent π^0 photoproduction. The Crystal Ball is uniquely suited for these studies because of the large acceptance, good direction and energy resolution and it is an inclusive detector for the $\pi^0\gamma$ final state and exclusive for background such as $2\pi^0$.

1.2 Summary of Results obtained with the Current DOE Grant

1. Over 55 refereed publications have appeared on meson production by π^- and K^- and on meson decays as measured with the Crystal Ball detector at the AGS. The final state particles include γ, π^0, $2\pi^0$, $3\pi^0$ and η. Particularly interesting are the three sets of data on the production of two π^0 mesons. The specific reactions are $\pi^- p \to \pi^0\pi^0 n$, $K^- p \to \pi^0\pi^0\Lambda$ and $K^- p \to \pi^0\pi^0\Sigma$. Flavor symmetry implies surprising relations between the five–fold differential cross sections, which have been very well verified experimentally.

2. All our data on γ, Λ, Σ^0 and K^0 production by K^- have now been fully analyzed and published.

3. Precission results have been obtained on the slope parameter for the $\eta \to 3\pi^0$ decay and on the branching ratio and Dalitz plot of $\eta \to \pi^0\gamma\gamma$. This work was done with the Crystal Ball detector at the MAMI facility using a sample of 9×10^6 η–mesons. Both decay modes provide fine tests of the applicability of Chiral Perturbation Theory at low energies.

4. We have made the most precise test of the validity of charge conjugation invariance of the electromagnetic interaction of hadrons and we have set a new upper limit on the occurrence of the C–forbidden decay $\eta \to \pi^0\pi^0\gamma$. We have also made a new search for CP violation in setting a new limit on $\eta \to 4\pi^0$.

5. We have made the first detailed measurement of nuclear π^0 photoproduction to a specific excited state in the residual nucleus, specifically to the 4.4 MeV state of ^{12}C. The Crystal Ball is particularly suited for measuring the $\pi^0\gamma$ final state with high precision. The success of this measurement opens new avenues for nuclear physics, such as measuring the matter form–factor of complex nuclei specifically of 208Pb and calcium isotopes.

6. We have made the first measurement of exclusive photoproduction of the cascade hyperon. This has been accomplished at JLab using the CLAS detector. It introduces a novel way for investigating the existence and determining the properties of the 33 predicted but undiscovered doubly strange cascade states. There are many interesting opportunities for seeing flavor physics in action when CLAS12 becomes available, or Hall D becomes reality.

1.3 Summary of Continued and New Research

1. High on the list on continued research is the analysis of our new data on π^0, $2\pi^0$, $3\pi^0$, η, $K^+\Lambda$ and $K^+\Sigma$ production obtained with the Crystal Ball at the MAMI-B and C facilities. The tagged incident photons were unpolarized, or either linearly or circularly polarized. This meson photoproduction program is complementary to the photoproduction program of charged mesons carried out at JLab (by other groups).

2. We plan to continue analyzing the large data set of η's to search for rare and forbidden η decays using the high resolution of the Crystal Ball to reduce the backgrounds.

3. New research includes the first round of measurements of η' and ω photoproduction with the completion of the upgrade of the MAMI-C facility ($E_\gamma(max) \sim 1.5$ GeV).

4. The successful installation and commissioning of the new frozen–spin longitudinally/transversely polarized hydrogen/deuterium target was the major achievement of the past year. The target required a major rearrangement of the Crystal Ball electronics which was successfully completed. This Mainz-built target has passed all the tests and now is fully operational in conjunction with the Crystal Ball detector. The first round of experiments on meson photoproduction with transversely polarized frozen spin hydrogen target was completed in the spring and summer of 2010. These measurements will be continued with longitudinally polarized hydrogen target and with deuterium targets providing new polarization data in the regions of the $\Delta(1232)$ and $S_{11}(1535)$ resonances in support of the program on the determination of the magnetic dipole moment of these two resonances.

5. We will continue the analysis of our cascade experiment with the CLAS detector at JLab. Everyone is anxious to find out the yield of new cascade states. Since the data taking with the upgraded CLAS detector went very smooth we have high expectations. Time permitting we will use the high η' production at JLab to measure rare and forbidden charged η' decays and other intriguing reactions, which can be investigated by CLAS with $8 - 12$ GeV photons in Hall B.

6. A new program which is in the gestation stage concerns coherent and non–coherent π^0 production on complex nuclei to probe the hadronic matter form factors. The Crystal Ball is particularly suited to study this. Targets under consideration are the calcium isotopes and ^{208}Pb. The first results on "Incoherent Neutral Pion Photoproduction on ^{12}C" are published in PRL. We were flattered by the nice review of both PRL referees. Specifically the Report of Referee A says: *"This manuscript deserves publication in Physical Review Letters. It reports on a ground–breaking experiment in "incoherent" nuclear pion photoproduction. For the first time, high quality data in neutral pion photoproduction on a nucleus to a specific excited state, the 4.4 MeV 2+ state in ^{12}C, are presented and remarkable agreement with the Δ–hole model prediction of 1985 is reported. I expect that this successful experiment will initiate further experimental and theoretical studies"*. Referee B wrote: *"Overall my opinion of this manuscript is very high, and I believe it should be published in Physical Review Letter. It involves an excellent group of experimentalists reporting a novel technique. The data they report should be of interest to a wide range of nuclear physicists, and the technique shows promise for additional interesting work..."*

1.4 Personnel

B. Nefkens	PhD (P.I.)
A. Starostin	PhD
S. Prakhov	PhD
J. Goetz	Grad Student
A. Lapik	PhD, Visiting Scientist
M. Korolija	PhD, Visiting Scientist
S. Upadhyayula	Undergrad

2 Results obtained with the Current DOE Grant

Most of the research performed in the last several years is centered around the use of the Crystal Ball Multiphoton Detector. There are four parts to our program:

Program IA is "The analysis, publication and interpretation of the data that were taken at the AGS using π^- and K^- incident beams."

Program IB is "Installation of the Crystal Ball with Peripherals at MAMI-C." This covers besides the physical apparatus the electronics for the CB, TAPS, PID, TAGGER and TRIGGER, the liquid H_2 (ℓH_2) target. Furthermore, we need to create the Monte Carlo of the full detector and test the setup.

Program IC is "Measurements of Meson Decays and Meson Photoproduction with the Crystal Ball at MAMI-B."

Program ID is "Measurements of Ξ Photoproduction with CLAS."

We begin with a description of the Mainz Microtron (MAMI) and the Crystal Ball detector.

2.1 The MAMI Facility

The Mainz Microtron (MAMI) is a multistage electron accelerator with a 100% duty factor. Until recently, the maximum electron energy was 855 MeV and the facility was named MAMI-B. It has been upgraded to an energy of 1.6 GeV, and is now called MAMI-C. Photons are created by bremsstrahlung and the post-bremsstrahlung electrons are tagged by the Glasgow Photon Tagger. When the electrons are not polarized, the photon beam is unpolarized. When the electrons are longitudinally polarized the resulting photon beam is circularly polarized. A beam of linearly polarized photons is routinely produced using coherent bremsstrahlung on a diamond radiator, which is carefully aligned in the electron beam with the aid of a special goniometer. The degree of linear polarization can be as high as 70%.

The Glasgow Photon Tagger consists of a 50 ton momentum-dispersed magnetic spectrometer. It focuses the post-bremsstrahlung electrons on the focal plane detector where the position and time of arrival of the electrons are established. The focal plane detector consists of 353 half-overlapping plastic scintillators. At 800 MeV the resolution is 2 MeV. The maximum tagged photon flux is 10^8 photons per second for the full range, which is $0.05E_0 < E_\gamma < 0.94E_0$. The photon tagger has been upgraded to 1.5 GeV to match MAMI-C.

Encouraged by the smooth and swift upgrade of MAMI-B which had been achieved at Mainz a few years ago we urged the accelerator group to push the new accelerator to the physical limits in energy. Happily they did this and soon reached a record of 1.604 GeV and maybe there are a few more MeV's to conquer. With another (refurbished) end-point tagger this has accessed new physics for us namely the study of η' decays as well as the features of the $\Lambda(1405)$, $a_0(980)$ and $f_0(980)$ which were not considered in the original plans. This could easily become a half to one year long new program. It could lengthen our stay at MAMI by a year. This new option is now being discussed in the Crystal Ball Collaboration.

2.2 The Crystal Ball Multiphoton Detector

The Crystal Ball itself consists of 672 optically isolated NaI(Tl) crystals which are shaped like truncated pyramids. The crystals are arranged in two hemispheres that combine to make a sphere with an entrance and exit tunnel for the beam. The CB has a spherical cavity for the liquid hydrogen target. The solid angle coverage of the NaI is 93% of 4π. The energy resolution for electromagnetic showers is $\Delta E/E = 0.017/[E(GeV)^{0.36}]$. Shower directions are measured with a resolution in the polar angle θ of $\sigma_\theta = 2-3^\circ$. The resolution in ϕ is $2^\circ/\sin\theta$. For the photoproduction experiments at Mainz, the CB detector has been expanded with a forward wall for which we use the TAPS detector. TAPS consists of a wall, circular in shape, which covers the exit tunnel of the CB sphere. TAPS consists of about 400 individual BaF_2 counters which are hexagonally shaped with a diameter of 59 mm. They are 12 RL long. Each counter is covered by its own 5 mm thick plastic scintillator in front, which serves as a charged-particle veto detector. The forward wall increases the acceptance of the CB to 97% of 4π. Another upgrade is the use of a high-efficiency central tracker. It consists of two coaxial cylindrical multiwire proportional chambers covering θ from 21° to 159°. It is located around the ℓH_2 target in the cavity of the CB sphere. Finally there is a Particle Identification Detector. It is a barrel around the ℓH_2 target located in the CB cavity and consists of 24 scintillation counters.

The web site for the Crystal Ball is `http://cbmaster.physics.ucla.edu/crystalball/crystalball.html`. It has many details on the set up and it has a full set of Crystal Ball reports.

2.3 Program IA: "Analysis of Crystal Ball data from the AGS."

With the writing of the paper on K^- inverse radiative capture in flight we have come to the completion of our program "The Crystal Ball at the AGS", (Program 1A). This program has been a success beyond our most optimistic expectations. It has resulted in over 55 refereed publications, over 20 in PR and PRL.

Thanks to the efforts of the theory groups of the University of Gent, Belgium who produced a successful model for radiative K^- capture we can fit our data to theory and extract physics. This radiative experiment has been called heroic as the potential background from misidentified π^0 and $2\pi^0$ production is over a hundred times the radiative cross section! Only the CB with its near 4π acceptance acting as both a coincidence counter for good gammas and anticounter for the bad ones from π^0 enabled us to pull off this experiment. (PhD thesis of Nakorn, and parallel analysis by Serguei.)

In 1992 our group brought the SLAC Crystal Ball to BNL for a series of experiments in hadron physics using π^- and K^- beams incident on a ℓH_2 target that was located in the center of the CB. The program also included studies of the neutral decay modes of the η, 28 reactions were investigated at the AGS. Sec.4.1.

The physics objectives of our CB research include: (a) the determination of the existence and properties of baryonic resonances including their mass, width, and magnetic dipole moment; (b) elastic and inelastic meson-nucleon scattering; (c) tests of chiral perturbation theory, the $1/N_c$ expansion, and various effective Lagrangian models; (d) the determination of the light quark masses; (e) investigations of the broken symmetries of flavor, isospin, G-parity, chiral symmetry, C, CP, T, and CPT invariance; and f) search for new particles (usually indirectly) such as leptoquarks, supersymmetric particles, and hybrid baryons. The above program is pursued using the production by π^- and K^- of the following: γ, π^0, $2\pi^0$, $3\pi^0$, η, and neutrons, as well as $\Lambda \to \pi^0 n \to 2\gamma n$, $\Sigma^0 \to \gamma\Lambda \to \gamma\pi^0 n \to 3\gamma n$, and $K^0 \to 2\pi^0 \to 4\gamma$. Typically, we measure the full angular distribution (20 angle bins) at many incident energies (19 for π^- and 8 for K^-). Our group was the first to apply a 4π

acceptance photon spectrometer to baryon spectroscopy, measuring simultaneously as many as seven channels.

Our long-range objective is to understand the structure of the proton and to study the origin of the mass of the elementary particles. At present the origin of the rest mass is a mystery. According to the Standard Model, some of the mass is due to the Higgs field. In the case of the proton, this accounts for only 2%. The rest is attributed to the quark condensate which is the complex mess of hypothetical interactions of the quarks with the vacuum. We are engaged in a program of comparing the magnitude of the mass difference between the up and down quark as revealed in measurements of isospin and charge symmetry violation and to do this for many different reactions and for all the baryon and meson isospin doublets. A similar mapping of the strange-down quark mass difference is also under way.

The data measured in the CB experiments at the AGS are characterized by high statistics, and complete or near-complete angular coverage; they are available for many different incident beam energies. Furthermore, event samples are very clean since the CB acts simultaneously as detector of the signal and as the veto counter for unwanted events which have a different number of photons. All of this is made possible by the use of the Crystal Ball detector which has excellent energy resolution, good photon detection capabilities, and especially because it has 93% of 4π acceptance.

The selection of the most important physics result to come out of our AGS run depends on one's taste. Our choice of the potentially greatest impact is the triple set of $\pi^0\pi^0$ productions: $\pi^-p \to \pi^0\pi^0 n$, $K^-p \to \pi^0\pi^0\Lambda$, and $K^-p \to \pi^0\pi^0\Sigma^0$. (A fourth set on $\gamma p \to \pi^0\pi^0 p$ is done by the CB at MAMI). The startling discovery is the strong dependence of the $\pi^0\pi^0$ invariant mass spectrum on the production angle. This implies that the famous σ meson does not play a major role in $\pi^0\pi^0$ production. Furthermore, the scattering lengths and the low-energy scattering phases which describe basic low-energy π-π scattering need to be reevaluated.

Another major discovery is the applicability of Dynamic Flavor Symmetry. This symmetry has its origin in the universality postulate of the strong interaction. It is a characteristic feature of the QCD Lagrangian for massless quarks. In practice it is broken in a well defined way due to the mass difference of the strange and down quarks. Dynamic Flavor Symmetry implies that the eta production reactions $\pi^-p \to \eta n$ and $K^-p \to \eta\Lambda$ should have very similar features of their differential cross sections and energy dependence of the total cross section. These features have indeed been observed in our η production experiments. Really spectacular is the prediction of Dynamic Flavor Symmetry that the five-fold differential cross section for $\pi^-p \to \pi^0\pi^0 n$ has the same features as for $K^-p \to \pi^0\pi^0\Lambda$, but is different than $K^-p \to \pi^0\pi^0\Sigma^0$; this is seen clearly in all our data.

As far as the η decays are concerned, our preference for the best physics is the excellent lower limit on the two charge-conjugation forbidden decays $\eta \to \pi^0\pi^0\gamma$ and $\eta \to \pi^0\pi^0\pi^0\gamma$, because they provide the best test of C-invariance with a sensitivity that is readily calculable; other tests of C have in general unknown sensitivity. A few of our recent results are shown on the back and front cover of this document. A complete list of the CB articles is given in Section 4.

2.4 Program IB: "Improvements of the Crystal Ball"

UCLA is now the sole custodian of the CB and we are in charge of improvement and development. Because of the fragility of NaI crystals and their high sensitivity to humidity, special measures are needed to ensure the safety of the Ball. The hygroscopic NaI is housed in two hermetically sealed evacuated hemispheres. During the stay in BNL the bottom hemisphere had a relatively high leak rate: $\sim 2-5$ torr/day. The leaks were detected and fixed in Mainz using a helium leak detector and sealed. In February–March of 2003 all CB crystals were visually inspected. The inspection did not indicate a significant decline in the quality of the crystals. In April-May 2003 all 672 CB PMTs were tested and installed on the hemispheres. A new movable Crystal Ball frame was designed, manufactured, and assembled. The frame allows adjustment of the hemisphere's position in all projections. The upper hemisphere can be lifted about 1 meter above the beam level allowing installation and maintenance of the central tracker and the particle ID counter.

A new fast readout electronics setup has been installed. Each CB crystal is equipped with an active splitter, a flash (sampling) ADC (FADC), a discriminator with rise-time compensation, a multihit TDC, and a 32–bit scaler. The new Crystal Ball FADC is one of the crucial components in achieving a superior energy resolution of the detector at high beam intensities. The FADC is a 32 channel 6U VME unit with 10 bits-per-sample resolution and 80 MHz maximum sampling rate. Each FADC channel may store up to 30K samples in the internal memory for later readout. The FADC does not use a VME interface and communicates using a GeSiCA VME readout unit via a fast optical link. The GeSiCA formats the FADC data into a data buffer. For the first stage of the MAMI experiment we limited the amount of information from the FADC by reading only three integrated values. The first value is proportional to the total energy deposited in the detector. It is an integral of the main pulse over about 500 ns. The second sum calculates the "pedestal" over 500 ns preceding the main pulse. The third number is the pulse integral over 500 ns of the tail of the pulse. The ratio of the first and the third values is used to identify overlapping events in the detector. The new FADCs allowed us to achieve a better resolution compared to the old electronics. For example, the width of the $\gamma\gamma$ invariant mass obtained at MAMI is typically 10–15% narrower than in our AGS experiments. The central piece of the electronics is the Trigger Control System (TCS). The system was originally designed in CERN for the COMPAS experiment. It's main purpose is to synchronize all the FADC, TDC and GeSiCA modules used for the Crystal Ball and the tagger readout. TCS also provides a fast data transfer from the GeSiCA's to the main DAQ computer. The system was purchased by the University of Mainz.

A new frozen-spin polarized target was designed and build by Mainz and Dubna groups for the experiments studying polarized and doubly polarized observables. The target was installed in the A2 experimental hall in the late 2009, early 2010 demanding a major modification of the Crystal Ball support frame, rearrangement of the Crystal Ball electronics and the cabling system. The target re-polarization procedure was implemented such that the whole Crystal Ball detector has to be moved about 4.5 meters downstream the beam line allowing the superconducting polarizing magnet to move in. After the polarization is completed the detector has to be returned to its working position with accuracy of ± 1 mm in $x-y$ projection and ± 2 mm in z. Considering that the combined weight of the Ball with the PMT's and the cables, plus the frame is approximately 12 tons, the moving becomes a challenging engineering task. The solution we have implemented is based on experience of the previous MAMI project – DAPHNE. The frame has been put on heavy–duty rollers and set on rails allowing about 4.5 meters movement. The Crystal Ball electronics have been mounted inside the CB frame such that the electronics and the detector move together excluding possible damages to the cables and the connectors.

The modification of the experimental setup was successfully completed in the April of

2010. During the scheduled downtime of several months from November of 2009 to April of 2010 the Crystal Ball was installed on the rails, the cables were modified, tested and rearranged. The Crystal Ball electronics was dismantled from the stationary racks and mounted again inside the Crystal Ball moving frame, assembled and debugged. We have also used this time to inspect throughly all the Crystal Ball PMT's by analyzing their electrical properties and quality of the output signals. About 50 installed PMT's and about 20 spare PMT's were fixed improving significantly the performance of the detector.

Although the specially designed rails and the heavy rollers provide smooth ride of the Crystal Ball, a new set of shock sensors was installed on the detector controlling its vertical and horizontal acceleration during the position change. The reading of the system is available only in the experimental hall at this time, however in the nearest future the data will be logged and published online.

Currently the Crystal Ball data acquisition system undergo a major upgrade of both, hardware and software components aiming to substantially increase speed of the DAQ. The upgrade will be completed in the early 2011, but even at this early stage the DAQ speed was increased by about 50% by including two new CPU's. The UCLA contribution to the DAQ upgrade included so far four new fast CPU's, new cables and connectors to the total amount of about 10k EURO.

2.5 Program IC: "Measurements of Meson Decays and Meson Photoproduction with the CB at MAMI-B"

This program covers the 10 experiments and tests which we have done with the upgraded CB at MAMI-B ($E_\gamma < 800$ MeV).

We have used 700 hours of MAMI machine time in Winter/Spring 2004 on engineering runs to make the entire CB detection system operational. Good data were taken for 3600 hours in the "Long Run" from June 2004 to April 2005 when we measured γ, π^0, $2\pi^0$, and η photoproduction on protons for E_γ up to 800 MeV. We have measured the following reactions:

1. $\vec{\gamma}p \to \Delta^+\gamma' \to \pi^0 p\gamma'$. Proposal MAMI-A2/1-02, approved and run successfully for 600 hours. We used linearly and circularly polarized photons. This reaction allows one to measure the magnetic dipole moment of the $\Delta(1232)\frac{3}{2}^+$ resonance. The unpolarized data were successfully analyzed by MAMI and UCLA groups. The extracted five-fold differential cross sections of $\gamma p \to \pi^0 p\gamma'$ were published in European Physics Journal A.

2. $\vec{\gamma}p \to \Delta^+\gamma' \to n\pi^+\gamma'$. Proposal MAMI-A2/1-03, approved and run successfully for 600 hours. This is an alternative measurement of the magnetic dipole moment of the $\Delta^+(1232)$, with different backgrounds and different theoretical analysis.

3. $\vec{\gamma}p \to p\pi^0\pi^0$. Proposal MAMI-A2/2-03, approved and run successfully for 500 hours with linearly and circularly polarized photons. This is a continuation of our $2\pi^0$ production program started at the AGS. Near threshold it is a test of χPT .

4. $\gamma A \to \pi\pi X$. Proposal MAMI-A2/3-03, approved and run successfully for 700 hours. This is an investigation of medium modifications in $\pi^0\pi^0$ photoproduction on complex nuclei.

5. $\gamma p \to \eta p$. Proposal MAMI-A2/4-04, approved and run successfully for 240 hours. Measurement of various neutral η decays such as the rate and Dalitz plot for $\eta \to \pi^0\gamma\gamma$, the π^0 slope in $\eta \to 3\pi^0$ and tests of C-invariance in $\eta \nrightarrow \pi^0\pi^0\gamma$, $\eta \nrightarrow \pi^0\pi^0\pi^0\gamma$, and $\eta \nrightarrow 3\gamma$. The data for the π^0 slope in $\eta \to 3\pi^0$ were analyzed and published in European Physics Journal A.

6. $\gamma A \to \pi^0 A$. Proposal MAMI-A2/5-04, approved and run successfully for 285 hours. Coherent π^0 production to investigate the neutron distribution in complex nuclei.

7. $\vec{\gamma} p \to \pi p$ near threshold. Proposal MAMI-A2/6-03, approved and run successfully for 200 hours. This is a good test of χPT .

8. $\gamma A \to \eta A$ near threshold. Proposal MAMI-A2/7-03, approved for 200 hours. Search for eta-mesic nuclei. The liquid ^3He target was supplied by the University of Basel and the ^3He gas for the target was supplied by the Institute for Nuclear Research from Moscow. The run was successfully completed in 2008.

9. Measurement of the mass of the η meson. Engineering run for $\sim$ 100 hours. The preliminary valued for the eta mass is $m_\eta = 547.76 \pm 0.042 \pm 0.101$ MeV. Our result favors the high mass value in support of the CERN experiment NA48.

10. π^0, η, and $2\pi^0$ photoproduction on the deuteron. Engineering run for about 100 hours. Test run to study the use of the deuteron as a neutron target.

2.6 Program ID: "Measurement of Ξ photoproduction at CLAS"

Cascade physics provides a new window on baryon physics which we like to investigate. To this purpose we have analyzed existing data from CLAS which was obtained for other purposes.

Using the data from the CLAS *g6a* run, we searched for events with two positive kaons in the final state, and found a significant peak at the mass of the $\Xi(1321)$. We estimate that the production rate of the $\Xi^-(1321)$ at CLAS is over 5000 per week. Further analysis, which included the data from the *g6b* and *g6c* runs at higher incident photon energy, led to the first observation of the photoproduction of the $\Xi(1530)$.

Analysis of the *g6c* data set, which is concentrated at high energy, yielded tantalizing results. The photoproduction of the $\Xi^0(1321)$ and $\Xi^0(1530)$ were both observed in the process $\gamma p \to K^+K^+\pi^-\Xi^0$. A major effect of the *g6c* cascade analysis was the realization by the CLAS collaboration that a more highly-segmented start counter was needed to handle the high rates. A new start counter was built and used in the *g11* run, which used photon energies up to 3.75 GeV. This data set contains a large number of $\Xi(1321)$ and $\Xi(1530)$ hyperons. For the UCLA group, this program has led to 12 invited talks, five contributed talks, two conference proceedings, and the detailed publication of the results in Phys. Rev. C **71**, 058201 (2005).

3 Continued and New Research

We have arranged the continued and proposed new research into five programs as follows:

Program IIA: Analysis of MAMI-B data taken with the Crystal Ball. It covers the data taken in the Long Run in '04/'05, summarized in program IC in the previous section.

Program IIB: New Experiments on η' and η decay and meson photoproduction with the CB at MAMI-C. This covers the neutral decays of the η' as well as the photoproduction of γ, π^0, $2\pi^0$, $3\pi^0$, η, ω, and η'. A major part will use polarized photon beams. Technically this is the new part of our Physics program. In actuality it is the extension of our existing research program from $E_\gamma = 0.8$ to 1.5 GeV. We have a large set of physics goals such as η' decay modes, the magnetic dipole moment of the $N(1535)\frac{1}{2}^-$ resonance, and a host of other observables and investigations. We will discuss them below. They are divided into the following sub-programs: Upgrades of the Crystal Ball (IIB-1), Neutral decay modes of the η' (IIB-2), η Decays (IIB-3), Magnetic Moment of the $N(1535)\frac{1}{2}^-$ (IIB-4), Other Meson Photoproduction Reactions (IIB-5), Miscellaneous (IIB-6).

Program IIC: Cascade Photoproduction. This project is the analysis and publication of the *g6* and *g11* data already obtained.

Program IID: Investigations of the Photoproduction and Decay of the 33 Missing Ξ^* Resonances using the JLab run CLAS *g12*. Data taking was completed in June 2008.

3.1 Program IIA "Analysis of MAMI-B Data taken with the CB"

At the top of our list of continued research projects is the analysis of the monumental pile of new data obtained in the "Long Run" on meson photoproduction. The (incomplete) list of the reactions and decays we study analysing the MAMI-B and MAMI-C data includes 38 items, see Tab. 3.1. Fortunately we have 12 talented young men (9) and women (3) analysing the data. Most of them (10) have already received their PhD's based on the results obtained with the Crystal Ball at MAMI-B experiments. They are working now on finalizing their data for publication. The UCLA group has selected as top priority the rare η decays, specifically the Dalitz plot and decay rate of $\eta \to \pi^0\gamma\gamma$. This decay mode provides a unique test of chiral perturbation theory (χPT): the first order is forbidden, and the second order is suppressed to a negligible magnitude by G-parity conservation, so we have a direct test of third and higher orders. There are plenty of theoretical calculations waiting to be tested. This decay mode, which was the thesis project of one of our UCLA grad student, Jason Brudvik, who graduated in 2007 is a natural follow-up to our successful experiment on various η decays at the AGS. That experiment provided a new value for $BR(\eta \to \pi^0\gamma\gamma)$ that is a factor of two smaller than the historic GAMS-2000 result. Our data support the χPT predictions. We would like to reduce the error on the BR by a factor of two. Furthermore we want to reduce the background (which we can do because we have the TAPS detector in the exit channel of the CB), so we can measure the Dalitz plot. The result of our AGS run has been published in PRC, and it contains the details of the complicated analysis as well as an overview of the theory. There is a large amount of work to be done. First the properties of the new components of the CB detector must be incorporated in the analysis and Monte Carlo programs. This includes the features and calibrations of the forward wall made up of the TAPS detector which alone has 510 BaF_2 counters, the central tracker which consists of two coaxial cylindrical multiwire proportional chambers, and the Particle Identification Detector (PID), which is a cylinder made of 24 scintillators surrounding the target. The branching ratio $BR(\eta \to \pi^0\gamma\gamma)$ is of order 10^{-4}, so we need to suppress the abundant neutral background channels of $2\pi^0$ production and the $\eta \to 2\gamma$ and $\eta \to 3\pi^0$ decays. This must be accomplished by exploiting the subtle differences in the kinematics of the $\pi^0\gamma\gamma$ signal and the background channels. We estimate that the analysis will take a minimum of three man-years. Other reactions that we are interested in analyzing soon include:

1. $2\pi^0$ photoproduction on the proton. We would like to investigate the angular dependence of the Dalitz plots, and compare them to our $2\pi^0$ data from π^- and K^- interactions measured at the AGS, Refs. [1–3].

2. We would like to complete the new determination of the η mass. There is an important, large experiment done at CERN (NA48) to measure CP violation in K^0. The calibration of the NA48 detector depends on the mass of the eta. NA48 has found in an independent test the mass of the η to be 0.5 MeV higher than the generally accepted value. Our measurement will tell who is correct: NA48, or the rest of the η community. Ref. 4.

3. The asymmetry with linearly polarized gammas in $\vec{\gamma}\mathrm{p} \to \pi^0\mathrm{p}$ near threshold is a very nice test of χPT as it has been calculated to the desired accuracy.

4. We are contributing to the large analysis of the radiative π^0 production reaction: $\vec{\gamma}\mathrm{p} \to \Delta^+ \to \Delta^+\gamma' \to \pi^0\mathrm{p}\gamma'$, which will give us the magnetic dipole moment of the Δ^+.

3.2 Program IIB: "Experiments in η' and η Decay and Meson Photoproduction with the CB at MAMI-C"

3.2.1 Program IIB-1: Upgrade of MAMI-B to MAMI-C

A major upgrade of the MAMI-B electron microtron has been successfully made in 2007 increasing the maximum energy of the beam from 0.8 GeV to 1.6 GeV. The name of the upgraded facility is MAMI-C. Also upgraded to 1.6 GeV is the Glasgow Photon Tagger. The list of processes we can study with the new machine includes 38 reactions and decay modes, see Tabl. 3.1.

A large part of our MAMI-C program utilizes the polarized frozen–spin proton/deuteron target. The installation and commissioning of the target in the A2 experimental hall began in November of 2009 and was successfully completed in April of 2010. A working temperature of astonishing 45 mK was achieved providing nearly 80% polarization at about 800 hours of relaxation time for the transversely polarized hydrogen. Installation of the frozen-spin target required a major modification of the Crystal Ball frame and electronics that was successfully completed in the spring of 2010.

Equally important is the upgrade of the Crystal Ball data acquisition system and the trigger logic. The upgraded system can potentially provide an event rate of several kHz. This would allow us to use much more open trigger permitting simultaneous investigation of all neutral reaction in our energy range. At the same time new sophisticated trigger logic implemented on multi-channel FPGA matrices will allow "smart" triggering while looking for the rare η' events making possible utilization of the MAMI electron beam high intensity.

Production Reactions			Decays of η/η'		Decays of ω	
$\gamma N \to \pi^0 N$	$\gamma A \to \pi^0 A'$	F.F.	$\eta/\eta' \nrightarrow 2\pi^0$	CP	$\omega \to \pi^0\gamma$	
$\gamma N \to 2\pi^0 N$	$\gamma A \to \pi^0\gamma A'$		$\eta/\eta' \to 3\pi^0$	G	$\omega \to \eta\gamma$	
$\gamma N \to 3\pi^0 N$	$\gamma A \to \pi^0\pi^0 A'$	M.M.	$\eta/\eta' \nrightarrow 4\pi^0$	CP	$\omega \to 2\pi^0\gamma$	
$\gamma N \to 4\pi^0 N$	$\gamma A \to \omega A'$	M.M.	$\eta/\eta' \to 2\gamma$	Anom.	$\omega \to \eta\pi^0\gamma$	
$\gamma N \to \eta N$			$\eta/\eta' \nrightarrow \pi^0\gamma$	J	$\omega \to 3\gamma$	
$\gamma N \to \rho N$			$\eta/\eta' \to 2\pi^0 2\gamma$	χPT	$\omega \nrightarrow \eta\pi^0$	C
$\gamma N \to \omega N$			$\eta/\eta' \nrightarrow 2\pi^0\gamma$	C	$\omega \nrightarrow 3\pi^0$	C
$\gamma N \to \eta' N$			$\eta/\eta' \nrightarrow 3\pi^0\gamma$	C		
$\gamma N \to \eta\pi^0 N$			$\eta/\eta' \to \pi^0\gamma\gamma$	χPT		
$\gamma N \to \eta 2\pi^0 N$			$\eta/\eta' \nrightarrow e\mu$	LF		
$\gamma N \to \omega\pi^0 N$			$\eta/\eta' \nrightarrow \pi^0 e\mu$	LF		
$\gamma p \to K_s\Sigma^+$			$\eta/\eta' \nrightarrow 3\gamma$	C		
$\gamma p \to K^+\Sigma^0$			$\eta' \to \eta\pi^0$	G		
$\gamma n \to K_s\Sigma^0$			$\eta' \to \eta\pi^0\pi^0$			
$\gamma p \to K^+\Lambda$			$\eta' \to \omega\gamma$			

Table 3.1: Reactions and processes which are being investigated at MAMI with the Crystal Ball detector. The symbol γ in the first two columns indicates that the incident beam can be linearly, circularly, or unpolarized photons; the symbol N is for proton (liquid hydrogen target), or a quasi free neutron (liquid deuterium target); F.F. is for hadronic matter form–factors and M.M. is for investigation of medium modification effects at normal nuclear density.

The end-point tagger is a very essential part of our program studying η' decay and production. The device will allow photon tagging for the highest 5% of the bremsstrahlung energy spectra produced by the 1.6 GeV MAMI-C electrons. It consists of a spectroscopic dipole magnet and a position sensitive detector in the form of a hodoscope. One of the existing prototypes of the main MAMI tagger magnet is used for this purpose. The magnet is already refurbished, tested and mapped. The beam geometry with the new end-point tagger included has been simulated. The new tagger will be installed directly before the main tagger magnet. Construction of the tagger ladder is underway. The first tests of the end-point tagger may take place in the middle of 2011.

3.2.2 Program IIB-2: Neutral Decay Modes of the η'

The η' meson has many interesting decay modes, which make it possible to probe a selection of top-rated hadron physics problems. One would like to investigate the mass difference of the u and d quarks. The idea is that the $\eta' \to \eta\pi^0\pi^0$ decay mode is an allowed strong interaction and the related decay $\eta' \to 3\pi^0$ is forbidden by G-parity. However, the latter decay occurs in reality because of η–π^0 mixing and this mixing is well described by the mass term of the QCD Lagrangian, $\mathcal{L}_m = -\Sigma\overline{\psi}m\psi$.

Gross, Treiman, and Wilczek [5] have obtained the relation $R^2 = \phi\Gamma(\eta' \to \eta\pi^0\pi^0)/\Gamma(\eta' \to 3\pi^0)$ where $R = (m_s - \hat{m})/(m_d - m_u)$, $\hat{m} = \frac{1}{2}(m_u + m_d)$, and ϕ is a numerical factor, namely the ratio of the phase spaces and the Clebsch-Gordan factors. The (current) quark masses are input to QCD. The quark masses cannot be determined directly because quarks are not free particles.

Another objective of the η' (and η) program is to investigate $\pi\pi$ and $\pi\eta$ interactions at low energy. The energy dependence (which is small) of $\pi\pi$ and $\pi\eta$ scattering is the origin of a small variation in the density distribution of the Dalitz plots for $\eta' \to \eta\pi^0\pi^0$, $\eta' \to 3\pi^0$, and $\eta \to 3\pi^0$. We want to measure all three. We have already done $\eta \to 3\pi^0$ [6]. The existing data on η' decay is rather sketchy. We would like to obtain a sample of 0.3 million η' decays. This will require a minor upgrade of the MAMI-C energy to 1.6 GeV. Preliminary investigations show that such an upgrade may be feasible. It is being actively pursued by the machine group in Mainz. Because of the superiority of the Crystal Ball detector, we will be well ahead of the possible competition that could come from the ELSA machine in Bonn if they were able to substantially upgrade their current facilities and detector.

A novel way to measure the $\pi\pi$ scattering length $a_2 - a_0$ is by a measurement of the cusp at the opening of the $\pi^0\pi^0 \to \pi^+\pi^-$ scattering channel. This has been proposed recently by N. Cabibbo [7] (see also [8]) for the decay $K^+ \to \pi^+\pi^0\pi^0$. This idea is also applicable to $\eta' \to \eta\pi^0\pi^0$, as shown by C.W. Wong [9], but with less sensitivity. Unfortunately the effect in $\eta \to 3\pi^0$ is too small to be measurable in the near future.

There are several other η' decays which are interesting for different reasons. The decay $\eta' \to 4\pi^0$ is forbidden by CP invariance. It can readily be searched for with the Crystal Ball as we have already demonstrated at the AGS with the η. We obtained the upper limit on the branching ratio which is still unchallenged: $BR(\eta \to 4\pi^0) \leq 6.9 \times 10^{-7}$ [10]. For the η', the upper limit is at present $BR(\eta' \to 4\pi^0) \leq 5 \times 10^{-4}$. With 1 M η', we can improve this by a factor of 10 or better. Because of the larger phase space, this would be a more sensitive limit than obtained from η decay.

The decay $\eta' \to 3\gamma$ is a direct test of C-invariance [11]. Again we could improve the existing limit $BR(\eta' \to 3\gamma) \leq 1 \times 10^{-4}$ by a big factor. Further details can be found in the MAMI proposal A2/3-05, see group bibliography number -387. The experiment was approved and is now running.

An important upgrade of the TAPS detector was started in 2008. The BaF crystals in the two inner rings of the TAPS forward wall are replaced with a thicker (20 *r.l.* instead of 12 *r.l.*) but four times smaller face area PbWO crystals. At the same time the readout electronics connected to the TAPS two inner rings is replaced with a faster one. The importance of the upgrade became clear after one year of operation of the TAPS detector with the 1.5 GeV MAMI-C beam. The improved TAPS will be faster, allowing higher beam intensity, and it will provide better energy resolution for the very forward angles reducing the leakage of the electromagnetic showers through the back side of the crystals. Both these improvements are very important for the success of the program studying η' decays.

3.2.3 Program IIB-3: Eta Decays

There are several reasons for having a long run dedicated to eta physics. The most important is a precision measurement of the π^0 slope parameter in $\eta \to 3\pi^0$ to search for a non-linear slope [6] as suggested to exist by B. Holstein. Secondly we need a good measurement of the Dalitz plot of the rare decay $\eta \to \pi^0\gamma\gamma$. Also, we would get improved tests of C and CP invariance. Presently the available supply of etas is as follows:

CB at AGS: 28 M,

CB at MAMI: 30 M,

KLOE at Frascati: 78 M.

We believe that the Crystal Ball is the best detector for the above two experiments. We would like to acquire 300 M etas. We are in the process of optimizing the η production by MAMI-C.

3.2.4 Program IIB-4: Measurement of the magnetic dipole moment of the $N(1535)\frac{1}{2}^-$

The static properties of baryons such as the magnetic dipole moment provide important tests of theoretical models for the non-perturbative domain of QCD such as quark models, chiral-soliton models, and lattice QCD calculations. A good example is provided by the magnetic dipole moment, μ, of the $N(1535)\frac{1}{2}^-$ resonance. For many years it was assumed that the $N(1535)\frac{1}{2}^-$ is a simple three-quark state. In the nonrelativistic SU(6) constituent quark model, the lowest-lying negative parity nucleon resonances are $|N^2P_{\frac{1}{2}}\rangle$ and $|N^4P_{\frac{1}{2}}\rangle$. For comparison, the ground-state baryon octet (N, Λ, Σ, Ξ) and decuplet (Δ, Ω^-) have the same S-wave spatial wave function with orbital angualar momentum $L = 0$ and $J = S$. The two lowest-lying negative-parity nucleon resonances observed are the $N(1535)\frac{1}{2}^-$ and $N(1650)\frac{1}{2}^-$. They are obtained as configuration mixtures of the $|N^2P_{\frac{1}{2}}\rangle$ and $|N^4P_{\frac{1}{2}}\rangle$ SU(6) states. Kaiser, Siegel and Weise proposed that the $N(1535)\frac{1}{2}^-$ should be considered as a $|K\Sigma\rangle$ quasi-bound state generated dynamically [12]. The determination of the magnetic dipole moment provides a possible way to experimentally distinguish between these two very different models. In the constituent quark model the μ of qqq baryons is made up of contributions from the quark spin and from orbital momentum, resulting in [13] $\mu[N^+(1535)\frac{1}{2}^-] = 1.89\ \mu_N$, and $\mu[N^0(1535)\frac{1}{2}^-] = 1.28\ \mu_N$.

In the picture of the $N(1535)\frac{1}{2}^{-}$ being a $|K\Sigma\rangle$ meson-baryon quasi-bound state, the magnetic moments are given by the sum of two hyperon magnetic moments:

$$\mu[N^+(1535)] = \tfrac{1}{3}\mu(\Sigma^0) + \tfrac{2}{3}\mu(\Sigma^+) = +1.86\mu_N, \quad (1)$$
$$\mu[N^0(1535)] = \tfrac{2}{3}\mu(\Sigma^-) + \tfrac{1}{3}\mu(\Sigma^0) = -0.56\mu_N. \quad (2)$$

The magnetic moments of the octet baryons are known accurately from spin-precession measurements, as is that of the Ω^- which belongs to a decuplet. All these particles have a long lifetime by strong interaction standards. Kondratyuk and Ponomarov [14] suggested using radiative π^+ scattering to determine $\mu(\Delta^{++})$. The reaction is $\pi^+p \to \Delta^{++} \to \Delta^{++}\gamma' \to \pi^+p\gamma'$. The method has been tried successfully by us [15] resulting in $\mu(\Delta^{++}) = 6.14\pm0.51\mu_N$ [16]. Radiative π^0 photoproduction is also the method we are using for the determination of $\mu(\Delta^+)$ (see sect. IIA). We are now proposing to use this technique for the determination of $\mu(S_{11})$. Phase I is $\gamma p \to N^+(1535)\frac{1}{2}^{-} \to N^+(1535) + \gamma' \to \eta p\gamma'$. The decay $\eta \to 2\gamma$ provides a clear way to detect the η. There is an extensive literature on the meaning of the magnetic dipole moment of an unstable particle [17–20]. In analogy to the mass of a resonance which is characterized by a complex value, so is the μ a complex parameter. Experimentally one must measure the five-fold differential cross section for $\gamma p \to \eta p\gamma'$ and the asymmetry Σ for linearly and the helicity asymmetry, A, for circularly polarized photons. All three parameters ($d^5\sigma$, Σ, and A) are measured simultaneously at MAMI. Because the signature of $\eta \to 2\gamma$ is so characteristic we expect little background from other eta decay modes. The main background is from $\gamma p \to \pi^0\eta p$ which fortunately is not large and this background reaction will be measured separately.

The Low theorem in the soft-photon limit $k' \to 0$ provides a model-independent relation between the cross sections for the $\gamma p \to \gamma'\eta p$ and $\gamma p \to \eta p$ processes based on gauge invariance.

Note that if the η is emitted in the forward direction with respect to the photon direction, the interference between the bremsstrahlung from the initial and final nucleon is destructive. For backward η emission the interference is constructive. More details are given in the MAMI proposal A2/4-05 which has been approved.

3.2.5 Program IIB-5: Other Meson Photoproduction experiments

At the recent CB collaboration meeting, we discussed a diverse array of fascinating hadron physics research. Besides the three advanced programs (IIB 2–4) which are the UCLA top priorities, there were 9 other projects presented in different stages of preparation. They are listed below with indications as to the scope of the physics. We have definite interests in other reactions as well, but we want to concentrate on the top three listed above.

a: Baryon spectroscopy using (neutral) meson photoproduction, specifically of π^0, $2\pi^0$, $3\pi^0$, η, $\pi^0\eta$, ω, η', and γ up to 1.6 GeV. When the upgraded MAMI-C facility and photon tagger went on the air at the beginning of 2007, the Crystal Ball Collaboration got to use the beam first. We have made a survey measuring the photoproduction of various mesons simultaneously. We used a soft, open trigger. This program used 300 hours.

b: Testing χPT and C-invariance in η' decays for 700 hours.

c: Test of χPT , C, and CP invariance in η meson decay for 950 hours.

d: Measuring the magnetic moment of the $N(1535)\frac{1}{2}^-$ using the process $\gamma p \to \eta p \gamma'$ for 1200 hours.

e: π^0, η, and η' production on deuterium for 500 hours. This is a careful study of the use of the deuteron as a neutron target.

f: Medium modification in ω photoproduction on complex nuclei for 1200 hours.

g: Threshold strangeness production for 1000 hours.

h: Total photon absorption in complex nuclei for 100 hours.

i: The GDH sum rule for protons and their partial channels for 1200 hours.

j: The GDH sum rule for neutrons for 800 hours.

k: The partial channels of the GDH sum rule for neutrons for 1200 hours.

l: $\vec{\gamma}\vec{d} \to np\pi^0$ for 600 hours.

m: Studies of $\gamma A \to ppX$ for 200 hours.

Part of the negotiations to bring the Crystal Ball detector to Mainz include a "Carte Blanche" for 2000 hours of beam per year for five years. The above list indicated 9950 hours without simultaneous running. There is clearly a lot of interest in the use of the Crystal Ball in Mainz.

Our program on meson photoproduction involves linearly and circularly polarized photon beams and they exist already at MAMI. We also need a longitudinally and transversely polarized hydrogen target and there is considerable experience at MAMI with such frozen spin targets. A new longitudinally polarized hydrogen target has been constructed by University of Mainz and has been installed and modified for the Crystal Ball.

3.2.6 Program IIB-6: Miscellaneous

Dr. Dan Watts, our collaborator originally from the University of Glasgow but now at the University of Edinburgh, has been awarded a sizable young-investigators award. He has proposed to build a proton polarimeter to be placed in the exit tunnel region of the CB. We are very happy that he was given this award and that it is being used for Crystal Ball physics. This new polarimeter has opened an entirely new area of photoproduction physics. We will now be able to do all double- and triple-polarization measurements needed to make an ambiguity-free determination of the scattering parameters of all two-body photoproduction reactions. We have begun to draw up such a list for π^0 and η photoproduction, and we are extremely excited about the many new possibilities that such a recoil proton polarimeter offers. It is likely to extend our stay at Mainz for some time.

3.3 Program IIC: "Measurements of Cascade Photoproduction with the CLAS Detector"

The interest in Cascade photoproduction lies in the untapped opportunities that spring from the narrowness of the Ξ^* states, which are typically 10–20 MeV. The narrowness of the Ξ^* states makes it possible to discover them in a missing mass plot, such as in the K^+K^+

missing mass in $\gamma p \to K^+K^+\Xi^*$, as well as in the invariant mass distribution of the cascade decay products, such as that of $\Xi^{*0} \to K^-\Sigma^+$.

The narrowness of the Ξ^*'s is related to the square of the number of light (u and d) quarks. Riska has noted [21] that $\Gamma_{N^*,\Delta^*} : \Gamma_{\Lambda^*,\Sigma^*} : \Gamma_{\Xi^*} \approx 3^2 : 2^2 : 1^2 = 9 : 4 : 1$, which is close to the experimental value. The narrowness allows one to determine the spin and parity by a Byers-Fenster [22] or Button-Shafer analysis, rather than a cumbersome partial wave analysis.

$SU(3)$ flavor symmetry provides powerful relations between the different baryon families. In many cases, the breaking of $SU(3)$ flavor symmetry is readily evaluated, as it is dominated by the mass term of the QCD Lagrangian, $\mathcal{L}_m = -\sum m\overline{\psi}\psi$.The QCD Lagrangian can be divided into two parts: $\mathcal{L}_{QCD} = \mathcal{L}_0 + \mathcal{L}_m$. $\mathcal{L}_0$ depends only on the quark and gluon fields, and is therefore identical for all six quarks. This feature is better known as the universality of the strong interaction.

Under $SU(3)$ flavor symmetry, the members of a particular multiplet are expected to have similar properties. This can manifest itself both in the static properties of the particles like the mass (note the similarity of the mass differences $\Delta m[N(1440)\frac{1}{2}^+ - N(939)\frac{1}{2}^+] \approx \Delta m[\Lambda(1600)\frac{1}{2}^+ - \Lambda(1115)\frac{1}{2}^+]$), and in the dynamical properties, as discussed in program IA of this proposal.

The new cascade run, CLAS *g12*, has been finished in 2008, see detailes in 3.3.2.

3.3.1 Analysis of the *g11* data set

The results on the photoproduction of the $\Xi^-(1321)$ and the $\Xi^-(1530)$ from the *g6a* and *g6b* data sets were published recently [23]. Included in the article were the first measurement of the cross section for the process $\gamma p \to K^+K^+\Xi^-(1321)$, and the first observation of the photoproduction of the first excited cascade state, the $\Xi^-(1530)\frac{3}{2}^+$.

Our collaborators at Jefferson Lab have finished calibrating the *g11* data set for $E_\gamma <$ 3.75 GeV. The results to be published from this analysis include the cross section for the photoproduction of the $\Xi^-(1321)$, a study of the production mechanism, and a search for excited cascade states.

To be done are the excitation functions and angular distributions for the photoproduction of both the charged and the neutral cascades for the *g11* run. The neutral cascade can be detected by adding a π^- to the final state, and looking for the process $\gamma p \to K^+K^+\pi^-\Xi^0$. The production mechanism for this process is very complicated, and a large number of events is needed to study it.

3.3.2 Cascade Hyperon production in the *g12* run

The main objective of the CLAS *g12* run was to obtain a large data sample produced at the maximum beam energy presently available at JLab, that is 5.7 GeV. After about 70 days of data taking the run was successfully completed on June 9th 2008 collecting about 26 G triggers. Prior to the run the detector and the trigger system were optimised to provide the best performance at the higher energy part of the photon spectrum. This was achieved by increasing the magnetic field in the CLAS toroid, and by placing the liquid hydrogen target 0.9 m upstream. The main production trigger accepted events with "two–prongs" plus a beam photon with energy above 4.4 GeV, or "three–prong" for all beam energies. A prong is a coincidence between a start counter and corresponding blocks of the wire chamber. This trigger configuration was successfully tested during the *g11* experiment.

Though the main purpose of the run is to search for exotic baryon states and to study photoproduction of cascades, an important addition to the value of the experiment was made by filling the CLAS gas Cerenkov counter. The Cerenkov counter permits separation between π^+/π^- and e^+/e^- allowing to study electomagnetic decays of η, η', ω and ϕ, such as $\eta \to e^+e^-$, with the *g12* data.

The analysis of cascade photoproduction from the *g12* run is the thesis topic of UCLA graduate student John Goetz. The "cooking" of the new data was completed in early 2010. There are some unresolved issues mainly concerning Monte Carlo production models, energy corrections, *etc*. Currently John is analyzing the data aiming to extract the total and the differential cross sections for the photoproduction of the cascade ground and the first excited state as well as the upper limits for the production of the higher excited and forbidden cascade states. This is scheduled to be done by the end of this year. A typical example of our data is shown in Figs. 7.1, 7.2, 7.3 and on the cover of this report.

3.4 Program IID: "New Initiatives for Investigating the Production and Decay of the 33 Missing Ξ Resonances"

The program on new studies of the Cascades is divided into two parts. The first part is planning for using Hall B after the proposed upgrade to 12 GeV. The second part concerns the possibilities of using the Hall D setup for cascade research. Finally, we draw attention to a workshop we have organized in cooperation with Jefferson Lab, entitled "Cascade Physics: A New Window on Baryon Spectroscopy".

3.4.1 Plans for Cascade physics in Hall B at 12 GeV

The proposed upgrade of Jefferson Lab to 12 GeV offers many new opportunities. The recent DOE level-CD1 approval of the upgrade plan is a strong statement that Jefferson Lab is going to play a major role in nuclear physics for the forseeable future. For this reason, JLab is and will likely remain the most suitable laboratory to pursue a program of cascade physics.

Many changes are envisioned in Hall B which will greatly enhance our ability to look for cascades. The new detector will consist of a cylindrically symmetric central detector with a solenoidal magnetic field, and a forward detector divided into six sectors based on the original CLAS geometry.

The cascade physics program is effected most by the addition of a vertex detector in the central detector. This allows the detection of detached vertices due to the relatively long lifetime of the Ξ and its decay products. For the decay chain $\Xi^- \to \pi^-\Lambda \to \pi^-\pi^-p$, there will be two such vertices, further aiding event selection.

A new feature of Hall B will be the addition of a "low-Q^2" tagger in lieu of the existing photon tagger. Instead of a traditional tagged-photon beam, CLAS will use a "post-tagging" scheme in which an electron beam is incident on the target, and detected at small angles ($< 1.2°$) after the target. This allows the use of near-real photons at energies up to the endpoint energy of JLab.

3.4.2 Possibilities for Cascade physics in Hall D

A new 4π detector at Jefferson Lab opens a wide range of options for cascade physics. The Hall D detector has different capabilities than the CLAS detector.

In contrast to Hall B, the Hall D plan calls for a real photon tagger, using coherent bremsstrahlung to get linearly polarized photons at energies in the photon energy range $8 < E_\gamma < 9$ GeV. This will allow the production of cascades with masses up to 3.2 GeV.

The detector package in Hall D uses a solenoidal magnet, inside of which is a set of cylindrical and planar drift chambers for charged-particle tracking, and a cylindrical barrel calorimeter for energy and TOF measurements. In the forward direction is a Čerenkov detector and a lead-glass calorimeter.

We are currently evaluating the possibility of using the Hall D detector for studies of cascade photoproduction. As the planned Hall D detector is much closer to a true 4π detector than CLAS, it may well prove superior for cascade physics.

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4 Publications

4.1 Publications of the Crystal Ball at AGS

The number in the first column refers to the last three digits of the Group Bibliography designation (see page 22).

Number	Reference	Description
-275	Phys. Rev. Lett. **84**, 4802 (2000)	$\eta \not\to 4\pi^0$; CP
-279	MENU 1999, πN Newsletter **15**, 25 (1999)	$\pi^- p \to \pi^0 n$
-281	Acta Phys. Pol. **B31**, 2239 (2000)	$\pi^- p \to \eta n$
-284	NIM **A462**, 463 (2001)	Neutron detection eff.
-285	Acta Phys. Pol. **B31**, 2669 (2000)	Prelim. results
-287	Phys. Rev. Lett. **85**, 5539, (2000)	$\pi^0\pi^0$ in medium
-288	Chiral Dyn. 2000, World Sci. 324 (2001)	Test χPT
-291	Chiral Dyn. 2000, World Sci. 253 (2001)	Goldstone bosons
-292	Phys. Rev. Lett. **87**, 192001 (2001)	$\eta \to 3\pi^0$ slope
-293	NSTAR 2001, World Sci. 427 (2001)	Flavor symmetry
-294	Phys. Rev. C **64**, 055205 (2001)	$K^- p \to \eta\Lambda$
-299	Phys. Rev. Lett. **88**, 231101 (2001)	$\Lambda(1670)\frac{1}{2}^-$
-300	Hadron 2001 AIP Conf. Pr. **619**, 693 (2002)	Prelim. results
-301	NSTAR 2001 World Sci. 279 (2001)	Prelim. results
-305	NANP 2001 Phys. Atom. Nucl. **65**, 2238 (2002)	$\eta \to \pi^0\gamma\gamma$
-307	Chiral Fluct Proc. Orsay 33 (2001)	$\pi^0\pi^0$ in media
-308	Chiral Fluct Proc. Orsay 275 (2001)	Where is σ-meson?
-309	Physica Scripta **T99**, 114 (2002)	η decays
-316	Phys. Rev. C **66**, 0552002 (2002)	Media Modif.
-319	2nd GDH, World Sci. 223 (2002)	Prelim. results
-320	Phys. Rev. C **67**, 068201 (2003)	$\pi^- p \to 3\pi^0 n$
-321	Phys. Rev. C **68**, 015206 (2003)	$K^- p \to 3\pi^0\Lambda$
-337	Phys. Rev. C **69**, 045202 (2004)	$\pi^- p \to \pi^0\pi^0 n$
-338	Phys. Rev. C **69**, 042202 (2004)	$K^- p \to \pi^0\pi^0\Lambda$
-339	Phys. Rev. Lett. **91**, 102301 (2003)	$\pi^- p \to \pi^0\pi^0 n$
-340	2nd Conf. NPP; Fizika **B13**, 593 (2004)	Review
-341	2nd Conf. NPP; Fizika **B13**, 189 (2004)	Review
-342	Prog. Th. Phys. Sup. **149**, 94 (2003)	Medium Modif.
-344	NSTAR 2002, World Sci. **B1** (2003)	Prelim. results
-346	Phys. Lett. **B588**, 29 (2004)	Does $\Sigma(1580)\frac{3}{2}^-$ exist?
-349	Phys. Rev. C **69**, 055206 (2004)	$\pi^- p \to \pi^0 n$
-350	Phys. Rev. C **70**, 034605 (2004)	$K^- p \to \pi^0\pi^0\Sigma^0$
-351	Phys. Rev. C **70**, 035204 (2004)	$\pi^- p \to \gamma n$
-353	Phys. Atom. Nucl. **66**, 110 (2003)	$\pi^- p \to \eta n$
-364	MENU 2004, Int. J. Mod. Ph. **A20**, 1575	Review
-365	MENU 2004, Int. J. Mod. Ph. **A20**, 1822	$\pi^- p \to \pi^0 n$
-366	Erice Sum. Sch. Prog. pN Ph **55**, 153 (2005)	Review
-368	Phys. Rev. Lett. **94**, 041601 (2005)	Test of C
-369	Phys. Rev. C. **72**, 025201 (2005)	$\eta \to \pi^0\gamma\gamma$
-370	Phys. Rev. C. **72**, 015203 (2005)	$\pi p \to \eta n$

Number	Reference	Description
-374	Phys. Rev. C. **72**, 015205 (2005)	$\pi^- p \to \pi^0 n$
-375	Phys. Rev. C. **72**, 035212 (2005)	$\eta \not\to 3\gamma$
-377	MENU 2004, IJ. Mod Phys. **A20**, 1814 (2005)	$\pi^- p \to \pi^0 n$
-378	N^* 2005 World Sci. **379**, (2005),	$2\pi^0$
-379	Fizika B **13**, 405 (2004)	$\pi^- p \to \pi^0 n$
-382	N^* 2005 World Sci. **286**, (2005)	CB@M
-393	MENU 2007, econf/C070910, (2007)	$K - n \to \pi^0\pi^0\Sigma$
-394	MENU 2007, econf/C070910, (2007)	$\eta \to \pi^0\gamma\gamma$
-397	Phys. Rev. C. **78**, 015206 (2008)	$\eta \to \pi^0\gamma\gamma$
-405	Phys. Rev. C. **80**, 025204 (2009)	$K^-p \to \pi^0\Lambda$, $K^-p \to \bar{K}^0 n$ $K^-p \to \pi^0\Sigma^0$
-408	Phys. Rev. C. **80**, 055207 (2009)	$\pi^-\ p \to \pi^0\ n$
-409	Phys. Rev. C. **82**, 015201 (2010)	$\gamma\Lambda$ and $\gamma\Sigma^0$

4.2 Other Publications

The number in the first column refers to the last three digits of the Group Bibliography designation (see below).

Number	Reference	Description
-280	Phys. Rev. D **63**, 052001 (2001)	charge sym. viol.
-303	MENU 2001, πN Newsletter **16**, 9 (2002)	Results
-304	Phys. Rev. D **65**, 112002 (2002)	$\mu^+ \not\to e^+\gamma$
-306	MENU 2001, πN Newslett. **16**, 289	Review
-310	Phys. Rev. C **66**, 054006 (2002)	charge sym.
-312	Baryons 2002, World Sci. 498 (2003)	Ξ prod.
-345	HYP03 Nucl. Phys. A 754, 272 (2005)	Ξ phys.
-354	Physica Scripta **T104**, 29 (2003)	WASA
-355	Physica Scripta **T104**, 98 (2003)	part. id.
-362	Phys. Rev. C **71**, 058201 (2005)	$\gamma p \to \Xi^- K^+ K^+$
-367	MENU 2004 IJ Mod Phys A	Review
-380	CIPANP 2006	Cascade
-399	Phys. Rev. C **76**, 025208 (2007)	$\gamma p \to\ K^+K^+(X)$ and $\gamma p \to\ K^+K^+\pi^-(X)$

4.3 Group Bibliography

UCLA-10-P25-350 *$K^-p \to \pi^0\pi^0\Sigma^0$ at p_{K^-} = 514–750 MeV/c and comparison with other $\pi^0\pi^0$ production.* S. Prakhov, B.M.K. Nefkens, C.E. Allgower, M.E. Sadler, V. Bekrenev, W.J. Briscoe, M. Clajus, J.R. Comfort, K. Craig, D. Grosnick, D. Isenhower, N. Knecht, D.D. Koetke, A. Kulbardis, N. Kozlenko, S. Kruglov, G. Lolos, V. Lopatin, D.M. Manley, R. Manweiler, A. Marušić, S. McDonald, J. Olmsted, Z. Papandreou, D. Peaslee, N. Phaisangittisakul, J.W. Price, A. Ramirez, M. Sadler, A. Shafi, H. Spinka, S. Stanislaus, A.B. Starostin, H.M. Staudenmaier, I. Strakovsky, I. Supek, and W.B. Tippens (Crystal Ball Collaboration), Phys. Rev. C **70**, 034605 (2004).

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Sadler, V. Bekrenev, W.J. Briscoe, M. Clajus, J.R. Comfort, K. Craig, D. Grosnick, D. Isenhower, N. Knecht, D.D. Koetke, A. Kulbardis, N. Kozlenko, S. Kruglov, G. Lolos, V. Lopatin, D.M. Manley, R. Manweiler, A. Marušić, S. McDonald, J. Olmsted, Z. Papandreou, D. Peaslee, N. Phaisangittisakul, J.W. Price, A. Ramirez, M. Sadler, H. Spinka, S. Stanislaus, A.B. Starostin, H.M. Staudenmaier, I. Strakovsky, I. Supek, and W.B. Tippens (Crystal Ball Collaboration), Phys. Rev. C **70**, 035204 (2004).

UCLA-10-P25-352 *Future experiments at MAMI with the Crystal Ball Detector*, A. Starostin, in Proceedings of the 4th International Conference on Perspectives in Hadronic Physics, Trieste, Italy, 12-16 May 2003, Eur. Phys. J. A**19**, Suppl. 1, 279 (2004).

UCLA-10-P25-353 *Measurement of the Total and Differential Cross Sections for the Reaction $\pi^- p \to \eta n$ with the Crystal Ball Detector*, N.G. Kozlenko, V.V. Abaev, V.S. Bekrenev, S.P. Kruglov, A.A. Koulbardis, I.V. Lopatin, A.B. Starostin, B. Draper, S. Hayden, J. Huddleston, D. Isenhower, C. Robinson, M. Sadler, C. Allgower, R. Cadman, H. Spinka, J. Comfort, K. Craig, A. Ramirez, T. Kycia, M. Clajus, A. Marušić, S. McDonald, B.M.K. Nefkens, N. Phaisangittisakul, S. Prakhov, J.W. Price, W.B. Tippens, J. Peterson, W.J. Briscoe A. Shafi, I.I. Strakovsky, H. Staudenmaier, D.M. Manley, J. Holmsted, D. Peaslee, N. knecht, G. Lolos, Z. Papandreou, I Supek, I. Slaus, A. Gibson, D. Grosnic, D. Koetke, R. Manweiler, and S. Stanislaus (Crystal Ball Collaboration), Phys. Atom. Nucl. **66**, 110 (2003).

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UCLA-10-P25-355 *Report on the Charged Decay Products Identification Possibilities in WASA*, M. Jacewicz, B.M.K. Nefkens, ... A. Starostin *et al.,* Physica Scripta Vol. T**104**, 98-100, (2003).

UCLA-10-P25-356 *Complete Angular Distribution Measurements of Two-Body Deuteron Photodisintegration between 0.5 and 3 GeV*, M. Mirazita, ... J.W. Price *et al.* (CLAS Collaboration), Phys. Rev. C **70**, 014005 (2004).

UCLA-10-P25-357 *Measurement of the Polarized Structure Function $\sigma_{LT'}$ for $p(\vec{e}, e'\pi^+)n$ in the $\Delta(1232)$ Resonance Region*, K. Joo, ... J.W. Price *et al.* (CLAS Collaboration), Phys. Rev. C **70**, 042201(R) (2004).

UCLA-10-P25-358 *Proton source Size Measurements in the $eA \to e'ppX$ Reaction*, A.V. Stavinsky, ... J.W. Price *et al.* (CLAS Collaboration), Phys. Rev. Lett. **93**, 192301 (2004).

UCLA-10-P25-359 *Onset of Asymptotic Scaling in Deuteron Photodisintegration*, P. Rossi, ... J.W. Price *et al.* (CLAS Collaboration), Phys. Rev. Lett. **94**, 012301 (2005).

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UCLA-10-P25-361 *Survey of $A_{LT'}$ asymmetries in semi-exclusive electron scattering on ^4He and ^{12}C*, D. Protopopescu, ... J.W. Price *et al.* (CLAS Collaboration), Nucl. Phys. **A748**, 357 (2005).

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UCLA-10-P25-364 *Highlights of Crystal Ball Physics* B.M.K. Nefkens, in *Proceedings of the 10th International Symposium on Meson-Nucleon Physics and the Structure of the Nucleon* (MENU2004), Beijing, China, 29 August–4 September 2004, eds. H.-C. Chiang and B.-S. Zou, Int. J. Mod. Phys. **A20**, 1575 (2005).

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UCLA-10-P25-369 *Measurement of the Branching Ratio for* $\eta \to \pi^0\gamma\gamma$ *Decay*, S. Prakhov, B.M.K. Nefkens, C.E. Allgower, V. Bekrenev, W.J. Briscoe, M. Clajus, J.R. Comfort, K. Craig, D. Grosnick, G.M. Huber, D. Isenhower, N. Knecht, D.D. Koetke, A. Kulbardis, N. Kozlenko, S. Kruglov, G. Lolos, I. Lopatin, D.M. Manley, R. Manweiler, A. Marušić, S. McDonald, J. Olmsted, Z. Papandreou, D. Peaslee, N. Phaisangittisakul, J.W. Price, A. Ramirez, M. Sadler, A. Shafi, H. Spinka, T.D S. Stanislaus, A. Starostin, H.M. Staudenmaier, I. Supek, and W.B. Tippens (Crystal Ball Collaboration), Phys. Rev. C **72**, 025201 (2005).

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UCLA-10-P25-372 *Radiative decays of the* $\Sigma^0(1385)$ *and* $\Lambda(1520)$ *hyperons*, S. Taylor, ... J.W. Price *et al.* (CLAS Collaboration), Phys. Rev. C **71**, 054609 (2005).

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UCLA-10-P25-407 *2009 Annual Progress Report to U.S. Department of Energy, UCLA Intermediate Energy Nuclear and Particle Physics Research Group*, B.M.K. Nefkens (Principal Investigator) *et al.* (2009).

UCLA-10-P25-408 *Differential Cross Sections of the Charge-Exchange Reaction* $\pi^- p \rightarrow \pi^0 n$ *in the Momentum Range from 103 to 178 MeV/c*, D. Mekterovic, I. Supek, B.M.K. Nefkens, A. Starostin, *et al.*, (Crystal Ball at AGS Collaboration) Phys. Rev. C **80**, 055207 (2009).

UCLA-10-P25-409 *Measurement of* K^-p *Radiative Capture to* $\gamma\Lambda$ *and* $\gamma\Sigma^0$ *for* P_{K^-} *between 514 and 750 MeV/c*, S. Prakhov, P. Vancraeyveld, N. Phaisangittisakul, B.M.K. Nefkens, *et al.*, (Crystal Ball at AGS Collaboration) Phys. Rev. C **82**, 015201 (2010).

UCLA-10-P25-410 *Radiative* π^0 *photoproduction on protons in the* $\Delta^+(1232)$ *region*, S. Schumann *et al.*, (Crystal Ball at MAMI Collaboration) Eur. Phys. J. A **43**, 269 (2010).

UCLA-10-P25-411 *Study of the* $\gamma p \rightarrow \eta p$ *reaction with the Crystal Ball detector at the Mainz Microtron(MAMI-C)*, E. F. McNicoll, S. Prakhov, I.I. Strakovsky, *et al.* (Crystal Ball Collaboration at MAMI), Phys. Rev. C **82**, 035208 (2010).

UCLA-10-P25-412 *2010 Annual Progress Report to U.S. Department of Energy, UCLA Intermediate Energy Nuclear and Particle Physics Research Group*, B.M.K. Nefkens (Principal Investigator) *et al.* (2010).

UCLA-10-P25-413 *First measurement of the circular beam asymmetry in the* $\gamma p \rightarrow \pi^0\eta p$ *reaction*, V.L. Kashevarov *et al.*, (Crystal Ball at MAMI Collaboration) Phys. Lett. **B693**, 551 (2010).

UCLA-10-P25-414 *Final Report to U.S. Department of Energy, UCLA Intermediate Energy Nuclear and Particle Physics Research Group*, B.M.K. Nefkens (Principal Investigator) *et al.* (2011).

5 Principal Collaborators

The principal collaboration for the UCLA Group is the Crystal Ball collaboration, originally at the AGS at Brookhaven National Laboratory and now at the Mainz Microtron in Germany. At JLab we use the CLAS facility.

5.1 The CB@AGS Collaboration

Institution	Members
UCLA	A. Starostin, B.M.K. Nefkens, J.W. Price, S.Prakhov, M. Clajus, A. Marusic, S. McDonald, N. Phaisangittisakul, W.B. Tippens
ACU	D. Isenhower, M. Sadler
ANL	C.E. Allgower, H. Spinka
ASU	J. Comfort, K. Craig, A.F. Ramirez
GWU	W.J. Briscoe, A. Shafi
Karlsruhe	H.M. Staudenmaier
Kent State	D.M. Manley, J.Olmsted
Maryland	D. Peaslee
PNPI	V. Bekrenev, A. Koulbardis, N. Kozlenko, S. Kruglov, I. Lopatin
Regina	N. Knecht, G. Lolos, Z. Papandreou
Valparaiso	D. Grosnick, D. Koetke, R. Manweiler, T.D.S. Stanislaus
Zagreb	I. Supek

5.2 The CB@MAMI Collaboration in early 2010

Institution	Lead Members	# Researchers/Postdocs		# Grad. Students	
		MAMI-B	MAMI-C	MAMI-B	MAMI-C
UCLA	B.M.K. Nefkens, A. Starostin	3	2	1	1(?)
Mainz Uni.	H.J. Arends, A. Denig M. Ostrick, A. Thomas	6	5	5	0
Basel Uni.	B. Krusche	1	3	2	3
Bonn Uni.	R. Beck	-	-	3	-
Catholic Uni.	D. Sober	-	-	-	-
Edinburgh Uni.	D. Watts	1	1	1	2
GWU	W.J. Briscoe	-	-	-	1
Giessen Uni.	V. Metag	2	2	2	1
Glasgow Uni.	J. Annand, G. Rosner	4	3	2	3
INFN Pavia	P. Pedroni	2	1	-	-
INR, Moscow	V. Lisin	3	3	-	-
Kent State Uni.	M. Manley	-	-	-	1
LPI, Moscow	L. Filkov	3	3	-	-
Mt. Allison Uni.	D. Hornidge	-	-	-	-
PNPI, Gatchina	S. Kruglov	2	2	-	-
Tübingen Uni.	P. Grabmayr	-	-	-	-
Zagreb Uni.	I. Supek	1	1	2	2

6 Biographical Sketches

Vita

Bernard M. K. Nefkens,

Professor of Physics, UCLA, Principal Investigator

Fellow of the American Physcial Society; Corresponding Member Royal Netherlands Academy of Arts and Sciences; Member New York Academy of Sciences.

Physics Department UCLA: Professor 1974–present; Assoc. Prof. 1968–1974; Assist. Prof. 1966–1968.

Univ. of Illinois at Urbana: Research Assist. Prof. 1962–1966.

Purdue University: Research Associate 1959–1962.

Doctor of Science, Univ. Of Nijmegen, the Netherlands, 1967; Doctorandus in Physics, Univ. of Utrecht, the Netherlands, 1959.

Saclay Visiting Scientist, 1988–1989 and 1978–1979; CERN Visiting Scientist, 1972–1973.

Fulbright Travel Grant, 1959; F.O.M. (Dutch NSF) Fellowship, 1956–1959.

Guest physicist appointments at Argonne, BNL, CERN, LBL and LANL.

Co-founder and Co-editor of the Pion-Nucleon Newsletter.

Co-founder of MENU (International Conference on Meson and Nucleon Physics).

Founder and Chair of the New Crystal Ball Collaboration. (12 Institutions) at BNL 1995–2002; Co-Founder in 2002 and Co-PI of the Crystal Ball at MAMI (16 Institutions).

Research Interests: basic symmetries: C, CP, T, Isospin, G-Parity, chirality, flavor. Non-perturbative QCD, confinement, origin of mass, production, interaction and decays of η η', Ξ physics.

Publications

Over 250 refereed research publications, review articles, and conference presentations.

1) Crystal Ball Results, see Sect. 4.1.

2) Others (non-Crystal-ball), see Sect. 4.2.

3) Some of my favorite papers; the numbers refer to the last three digits of the Group Bibliography designation (see page 22):

   Highlights of Crystal Ball Physics [-366]: $K^- p \to \pi^0\pi^0\Lambda$ [-338], $K^- p \to \pi^0\pi^0\Sigma^0$ [-350], $\pi^- p \to \pi^0\pi^0 n$ [-339], and $\gamma p \to \pi^0\pi^0 p$ [-385]

   New tests of C, CP invariance and χPT in η decays [-309]; The Photoproduction of the Cascade Hyperon [-312]

   Review of Meson-Nucleon Physics [-306]; Flavor Symmetry of the Strong Interaction [-293]; recent MAMI results [-404], [-410], [-411].

Prakhov, Serguei N., PhD

Staff Research Associate, Department of Physics and Astronomy, UCLA

Education

Ph.D.	Joint Institute for Nuclear Research, Russia	1999
	Dissertation: *Test of OZI rule in annihilation of antiprotons at rest*	
Master of Science	Moscow Engineer Physical Institute, Russia	1985

Research Positions

Staff Research Associate	University of California, Los Angeles	9/2006 – present
Postgraduate Researcher	University of California, Los Angeles	9/2000 – 8/2006
Visiting Scholar	University of California, Los Angeles	8/1999 – 8/2000
Research Scientist	JINR, Dubna, Russia	Ph.D. – 8/1999

Recent Talks and Conference Presentations

1. S. Prakhov, *Measurement of the* $\gamma p \to \pi^0 \gamma p$ *with the CB at MAMI-C*, CB-MAMI collaboration meeting, Mainz, Germany, March 8-10, 2010.

2. S. Prakhov, *Study of the* $\eta \to 3\pi^0$ *decay with the Crystal Ball at MAMI-C*, Workshop on Chiral Dynamics 2009, Bern, Switzerland, July 6-10, 2009.

3. S. Prakhov, *Study of the* $\eta' \to \pi^0\pi^0\eta$ *decay with the Crystal Ball at MAMI-C*, PrimeNet meeting, Frascati, Italy, April 8, 2009.

4. S. Prakhov, *Study of the* $\eta \to 3\pi^0$ *decay with the Crystal Ball at MAMI-C*, PrimeNet meeting, Frascati, Italy, April 8, 2009.

Selected Publications

1. E. F. McNicoll, S. Prakhov *et al.*, *Study of the* $\gamma p \to \eta p$ *reaction with the Crystal Ball detector at the Mainz Microtron (MAMI-C)*, Phys. Rev. C **82** (2010) 035208.

2. S. Prakhov *et al.*, *Measurement of* $K^- p$ *radiative capture to* $\gamma\Lambda$ *and* $\gamma\Sigma^0$ *for* p_{K^-} *between 514 and 750 MeV/c*, Phys. Rev. C **82** (2010) 015201.

3. S. Prakhov *et al.*, *Measurement of* $\pi^0\Lambda$, $\bar{K}^0 n$, *and* $\pi^0\Sigma^0$ *production in* $K^- p$ *interactions for* p_{K^-} *between 514 and 750 MeV/c*, Phys. Rev. C **80** (2009) 025204.

4. S. Prakhov *et al.*, *Measurement of the slope parameter* α *for the* $\eta \to 3\pi^0$ *decay with the Crystal Ball detector at the Mainz Microtron*, Phys. Rev. C **79** (2009) 035204.

5. S. Prakhov *et al.*, *Measurement of the invariant-mass spectrum for the two photons from the* $\eta \to \pi^0\gamma\gamma$ *decay*, Phys. Rev. C **78** (2008) 015206.

6. S. Prakhov *et al.*, *Measurement of* $\pi^- p \to \eta n$ *from threshold to* $p_{\pi^-} = 747$ *MeV/c*, Phys. Rev. C **72** (2005) 015203.

7. S. Prakhov *et al.*, $K^- p \to \pi^0\pi^0\Sigma^0$ *at* $p_{K^-} = 514 - 750$ *MeV/c and comparison with other* $\pi^0\pi^0$ *production*, Phys. Rev. C **70** (2004) 034605

8. S. Prakhov *et al.*, *Measurement of* $\pi^- p \to \pi^0\pi^0 n$ *from threshold to* $p_{\pi^-} = 750$ *MeV/c*, Phys. Rev. C **69** (2004) 045202

9. S. Prakhov *et al.*, *Reaction* $K^- p \to \pi^0\pi^0\Lambda$ *from* p_{K^-} *=514 to 750 MeV/c*, Phys. Rev. C **69** (2004) 042202.

Starostin, Aleksandr B., PhD

Research Assistant, Department of Physics and Astronomy, UCLA

Education

Ph.D.	Petersburg Nuclear Physics Institute, Russia Dissertation: "π^0-pair Production on Nuclei"	2001
Master of Science	Petersburg Technical University, Russia	1992

Research Positions

Research Assistant	University of California, Los Angeles	2006 – present
Staff Research Associate	University of California, Los Angeles	1998 – 2006
Senior Scientist	PNPI, Gatchina, Russia	1992 – 1998

Awards

Russian Federation State Stipend, Fellow 1997-1998

Recent Talks and Seminars

1. *Spectroscopy of light baryons: from N^* to Ξ^**, Seminar at The Temple University, Philadelphia, PA, Apr. 2010.
2. *Status of light baryon spectroscopy*, Seminar at College of William and Marry, Williamsburg, VA, Mar, 2010.
3. *Current and future experiments with the Crystal Ball*, Seminar at Petersburg Nuclear Physics Inst., Gatchina, Russia, Nov. 2009.
4. *Spectroscopy of light baryons: from N^* to Ξ^**, Hall-B Physics Seminar, JLab, VA, Oct. 2009.

Recent Publications

1. E. F. McNicoll *et al.*, *Study of the $\gamma p \to \eta p$ reaction with the Crystal Ball detector at MAMI-C*, Phys. Rev. C **82**, 035208 (2010).
2. S. Schumann *et al.*, *Radiative π^0 photoproduction on protons in the $\Delta^+(1232)$ region*, Eur. Phys. J. A **43** (2010) 269.
3. S. Prakhov *et al.*, *Measurement of K^-p radiative capture to $\gamma\Lambda$ and $\gamma\Sigma^0$ for p_{K^-} between 514 and 750 MeV/c*, Phys. Rev. C **82** (2010) 015201.
4. D. Mekterovic *et al.*, *Diff, cross sections of $\pi^-p \to \pi^0 n$ in the momentum range from 103 to 178 MeV/c*, Phys. Rev. C **80** (2009) 055207.
5. A. Starostin *et al.*, *Search for the charge-conjugation-forbidden decay $\omega \to \eta\pi^0$*, Phys. Rev. C **79** (2009) 065201.
6. A. Starostin, *Hadron physics with the Crystal Ball at MAMI*, Int. J. Mod. Phys. A **24** (2009) 287.
7. C. M. Tarbert *et al.*, *Incoherent Neutral Pion Photoproduction on ^{12}C*, Phys. Rev. Lett. **100** (2008) 132301.

7 Student Tracking Information

7.1 Students from CB@AGS Collaboration

The eight graduate students listed in the table below from various universities obtained the material for their Ph.D. theses from the experiments done with the Crystal Ball at the AGS. Without our DOE grant as the PI on the Crystal Ball, this would not have been possible. Several students spent extended time at UCLA in the analysis and writing phases of their theses.

Student Name	Year	Adviser Name	Institution
A. Starostin	2001	S. Kruglov [with B. Nefkens(UCLA)]	Gatchina
N. Phaisangittisakul	2001	B. Nefkens	UCLA
K. Craig	2001	J. Comfort	Arizona State
J. Olmsted	2001	M. Manley	Kent State
A. Shafi	2003	W. Briscoe	GWU
N. Kozlenko	2010	S. Kruglov	Gatchina
N. Knecht	2002	G. Lolos	Regina
T. Ramirez	2004	J. Comfort	Arizona State
D. Mekterovic	2010	I. Supek	Zagreb

7.2 Students from CB@MAMI-B Collaboration

The Crystal Ball at MAMI-B has 10 Ph.D. graduates, listed below, including three women who are got their degree on the data that were taken on the inaugural "Long Run" in 2004–2005. Without our DOE grant, the Crystal Ball would not be in Mainz, and most of the students would be elsewhere, perhaps in industry. They joined in 2003 or 2004.

Student's Name	Year	Adviser Name	Institution
Jason Brudvik	2007	B.M.K. Nefkens	UCLA
Benedicte Boillat	2008	B. Krusche	Basel Uni.
Evangeline Downie	2007	J. Annand	Glasgow Uni.
Mauricio Fabregate	2007	A. Thomas	Mainz Uni.
Ralf Gregor	2007	V. Metag	Giessen Uni.
Dirk Krambrich	2007	R. Beck	Mainz Uni.
Stefan Lugert	2007	V. Metag	Giessen Uni.
Sven Schumann	2007	R. Beck	Mainz Uni.
Claire Tarbert	2007	D. Watts	Edinburgh Uni.
Fabien Zehr	2008	B. Krusche	Basel Uni.

7.3 Students from CB@MAMI-C Collaboration

Below are listed students for advanced degree from late MAMI-B and early MAMI-C Crystal Ball experiments including five women. Data were already obtained for part of the theses during the 2007 MAMI-C run. More data were collected in 2008-2009.

Student's Name	Institution	Adviser Name	Subject of the Thesis
Richard Codling	Glasgow	J. Annand	$\mu(\Delta^+(1232))$
Eilidh McNicoll	Glasgow	J. Annand	$\gamma p \to \eta p$
Jamie Robinson	Glasgow	J. Annand	
D. Howdle	Glasgow	J. Annand	
Marc Unverzagt	Bonn	R. Beck	π^0 slope of $\eta \to 3\pi^0$
Alexander Nikolaev	Bonn	R. Beck	η mass
Patricia Aguar Bartolome	Mainz	A. Thomas	
Fernando Soler	Mainz	M. Ostrick	Pair Spectrometer
Leyla Karolin Akasoy[1]	Mainz	M. Ostrick	End-Point Tagger
Tom Jude	Edinburgh	D. Watts	
Mark Sikora	Edinburgh	D. Watts	
Berhan Taddesse Demissie	GWU	B. Briscoe	photoproduction off the frozen-spin tgt.
Therese Challand	Basel	B. Krusche	η production off the neutron
Francis Phéron	Basel	B. Krusche	η-mesic Nuclei
Dominik Werthmüller	Basel	B. Krusche	η' Mesons off Deuterium
Michaela Thiel	V. Metag	Giessen	medium modification
Henning Berghuser	V. Metag	Giessen	

7.4 UCLA Student Tracking

Name	Entered Grad. School	Joined Group	Year Ph.D.	Mentor
J. Brudvik[2]	2000	2002	recv'd 2007	Prof. B. Nefkens
J. Goetz	2004	2004	2010	Prof. B. Nefkens

[1]Diploma student
[2]Stint Fellow 2002–2003

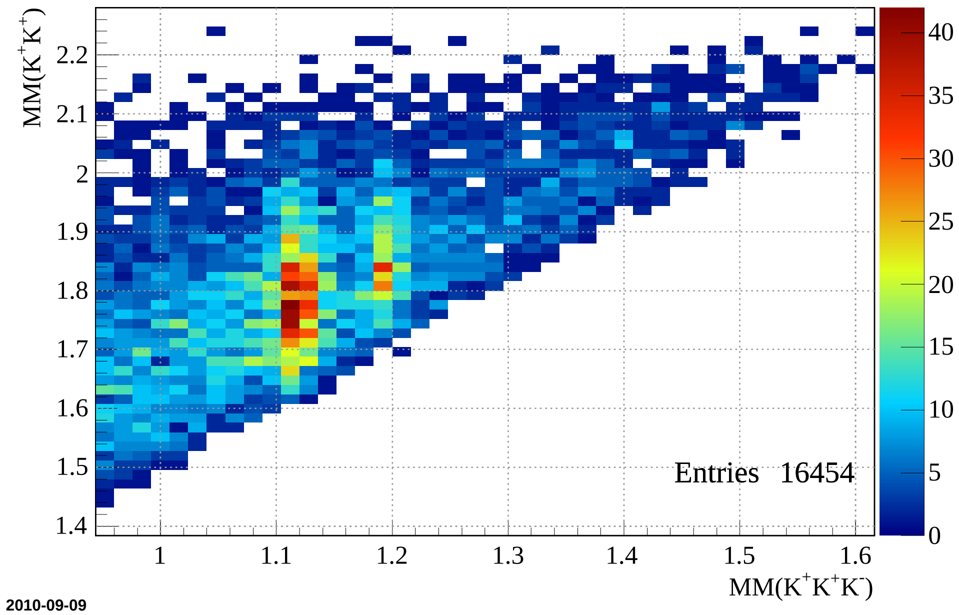

Figure 7.1: Missing mass off K^+K^+ vs. missing mass off $K^+K^+K^-$ in the reaction $\gamma p \to K^+K^+K^-X^0$ from the *g12* experiment. The two vertical bands at 1.1 and 1.2 GeV correspond to the $\Lambda(1115)$ and $\Sigma^0(1189)$ respectively.

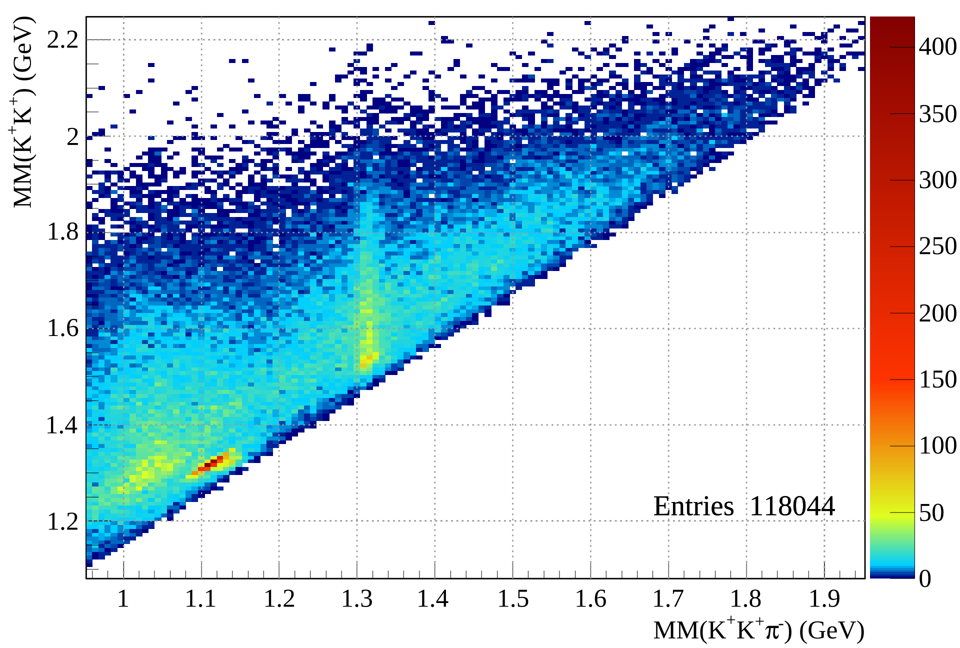

Figure 7.2: Missing mass off K^+K^+ vs. missing mass off $K^+K^+\pi^-$ in the reaction $\gamma p \to K^+K^+\pi^-X^0$ from the *g12* experiment. The vertical band at 1.3 GeV corresponds to the neutral ground state $\Xi^0(1315)$, the events at 1.5 GeV on the *y*-axis of which are from the decay of the $\Xi^{*-}(1530)$. The two enhancements at $MM(K^+K^+) = 1.3$ GeV correspond the ground state $\Xi^-(1320)$. The pion in these events came from either the ground state cascade decay ($\Xi^- \to \Lambda\pi^-$) or the subsequent Λ-decay ($\Lambda \to p\pi^-$).

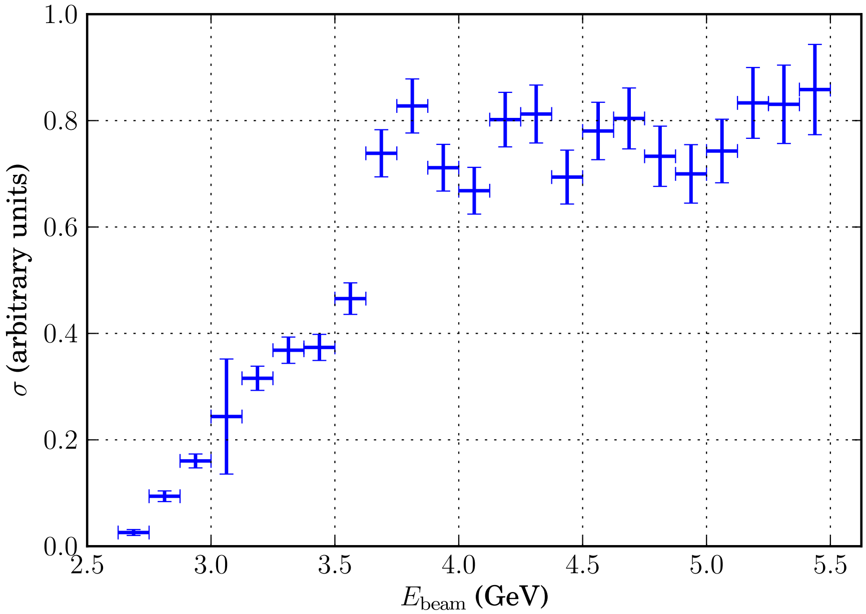

Figure 7.3: Total cross section for the photoproduction of $\Xi^-(1320)$ from the *g12* experiment. Acceptance corrections, while included in this plot, have yet to be finalized and so arbitrary units are used.