Exp.-Nr. A2/2-03
Eingang:
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# Mainz Microtron MAMI

**Collaboration A2:** "Real Photon Experiments"
Spokesperson: R. Beck

**Proposal for an Experiment**

## Measurement of the $2\pi^0$ Photoproduction off the Proton at Threshold and in the second Resonance Region

**Collaborators:**

Crystal Ball @ MAMI and TAPS collaboration

**Spokespersons for Experiment:** M. Kotulla - Basel, P. Pedroni - Pavia

**Abstract of Physics:**

We propose to perform a precise measurement of the reaction $\vec{\gamma}p \to 2\pi^0 p$ from threshold up to the second resonance region. HBChPT predicts that pion loops are the dominant reaction mechanism at threshold, therefore, the measurement of the cross section will be a crucial test of the pion loop mechanics in HBChPT.

The five fold differential cross section (Dalitz plots and angular distributions) and the photon asymmetry will allow to study the resonances in the second resonance region. In particular the properties of the $P_{11}(1440)$ resonance and its decay channels into $p(\pi\pi)_{s-wave}$ and $\Delta\pi$ should be extracted precisely using a partial wave analysis.

This experiment will provide an important precision test for the theoretical ingredients of both the ChPT as well as the resonances in the non-perturbative domain of QCD.

**Abstract of Equipment:**

We require a beam of tagged linearly polarized photons incident on a liquid hydrogen target and the detection of the $2\pi^0$ mesons. The $4\pi$ photon spectrometer, Crystal Ball in combination with TAPS as forward wall, will be used to measure the four decay photons of the $2\pi^0$ mesons in the final state. The Glasgow tagging system will provide the intense, linearly polarized photon beam.

**MAMI–Specifications:**

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|---|---|
| beam energy | 880 MeV |
| beam current | < 100 nA |
| time structure | cw |
| polarization | linearly polarized photons |

**Experiment–Specifications:**

| | |
|---|---|
| experimental hall/beam | A2 |
| detector | Crystal Ball and TAPS as forward wall |
| target material | liquid hydrogen |

**Beam Time Request:**

| | |
|---|---|
| set–up without beam | Crystal Ball and TAPS setup time (≈ 3 mo.) |
| set–up/tests with beam | 300 hours (in parallel with MAMI/A2/1-02) |
| data taking | 500 hours |
| | (300 hours in parallel with MAMI/A2/1-02) |

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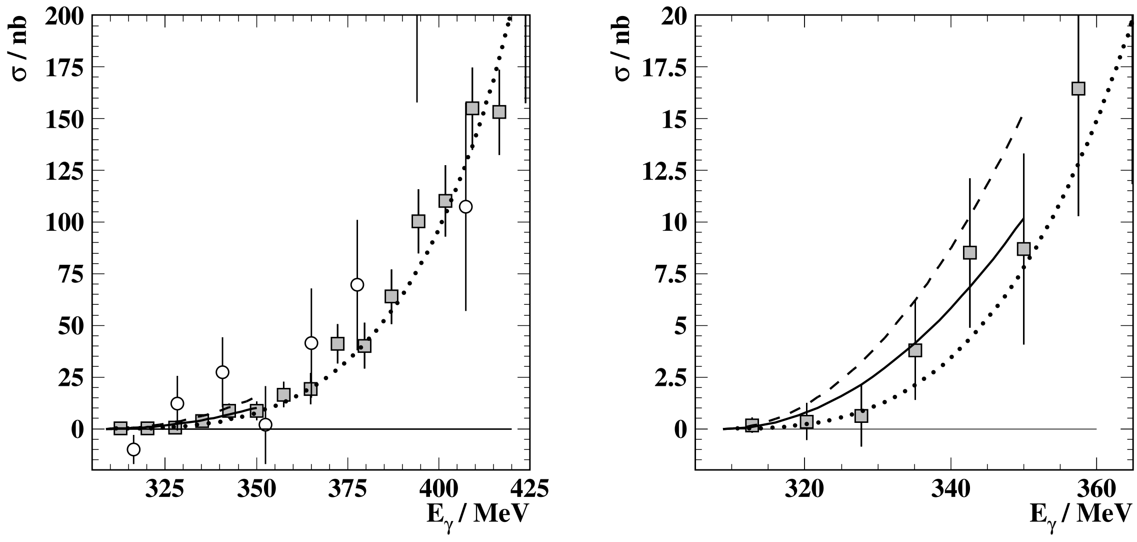


Figure 1: Total cross section for the reaction $\gamma p \to \pi^0\pi^0 p$ at threshold ([?]: grey squares, [?]: open circles) for incident energies up to 360 MeV (right) and 425 MeV (left), respectively. The error bars denote the statistical error. The prediction of the ChPT calculation [?] is shown (solid curve) together with its upper limit (dashed curve) and the prediction of Ref. [?] (dotted curve).

# 1 Test of Chiral Perturbation Theory

In the low energy regime where properties of the lowest lying baryons and mesons are studied, an approach exploiting the approximate Goldstone boson nature of the pion has been developed: chiral perturbation theory (ChPT) [?, ?]. This effective field theory has been extended to the nucleon sector (HBChPT[1]) [?, ?]. In general, it turns out, that ChPT is in good agreement with experiment in describing $\pi - N$ scattering [?]. From the study of $\pi\pi$ production processes, complementary information to the study of the single pion photoproduction channels can be gained. ChPT predicts that the $\pi^0\pi^0$ photoproduction channel is dramatically enhanced due to chiral (pion) loops [?] which appear in leading (non vanishing) order $q^3$. This is a counter-intuitive result, since in the case of single pion production the cross sections for charged pions are considerably larger than the ones with neutral pions in the final state. In a calculation up to order $M_\pi^2$, the pion loops at order $q^3$ are responsible for two thirds of the total cross section [?]. This fact makes this channel unique, because unlike in other channels where the loops are adding some contribution to the dominant tree graphs, here they are absolutely dominating. In [?], the following prediction for the near threshold cross section was given:

$$\sigma_{tot}(E_\gamma) = 0.6 \text{ nb}((E_\gamma - E_\gamma^{thr})/10 \text{ MeV})^2 \tag{1}$$

where $E_\gamma$ denotes the photon beam energy and $E_\gamma^{thr}$ the production threshold of 308.8 MeV. The largest resonance contribution at order $M_\pi^2$ comes from the $P_{11}(1440)$ resonance via the $N^*N\pi\pi$ s-wave vertex. Actually, the uncertainty of the coupling of the $P_{11}(1440)$ to the s-wave $\pi\pi$ channel was a limiting factor for the accuracy of the ChPT calculation [?]. Therefore, for the most extreme case of this coupling, an upper limit for this cross section was given in addition by increasing the constant in Eq. 1 from 0.6 nb to 0.9 nb.

Completing the overview of theoretical calculations of the reaction $\gamma p \to \pi^0\pi^0 p$ close to threshold, this channel is also described in a recent version of the Gomez Tejedor-Oset model [?]. This model is based on a set of tree level diagrams including pions, nucleons and nucleonic

[1] ChPT is used in this paper as a synonym for HBChPT

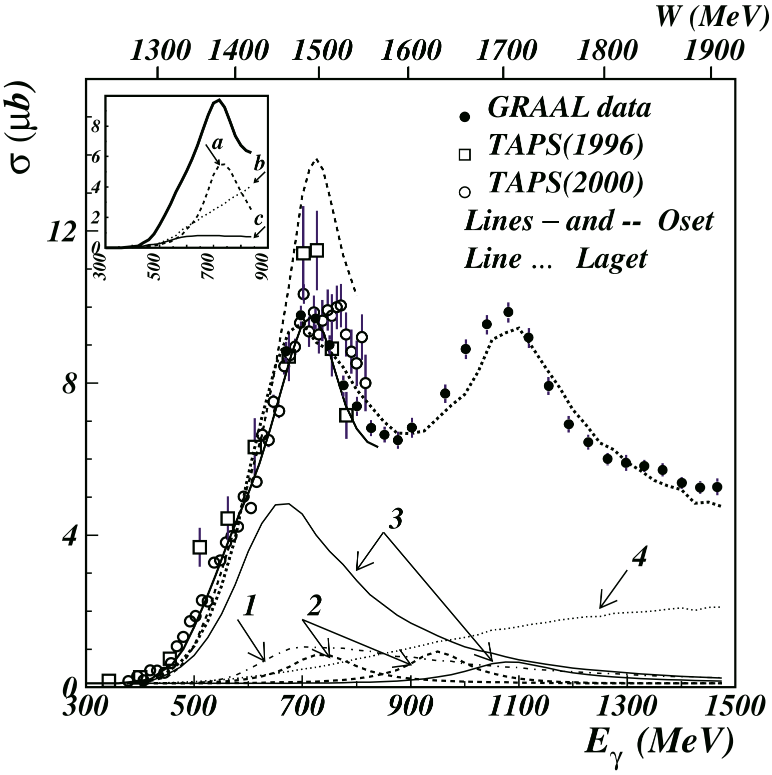


Figure 2: Total cross section for the reaction $\gamma p \rightarrow \pi^0\pi^0 p$, GRAAL data (full circles), TAPS data ([?]: open circles, [?]: squares). The numbered lines indicate in the Laget model [?] the processes $P_{11}(1440) \rightarrow \Delta\pi$ (line 1), $D_{13}(1520)/\ D_{13}(1700) \rightarrow \Delta\pi$ (line 2), $P_{11}(1440)/\ P_{11}(1710) \rightarrow \sigma p$ (line 3) and $\gamma p \rightarrow \sigma p$ (line 4).

resonances. In a recent work, particular emphasis was put on the re-scattering of pions in the iso-spin $I$=0 channel [?]. Double pion photoproduction via the $\Delta$ Kroll-Rudermann term is not possible for the $2\pi^0$ final state. In case of a $\pi^-\pi^+$ Kroll-Rudermann term, the charged pions can re-scatter into two neutral pions generating dynamically a $\pi\pi$ loop. This effect doubles the cross section in the threshold region and is regarded by the authors as being reminiscent of the explicit chiral loop effect described before.
In the past, three measurements of the reaction $\gamma p \rightarrow \pi^0\pi^0 p$ below 450 MeV beam energy have been carried out [?, ?, ?]. The third experiment achieved a big improvement in statistics and therefore could be conclusively compared to the ChPT calculation [?]. The total cross section for the threshold region is shown in Fig. 1. Although the agreement of these data to the ChPT calculation is good, the statistical precision in not sufficient for a discrimination of the ChPT calculation [?] and e.g. the Valencia model [?]. Furthermore, pion loops are at the very heart of ChPT calculations, so that a precision measurement of the $2\pi^0$ cross section at threshold would provide a significant test of the mechanics of ChPT. Also, the comparison of the results with theory indirectly impact a large number of other processes, where pion loops add a smaller, but nevertheless important contribution. The photon beam asymmetry $\Sigma$ measured with a coherent peak set at 350 MeV will add a further valuable constraint on the test of the ChPT calculations.

## 2 Reaction Mechanisms in the second Resonance Region

Nucleon resonances are studied in a variety of experiments in an attempt to obtain information on the structure of the nucleon by comparison to quark model calculations. Most information

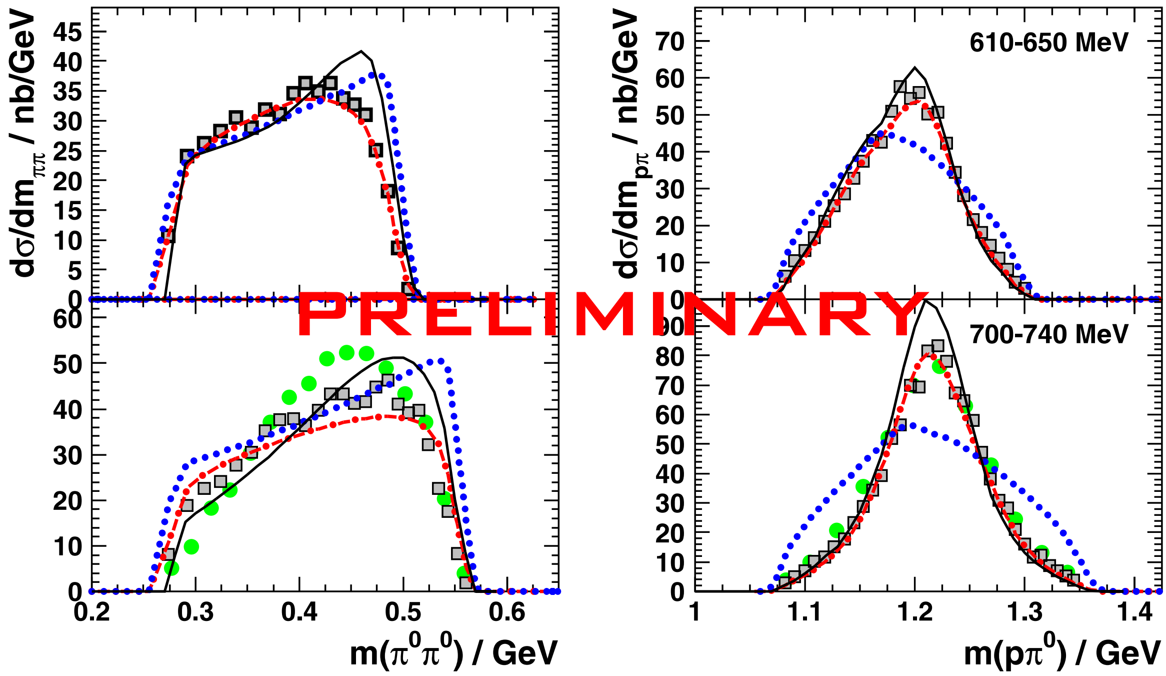


Figure 3: Invariant mass of $\pi^0\pi^0$ and $\pi^0 p$ for different bins of beam energy (full squares). The GRAAL data is shown by the full circles. The curves show $\sigma N$ phase space (dotted), $\Delta\pi$ phase space (dashed dotted) and the model calculation [?] (full curve).

has been gathered through $\pi N$ scattering and $\pi$ photoproduction. A complementary access is the double $\pi$ production where the $2\pi^0$ channel turns out to be the most selective one. Because of the vanishing charge of the $\pi^0$, Born terms as well as direct production terms ($\Delta$-Kroll-Rudermann, $\Delta$-pion pole) are very much suppressed. Previously, two measurements of the reaction $\gamma p \to \pi^0\pi^0 p$ were intensively studied in order to extract information on nucleon resonances. The MAMI results [?] were interpreted by the Valencia model [?] and gave a strong indication for a dominance for the $D_{13}(1520) \to \Delta\pi$. In a recent paper, the GRAAL collaboration reported on a measurement of the $2\pi^0$ channel from 650 MeV up to 1500 MeV [?] (compare Fig 2). These data were interpreted by an extention of the Laget-Murphy model [?]. Despite the poor coverage of the $P_{11}(1440)$ resonance with the incident beam energy, the authors emphasized that the data could be only explained by a dominance of the $P_{11}(1440) \to \sigma N$ reaction process.

New preliminary invariant mass distributions [?] measured with the TAPS spectrometer at MAMI for two incident beam energies are shown in Fig. 3. They are compared to a $\Delta\pi$ phase space and a $\sigma N$ phase space simulations and to the Valencia model calculation [?]. For the $\sigma$ a Breit-Wigner with a pole and a width of 800 MeV according to the Laget-Murphy model was assumed [?]. The GRAAL data around 720 MeV beam energy agrees very well with our $m_{\pi^0 p}$ data, whereas in the case of $m_{\pi^0\pi^0}$, the agreement is worse. In the $m_{\pi^0 p}$ distributions, the $\Delta\pi$ intermediate state dominates starting already at 600 MeV beam energy. The other phase space distributions cannot describe the data. In the $m_{\pi^0\pi^0}$ distributions the differences between the different reaction processes is much less discriminative. The dominance of the $\Delta\pi$ intermediate state in the $2\pi^0$ production channel seems to be the more obvious explanation, although no interference effects are taken into account in this simplified comparisons. This observation is in contradiction to the $\sigma N$ dominance claimed in the Laget Model [?].

Furthermore, a preliminary partial wave analysis of the data [?] has been performed within the isobar model. The analysis includes so far in addition to the s-channel processes describing the production and decay of the resonances also the production of $\Delta\pi$ by t-channel $\rho$-exchange. The

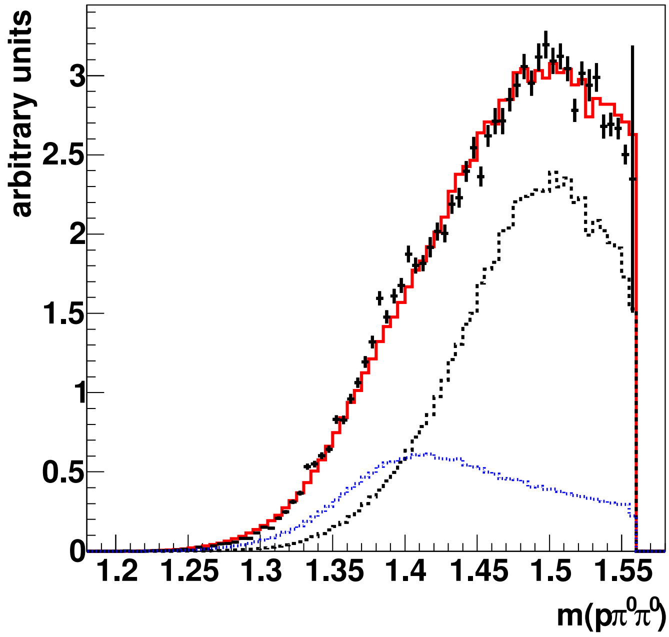


Figure 4: Preliminary partial wave analysis of the data [?] as a function of the $\gamma p$ CM energy $\sqrt{s}$ [?]. The dashed curve shows the $D_{13}$ and the dotted the $P_{11}$ partial wave. The data is shown in arbitrary units.

angular dependence of the amplitudes has been calculated using the operator formalism [?, ?] and the resonances are presently introduced as Breit-Wigner resonances. To fit the amplitudes to the data an event based maximum likelihood fit has been performed. This method has one big advantage compared to fits performed only to total and differential cross sections: It takes all the correlations between the 5 different variables the $p\pi^0\pi^0$ final state depends on properly into account. The information on the correlation gets lost if only differential cross sections are considered since they correspond to projections of the multi-dimensional phase space. The preliminary partial wave analysis [?] confirms the dominance of the $D_{13}(1520) \rightarrow \Delta\pi$ amplitude found by the Valencia group [?] (see Fig. 4 and Fig. 5). A dominant contribution from the $P_{11}(1440) \rightarrow p\sigma$ [?] is found to be in disagreement with the data. Event hough the result is still very preliminary it is interesting to note, that the fit prefers a significant smaller width for the $P_{11}(1440)$ than given by the PDG.

We propose to measure the $2\pi^0$ channel with superior statistics to be able to extract very precise Dalitz plots and angular distributions. The excellent coverage of the three-body phase space with 100% acceptance together with the excellent MAMI tagged photon facility will ensure a very small systematic error of the measured cross sections. We will exploit the photon beam asymmetry $\Sigma$ using a linearly polarized photon beam in order to have better sensitivity for the reaction mechanisms involved in the reaction $\gamma p \rightarrow \pi^0\pi^0 p$. Linear polarized photons will provide additional constraints for the partial wave analysis which will help to determine the contributing amplitudes with higher precision. These measurements should e.g. help to determine the resonance parameters of the $P_{11}(1440)$ including its relative decay modes into $\Delta\pi$ and $N\sigma$ as well as its contribution relative to the $D_{13}(1520)$. For these studies, we propose to measure the major part of the beamtime with the coherent peak set at about 450 MeV. This is the energy range where one can expect to be most sensitive to the contribution of the $P_{11}(1440)$ resonance.

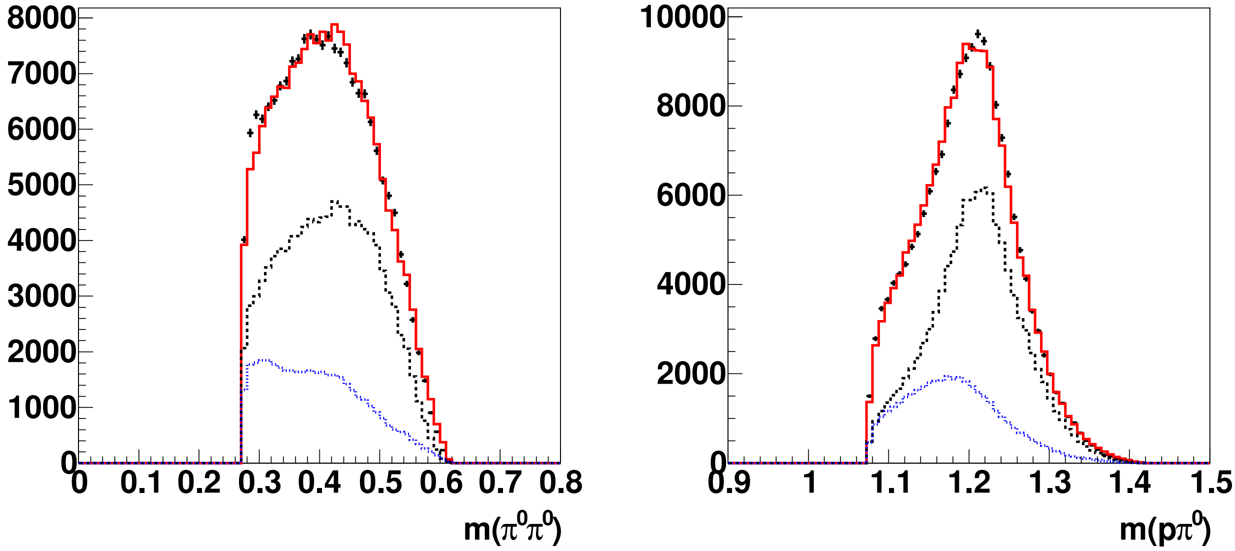


Figure 5: Preliminary partial wave analysis of the data [?, ?]. The dashed curve shows the $D_{13}$ and the dotted the $P_{11}$ partial wave. The data is shown in arbitrary units integrated over incident energies from threshold up to 820 MeV. Left: as a function of the invariant mass of the $\pi^0\pi^0$ system, right: as a function of the invariant mass of the $p\pi^0$ system.

# 3 Experiment

We propose to use the Crystal Ball spectrometer as the central detector with TAPS as the forward wall for the detection of photons. This combination has a geometrical acceptance close to $4\pi$, a high photon detection efficiency with excellent energy and angular resolutions.
The $\gamma p \to \pi^0\pi^0 p$ reaction channel will be identified by measuring the 4-momenta of the two $\pi^0$ mesons, whereas the proton needs not to be detected in order to ensure a background free identification of the reaction. The $\pi^0$ mesons will be detected via their two photon decay channel and identified in a standard invariant mass analysis from the measured photon momenta. Events will be selected such that both of the two photon invariant masses fulfill simultaneously the invariant mass condition for a $\pi^0$ meson (compare Fig. 7). Furthermore, the mass $M_X$ of a missing particle will be calculated (see Fig. 7). In case of the reaction $\gamma p \to \pi^0\pi^0 p$ the missing mass $M_X$ must be equal to the mass of the (undetected) proton $m_p$. Above the $\eta$ production threshold of 707 MeV, the $\eta \to 3\pi^0$ decay is a potential background source for the $2\pi^0$ channel via events where only two of the three $\pi^0$ mesons are detected. Due to the excellent coverage of phase space, the probability that two photons escape detection is very small. In Fig. 7 the $\eta$ background contribution scaled by a factor 15 is shown in the missing mass distribution $M_X$. Applying a cut on in this missing mass distribution ensures that the $\eta$ background is below 0.2% of the total $2\pi^0$ rate with a negligible loss of the true $2\pi^0$ signal. The central tracker device based on the DAPHNE cylindrical multi wire proportional chamber will be used to enhance the particle identification capabilities of the setup, i.e. to discriminate charged and neutral particles. The chamber will be inserted into the Crystal Ball beam cavity.
The overall efficiency of the experimental apparatus for the reaction $\gamma p \to \pi^0\pi^0 p$ at an incident beam energy $E_\gamma = 700$ MeV is shown in Fig. 8. The distributions have been obtained with a GEANT based Monte Carlo simulation code developed for the experiments with the Crystal Ball at MAMI. The code includes a detailed description of the Crystal Ball detector as well as the TAPS forward wall, the central tracker and the liquid hydrogen target. The analysis of the Monte Carlo data is performed with the Analyzer software package initially developed for the Crystal Ball AGS experiments. The Analyzer modified for the MAMI experiments includes a

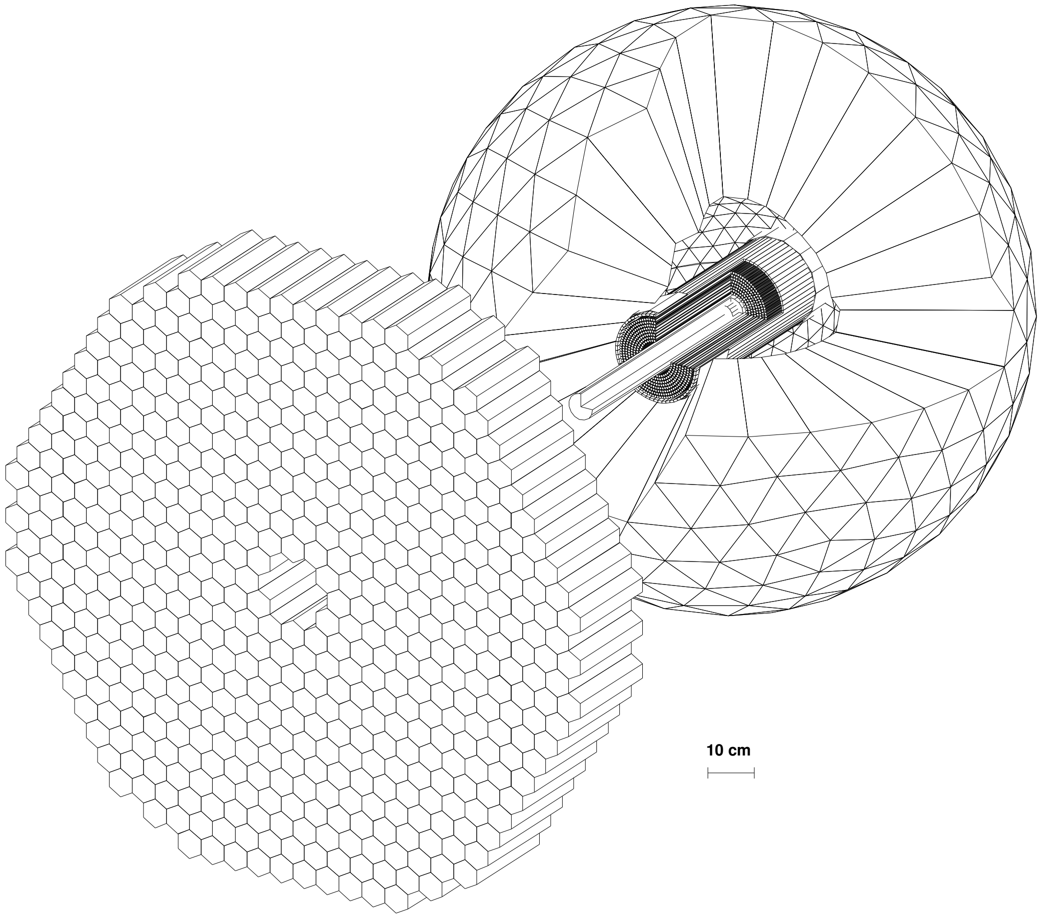


Figure 6: The experimental apparatus proposed for the measurements of the reaction $\gamma p \to \pi^0\pi^0 p$. To show the position of the cylindrical wire chamber and the target inside the Crystal Ball some of the Crystal Ball crystals have been omitted. The central detector, the Crystal Ball, TAPS as forward wall, the cylindrical wire chamber, and the liquid hydrogen target are described in the proposal for the measurement of the magnetic moment of the $\Delta^+(1232)$ resonance [**?**].

TAPS cluster recognition routine as well as track reconstruction in the cylindrical wire chamber. The acceptance is shown for events in which both two $\pi^0$ are detected.
The trigger conditions for the experiment require a coincidence between four cluster either in the CB or TAPS detector. This experiment will be performed during the measurement of the magnetic moment of the $\Delta^+(1232)$ resonance in the reaction $\gamma p \to \gamma\pi^0 p$. Since the trigger condition for this reaction will base on the detection of three coincident clusters in the detector system, the measurement of the $2\pi^0$ channel is automatically guaranteed without any suppression factor. The expected event rate of 2.5 kHz is mainly determined by the $\gamma p \to \pi^0 p$ and $\gamma p \to \pi^+ n$ processes. Since the detection of the proton suffers from energy losses, the contribution of $\gamma p \to \pi^0 p$ can be decreased by requiring at least three coincident clusters in the photon detectors.
The implementation for the new Crystal Ball and TAPS readout electronics is underway. The anticipated readout speed for the new data acquisition system is 1 kHz plus. Additional trigger conditions will be applied if necessary in order to keep the event rate under 1 kHz and the data acquisition system live time above 70%. The proposed algorithm utilizes a block of fast logic matrices to analyze the pattern of crystals in both photon detectors. The pattern recognition unit provides information on the number of clusters in the detectors within 300 nsec after the event has been detected. The algorithm as well as the electronics hardware have been developed

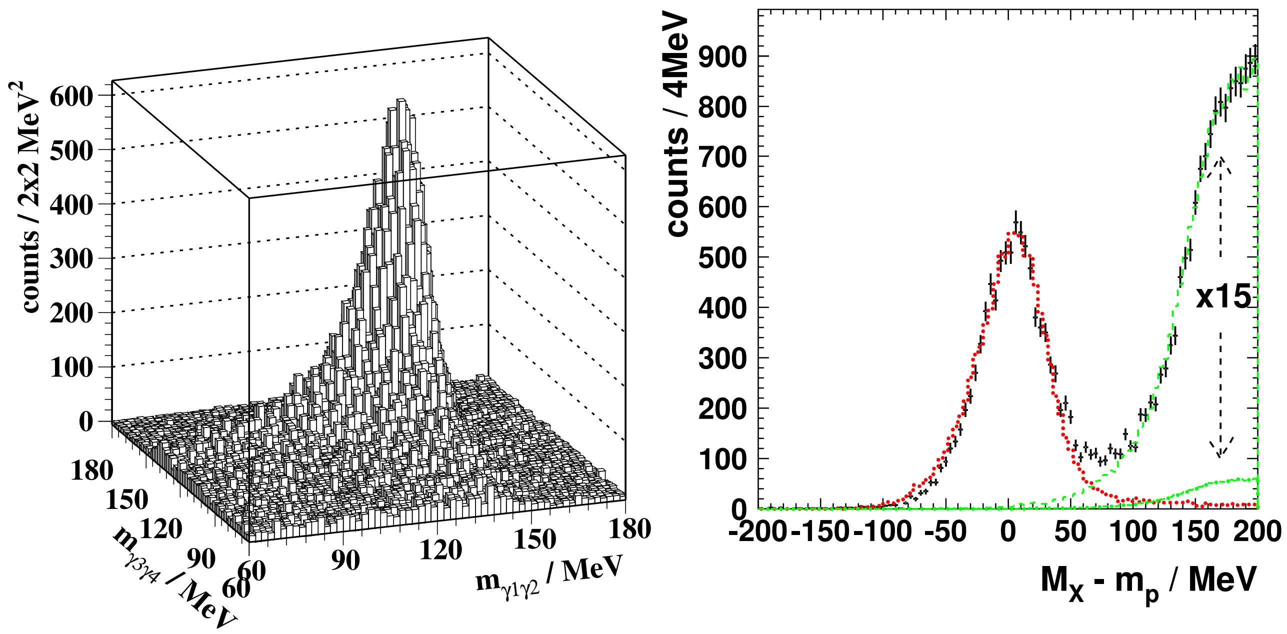


Figure 7: Left: Two photon invariant masses $m_{\gamma 1\gamma 2}$ vs $m_{\gamma 3\gamma 4}$. Right: Missing mass $M_X - m_p$ derived from two detected $\pi^0$ mesons for incident beam energies $E_\gamma$ 780 $\leq$ 820 MeV (symbols with errors: TAPS data, dotted line: $2\pi^0$ sim., dashed line: $\eta$ sim., dashed dotted line: expected $\eta$ contribution for the proposed CB and TAPS setup).

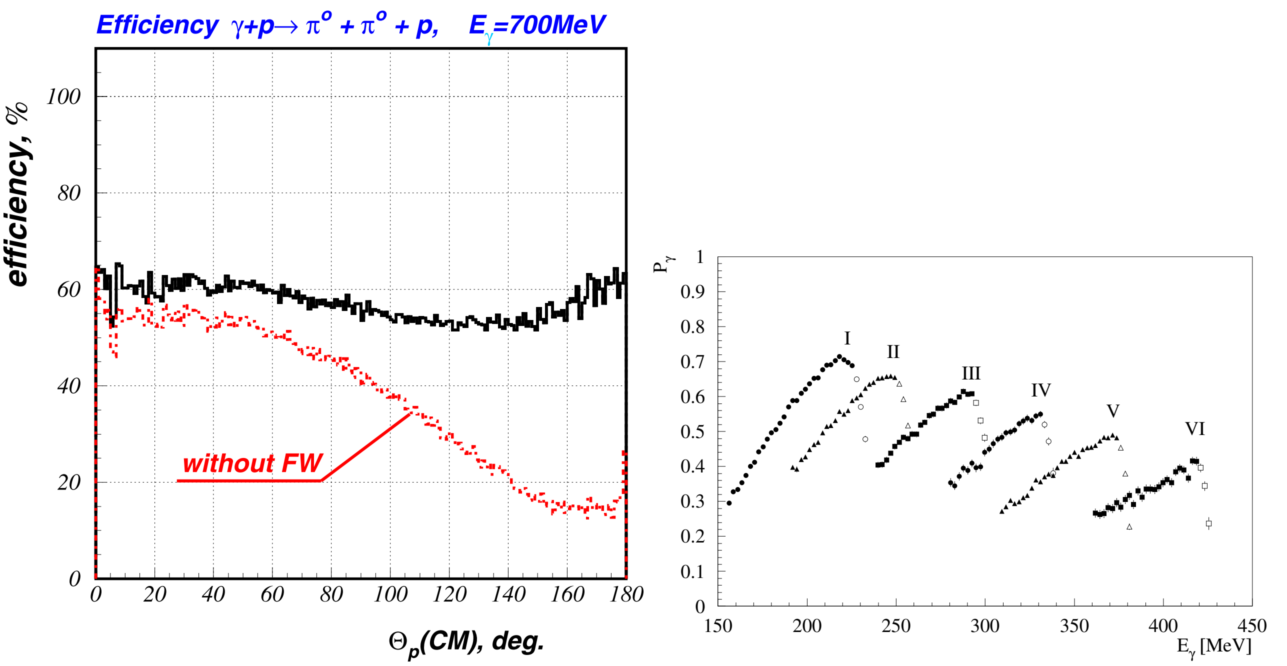


Figure 8: Left: Efficiency for the $2\pi^0$ channel using the Crystal Ball alone and the combined Crystal Ball-TAPS detector system. Right: The photon polarization for linearly polarized photons as a function of the photon energy for an electron energy of 855 MeV.

at the University of Uppsala (Sweden) for the WASA experiment [?].

# 4 Event Rates

The proposed experiment will use the MAMI/Glasgow Tagged Photon beam in the MAMI A2 area that has been used successfully for many years.
The parameters entering the count rate estimate and resulting beam time request are:

- Incoming electron beam energy: $E_0 = 882$ MeV.
- Tagged photon energy range: $E_\gamma^t = 295 - 820$ MeV.
- Max. electron count rate in the tagger: $N_e = 5 \times 10^5 \frac{1}{s} \frac{1}{MeV}$.
- Tagging efficiency: $\varepsilon_t \approx 50\%$.
- Number of protons in a 5 cm long $LH_2$ target (existing DAPHNE cryo target): $N_t = 2.1 \times 10^{23} \frac{1}{cm^2}$.
- Detection efficiency: $\varepsilon_{CB} \approx 60\%$. (see Fig. 8).
- Data acquisition system live time: $\varepsilon_{DA} \approx 70\%$.

## 4.1 Threshold Production

We consider the following properties in the beam energy range below 350 MeV.

- Average electron count rate in the tagger: $N_e = 5 \times 10^5 \frac{1}{s} \frac{1}{MeV}$.
- Total threshold cross section for $\gamma p \to \pi^0\pi^0 p$: $\sigma_t \sim 5$ nb (see Fig. 1).

The resulting number of events expected per hour for the first 40 MeV above the production threshold is

$$N_{2\pi^0} = N_{e^-} \varepsilon_t \; \sigma_t \; N_t \; \varepsilon_{CB} \; \varepsilon_{DA} \approx 16 \; h^{-1}. \qquad (2)$$

The beam time requested for the production data taking is 500 hours. This will provide about 7900 two-$\pi^0$ events in the incident beam energy range below 350 MeV.
The photon asymmetry $\Sigma$ will be measured with the coherent peak set at about 350 MeV. The linearly polarized photons cover the range between threshold and 350 MeV with a mean polarization $P_\gamma \approx 45\%$. The expected accuracy for 200 hours of beam time in the photon asymmetry for 4 data points in the total cross section is

$$\Delta\Sigma = \frac{1}{P_\gamma} \frac{1}{\sqrt{N}} \approx 0.08 \qquad (3)$$

## 4.2 Second Resonance Region

We consider the following properties in the beam energy range up to 820 MeV.

- Average electron count rate in the tagger: $N_e = 2 \times 10^5 \frac{1}{s} \frac{1}{MeV}$.
- Total threshold cross section for $\gamma p \to \pi^0\pi^0 p$: $\sigma_t \sim 4.5$ $\mu$b (see Fig. 2).

The resulting number of events expected per hour for the first 40 MeV above the production threshold is

$$N_{2\pi^0} = N_{e^-} \varepsilon_t \; \sigma_t \; N_t \; \varepsilon_{CB} \; \varepsilon_{DA} \approx 70000 \; h^{-1}. \tag{4}$$

The beam time requested for the production data taking is 500 hours. This will provide about $3.5 \times 10^6$ two-$\pi^0$ events in the full beam energy range.
The average expected rate for a differential cross section ($d\sigma/dm_{\pi^0\pi^0}$) in $\pm 10$ MeV incident photon energy bins and 20 data points is 7000 counts for the whole data set and 4200 for the 300 hours of polarized data taking. The photon asymmetry $\Sigma$ will be measured with the coherent peak set at about 450 MeV. The linearly polarized photons cover the range between 370-450 MeV with a mean polarization $P_\gamma \approx 35\%$. The expected accuracy in the photon asymmetry is

$$\Delta\Sigma = \frac{1}{P_\gamma} \frac{1}{\sqrt{N}} \approx 0.04 \tag{5}$$

per data point.

# 5 Beam Time Request

We request for the measurement of the reaction $\vec{\gamma} p \to 2\pi^0 p$ the following amount of beam time:

- Threshold region: coherent peak at 350 MeV: **200 h**.
- Investigation of the $P_{11}(1440)$: coherent peak at 450 MeV: **300 h**
- Total requested beam time: **500 h** (300 h in parallel with proposal MAMI/A2/1-02).