THE CRYSTAL BALL AT MAMI *

D. P. WATTS FOR THE CRYSTALBALL@MAMI COLLABORATION
School of Physics, University of Edinburgh, UK
E-mail: daniel.watts@ed.ac.uk

The Crystal Ball and TAPS detector systems provide a highly segmented photon and hadron calorimeter for use with the Glasgow Tagger at the upgraded MAMI electron beam facility. The facility will provide very high quality photonucleon and photonuclear data for incident E_γ up to ∼1.4 GeV. Some preliminary results will be presented and future plans for double-polarisation measurements in meson photoproduction will be outlined

1. MAMI

1.1. *The MAMI facility*

The Crystal Ball is now the central detector facility to be used in experiments with the Glasgow Tagger at the MAMI electron microtron in Mainz, Germany. The MAMI-B[1] electron beam facility produces a 0.85 GeV high quality ∼100% duty factor electron beam. The facility is presently being upgraded to MAMI-C[2] which will involve the inclusion of a further microtron stage to give an output beam energy of 1.5 GeV. The MAMI electron beam can be passed to 4 experimental halls. The Crystal Ball[3] and TAPS[4]calorimeters are used in the real photon (A2) hall where the electron beam produces an intense (∼10^8 γ $\sec^{-1}$) beam of real photons through bremsstrahlung in a thin metal foil radiator. By employing a crystalline radiator (diamond) linear polarisation of up to ∼90% can be achieved. Circular polarisation of up to ∼85% can be achieved using longitudinally polarised electrons from MAMI. Following the bremsstrahlung process the scattered electrons are momentum analysed in the Glasgow Tagger, a magnetic spectrometer[5] which provides a determination of the energy of the associated bremsstrahlung photon with a resolution of ∼2

*This research is part of the EU integrated infrastructure initiative hadronphysics project under contract number RII3-CT-2004-506078

MeV. Improved resolution and flux can be achieved for smaller sub ranges of photon energy by using a more highly segmented focal plane microscope subdetector system[6]. The MAMI photon beam compares favourably with other facilities available in this E_γ range as can be seen in Fig.1

	E_γ^{max} (GeV)	I_γ^{max} ($s^{-1}MeV^{-1}$)	ΔE_γ^{FWHM} (MeV)	Pol_γ^{lin} (%)	Pol_γ^{circ} (%)
ELSA	3.5	10^4	5	70	80
Graal	1.5	10^3	15	100	100
Jefferson Lab	5.4	10^4	5	70	80
Legs	0.45	10^3	5	100	100
MAMI B C	**0.8** **1.5**	**10^5**	**1**	**70**	**80**
SPring-8	3.0	10^3	30	100	100

Figure 1. Comparison of the major gamma beam facilities

1.2. *The Crystal Ball*

The Crystal Ball (Fig. 2) was conceived and built in the mid 1970s at SLAC and was the central detector system in experiments at SPEAR, DORIS and Brookhaven National Laboratory before arriving at MAMI. The Crystal Ball is a 672 element NaI detector covering 94% of 4π. Each element is shaped like a a truncated pyramid $\sim$41cm long. Photons incident on the ball produce an electromagnetic shower which generally deposits energy in a number of crystals (typically 98% of the deposited energy is contained in a cluster of 13 crystals). From analysing the centre of gravity of the shower angular resolutions for the photon of 2-3° in theta and 2°/sinθ in phi are achieved. The scintillation light deposited in each crystal is read by its own 2 inch Photomultiplier tube (PMT) and the high light output of NaI results in a good determination of the photon energy ($\sigma/E \sim 1.7\%/E^{0.4}$(GeV)).

There has been a complete overhaul of the electronics for the Crystal Ball with its move to Mainz[7]. The output signal from each PMT is fed to a split-delay module. One output branch feeds to the trigger logic, a second feeds individual multi-hit TDCs and scalers via a dual threshold discriminator and a third is fed to a 40 MHz sampling ADC. The ADC modules also have an 80 MHz sampling capability which may be exploited in the future. The sampling of different regions of the pulse shape enables correction for remnant light present in the crystals before the event of interest, which improves the energy resolution.

A detector subsystem consisting of two cylindrical MWPCs and a 24 element barrel of plastic scintillators gives a good separation of protons and pions and gives track resolutions of $\sigma_\theta \sim 1.5°$ and $\sigma_\phi \sim 1.3°$.

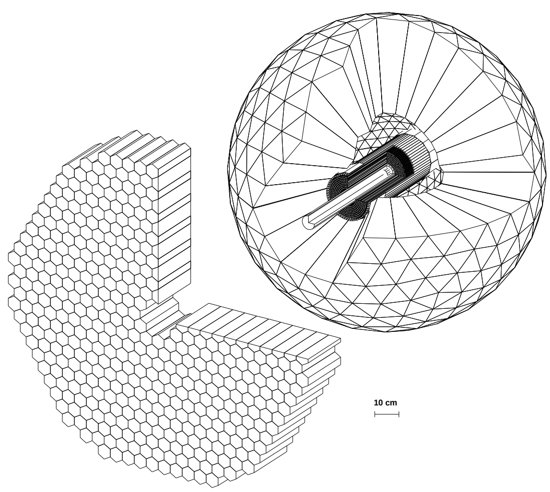

Figure 2. The Crystal Ball and TAPS detectors in the A2 hall at Mainz (with sections removed to allow visibility of the detector elements)

1.3. *TAPS*

The TAPS detector system covers the angular range $\theta = 1° - 20°$ which is not covered by the Crystal Ball. This is an important part of the phase space for fixed target experiments with high beam momenta. TAPS consists of 510 hexagonally shaped BaF2 detectors each 25 cm long corresponding to 12 radiation lengths. TAPS is a versatile detector system and has been employed at MAMI, GSI, Ganil, CERN and most recently with the Crystal Barrel at Bonn. BaF_2 scintillator has two scintillation components, a fast component which lasts for ~20ns and a slow component which lasts for ~2μs. Different particle species produce different relative light yields in the two scintillation components and this additional pulse shape information can be used along with time-of-flight and ΔE information in particle identification. The energy resolution for the detector is of similar order to that obtained in the Crystal Ball ($\sigma/E \sim 0.59\ E^{-1/2}(GeV) + 1.9\%$). New VME based readout electronics for the TAPS detectors have been constructed[8]. The new design improves significantly on the previous system by allowing the signal information to be digitised close to the detectors which eliminates problems associated with passing analogue signals the long distance to the control room such as attenuation, shaping and cross talk.

1.4. *Targets*

The MAMI facility has a good range of targets either presently available or in development for use in the Crystal Ball programme. Cryogenic target systems capable of liquefying both hydrogen and deuterium are presently available. A system for accurately mounting solid targets has been operated successfully. A Mainz frozen spin target is due to be completed in 2007 which can use either butanol or deuterated-butanol targets to give a source of longitudinally polarised protons or neutrons respectively. In 2008 a polarised ^{3}He gas target will additionally become available and will offer an alternative source of polarised neutrons.

2. Experimental programme

The experimental programme at MAMI primarily exploits the 4π detection capability and uniquely intense photon flux available at MAMI. This powerful combination is particularly well suited to making measurements of small cross sections or measurements where very accurate and comprehensive determinations are necessary to extract the important physics.

The main themes of the MAMI programme include:

- Precision determinations of nucleon resonance properties
- Tests of low energy theorems
- Tests of fundamental symmetries
- In medium properties of hadrons
- Nuclear structure

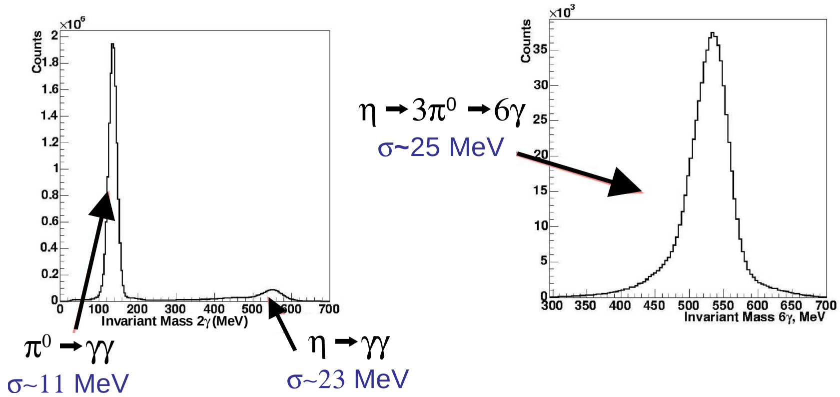

Figure 3. Reconstructed invariant mass spectra (preliminary).

3. Experiments in the first round

The first round of experiments employed H_2, D_2 and nuclear targets and was successfully completed in the period June 2004 to April 2005. Data taking will resume in 2006 following the completion of the upgrade of the MAMI facility and the Glasgow photon tagging spectrometer. The Crystal Ball experiment took ~3600 hours of beamtime in the first round of experiments, giving data for 10 approved proposals and providing the thesis data for 13 Ph.D students. A brief outline of the experiments already completed and some preliminary analyses are presented in the following sections.

3.1. *Liquid Hydrogen Target*

The high granularity and almost complete kinematic coverage of the Crystal Ball and TAPS results in good quality reconstruction of π^0 and η mesons as can be seen from the preliminary spectra in Fig. 3. The majority of proposals completed in the first round measured meson photoproduction reactions from the liquid hydrogen target. The first experiment comprised a measurement of π^o photoproduction in which the crystalline (diamond) radiator was oriented to produce a high degree of linear polarisation for E_γ around pion production threshold, giving accurate asymmetry and cross section data to extract the S and P wave strength and test predictions from chiral perturbation theory (χPT). The later experiments were carried out with high degrees of linear polarisation in the E_γ=0.4-0.5 GeV region, above the peak of the Δ resonance and in the threshold region of 2π production. The new data for the 2π reaction near threshold will also test χPT,

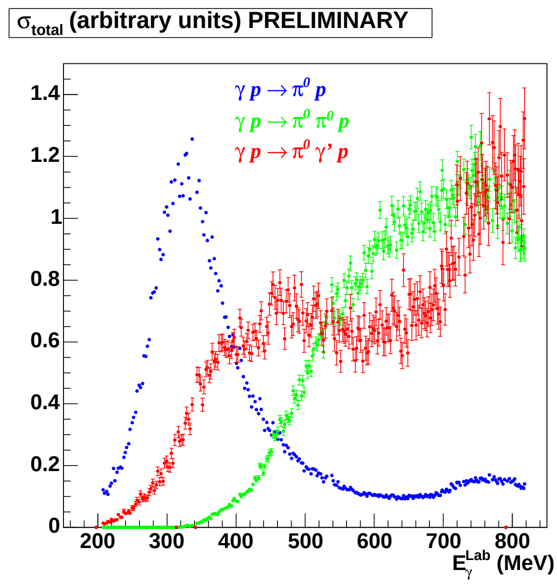

Figure 4. The preliminary yields of various reactions from a liquid hydrogen target. The different channels are indicated in the figure.

in particular pion loop mechanics, and will allow detailed investigation of the resonances in the second resonance region. The analysis of the large sample of $\eta \to \pi^0\gamma\gamma$ will test the third order terms in the χPT momentum expansion and the $\eta \to 3\pi^0$ data will also give important tests of the theory.

A further important physics goal of the first round programme is to obtain an accurate determination of the magnetic dipole moment of the first excited state of the proton, the $\Delta(1232)$, which will provide an elegant test of various theoretical descriptions of the hadron. Sensitivity to the dipole moment arises from the contribution of the $\Delta^+ \to \Delta^+\gamma$ self-decay process in the reaction amplitude.of the $\gamma + p \to p\pi^0\gamma$ reaction. As well as increasing the data set for $\gamma + p \to p\pi^0\gamma$ by over an order of magnitude the new measurement will give a determination of reaction asymmetries for both linear and circular incident photon polarisations, which are predicted to give additional sensitivities to the value of μ_{Δ^+}. The experiment also allowed a simultaneous determination of the $\gamma + p \to n\pi^+\gamma$ reaction which gives important additional tests of the modelling of the background bremsstrahlung processes as well as giving a further independent measure of μ_{Δ^+}. The analysis of the data taken with the liquid H_2 target is presently in progress but some very preliminary yields[9] are shown in Fig. 4.

3.2. *A≥2 targets*

The first round of data taking also included ^{7}Li, ^{12}C, H_2O, ^{40}Ca and ^{208}Pb targets. The 2π production from these targets will be analysed to investigate modification of the π-π interaction in the I=J=0 channel. The ^{7}Li data will be used to search for evidence of η-mesic nuclear states.

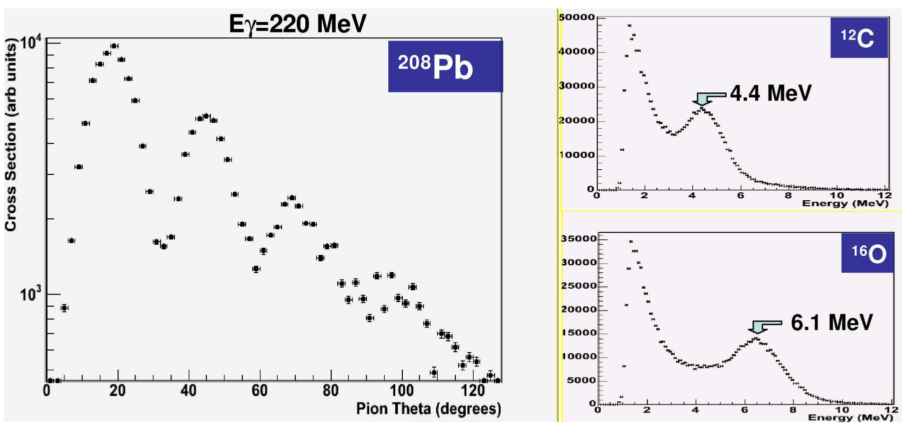

Figure 5. Left; Preliminary π^0 angular distribution from the ^{208}Pb(γ, π^0) reaction. Right: Coincident low energy events in the Crystal Ball showing γ from the decay of the 2^+ state at 4.4 MeV in ^{12}C and states around 6.1 MeV in ^{16}O

Analysis of single π^0 production is also in progress, with the primary motivation to more firmly establish the matter distribution of nuclei. In the coherent production of a π^0 from the nucleus the amplitudes for production from all nucleons in the nucleus adds coherently and the diffraction pattern in the angular distribution of the outgoing π^0 contains information on the matter form factor. The high detection efficiency and high uniformity of the Crystal Ball will eliminate many of the systematic errors in extracting this coherent strength from the incoherent events which leave the nucleus in an excited state. The diffraction spectra for the ^{208}Pb are visible even with a first crude analysis as can be seen in Fig 5. Also shown in the figure are the energies of the low energy uncharged clusters occurring in coincidence with the π^0. It is clear that valuable information on low energy nuclear decay gamma rays are visible in the Crystal Ball. Their analysis will allow the coherent events to be extracted over a wider E_γ range and allow the incoherent strength to some low lying discrete residual states to be studied in detail for the first time. The capability for detection of decay gammas with the CB will also have applications in other future experiments on nuclei.

4. Future Programme

Present plans for the future programme for the Crystal Ball at MAMI-C include further detailed measurements of η and η' branching ratios to test χPT and C, CP invariance[11], threshold strangeness production, continuation of the programme to measure the magnetic moments of nucleon resonances[12], investigation of medium modification of mesons[13] and studies of nuclear correlations[14]. A major theme in the future programme will be accurate measurements of double-polarisation observables in meson photoproduction and these plans will be highlighted in the remainder of this contribution because of the relevance to the topic of the conference.

4.1. *Double polarisation observables*

The photoproduction of pseudo-scaler mesons from the nucleon can be described with 4 complex amplitudes. This leads to 16 experimental observables in the reaction: the cross section (σ), three single polarisation observables (Σ, P, T) and three quartets of double polarisation observables for beam-target (E,F,G,H) beam-recoil ($C_{x'}$, $C_{z'}$, $O_{x'}$, $O_{z'}$) and target-recoil ($T_{x'}$, $T_{z'}$, $L_{x'}$, $L_{z'}$). The need to measure double-polarisation observables to improve our knowledge of the amplitudes has become increasingly apparent in recent years. For example a first measurement of E for $\vec{\gamma} + \vec{p} \rightarrow p\pi^0$ showed the need for a significant revision of the helicity amplitudes even for the "well established" $D_{13}(1520)$ resonance[10].

The availability of an intense polarised photon beam, polarised nucleon targets and a $\sim 4\pi$ detector system at Mainz will allow accurate determination of a range of double polarisation observables. The E observable is accessed with a longitudinally polarised nucleon target and circularly polarised photons. New measurements with MAMI-C will greatly improve the statistical accuracy and the E_γ range of the experimental data for π^0, η and 2π production channels, and assess their contributions to the Gerasimov Drell Hearn sum rule. The expected accuracy of the proposed E measurements[15] for the p$(\vec{\gamma}, \pi^0)p$ reaction and indications of the sensitivity of the variable to different resonances based on the MAID partial wave analysis (PWA) are shown in Fig.6. The measurement on the neutron

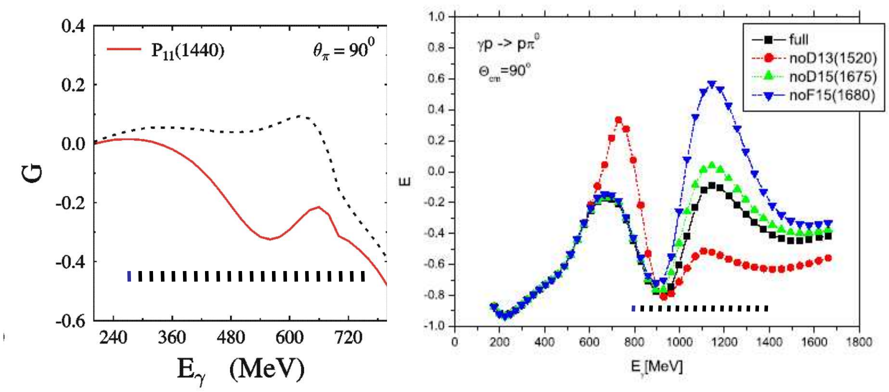

Figure 6. LEFT: The vertical bands show the expected accuracy in the determination of the G observable for $p(\gamma, p)\pi^0$ in an E_γ bin of ± 10 MeV, a θ_π bin of $10°$ and a 600 hour beamtime. Curves show results from the MAID PWA with and without the roper resonance RIGHT: Vertical bands give the expected accuracy for the E observable in a 250 hour beamtime with the same E_γ, θ_π binning. The curves show the values of the E variable extracted from MAID

target will allow a complementary determination of E to test the isospin structure of the resonances and allow investigation of resonances which only couple strongly to the neutron. The determination of the $p(\vec{\gamma}, \eta)p$ reactions, will be particularly interesting because of the sensitivity expected to the $D_{15}(1675)$ which is one possible explanation of the structure in the cross sections measured at GRAAL.

The G observable will be obtained[16] for $p(\vec{\gamma}, \pi^0)p$ and $p(\vec{\gamma}, \pi^+)n$ reactions from a linearly polarised photon beam with a longitudinally polarised target. The suitability of the observable for detailed studies of the poorly established $P_{11}(1440)$ (Roper) resonance is indicated from the MAID PWA predictions shown in Fig. 6. The expected accuracy of the experimental data is also indicated in the figure.

The beam-target observables will give high quality data to add to the worlds database used in partial wave analyses. However, an unambiguous determination of the amplitudes would require 8 observables and necessitates measurements of double-polarisation observables involving recoil polarisation. As a further step towards this goal we recently proposed[17] to setup a nucleon polarimetry capability. The polarimeter would comprise a graphite scatterer, placed in the downstream exit of the Crystal Ball, and use the highly segmented TAPS array to detect the scattered nucleons. The nucleons will be tracked into the graphite scatterer using reaction kinematics or a tracker system. In combination with the polarised MAMI beam the polarimeter will make possible determination of the $C_{x'}$ and $O_{x'}$ beam-recoil observables. Further, the single polarisation observables, P and T will also be accessible (T can be extracted as the y component of recoil polarisation with a linearly polarised photon beam). The expected experimental accuracy, estimated using realistic polarimeter parameters for a 7cm thick graphite scatterer, is shown in Fig.7.

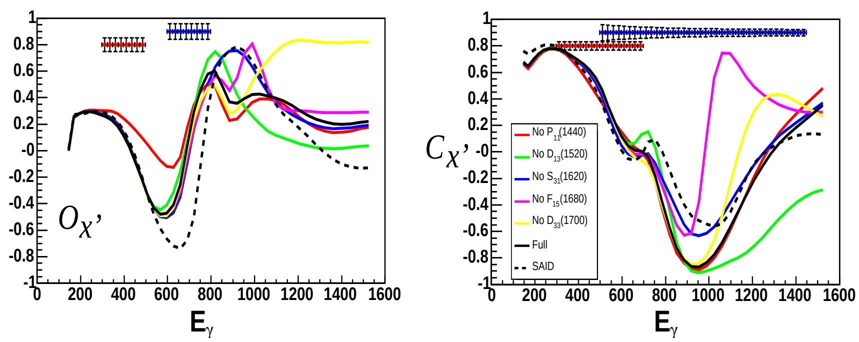

Figure 7. The data points show the expected statistical accuracy of the $O_{x'}$ (Left) and $C_{x'}$ (Right) measurements in a θ_π bin of $\pm 10°$ for a 300 hour run with 0.85 GeV beam energy (red - lower points) and a 600 hour run at 1.5 GeV (blue - upper points). The curves show the values extracted from the SAID and MAID PWA (see key in the figure)

In conclusion, the Crystal Ball at MAMI programme is successfully underway and this powerful combination can be expected to contribute high quality data on meson photoproduction up to $E_\gamma \sim$1.4 GeV, most with polarisation information.

References

1. http://www.kph.uni-mainz.de
2. A. Jankowiak et. al., Proc. EPAC2002, Paris (2002)
3. E.D. Bloom and C.W. Peck, Ann. Rev. Nucl. Part. Sci, vol. 33 ,p143 (1983)
4. R. Novotny et. al., IEEE Trans Nucl. Sci 38 p379 (1991).
5. I. Anthony et. al., Nucl. Instr. And Meth., A301, p230, (1991)
6. A. Reiter et. al., http://wwwa2.kph.uni-mainz.de/microscope/
7. D. Krambrich, Ph.D thesis (Mainz 2005) in preparation; D.P. Watts, Calorimetry in particle physics, Perugia 2004, p116-123
8. P. Drexler et. al., IEEE Trans. Nucl. Sci 50 p.969 (2003).
9. A. Starostin, *private communication.*
10. J. Ahrens *et. al.*, Phys. Rev. Lett. 88 232002 (2002); *ibid.* 84, 5950 (2000).

11. A. Starostin *et. al.*MAMI/A2/2-05, B. Nefkens *et. al.*MAMI/A2/3-05
12. M. Kotulla *et. al.* MAMI/A2/4-05
13. V. Metag *et. al.* MAMI/A2/1-05
14. I. Macgregor *et. al.* MAMI/A2/6-05
15. P. Pedroni *et. al.* MAMI/A2/9–05; B. Krusche *it. al.* MAMI/A2/10-05
16. R. Beck *et. al.* MAMI/A2/8-05
17. D. Watts *et. al.* MAMI/A2/5-05