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Future experiments at MAMI

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Abstract. A new experimental program is about to get underway at the Mainz Microtron (MAMI) Facility. The experimental apparatus consists of the famous Crystal Ball together with TAPS detector as a forward wall, and a central tracker. This configuration provides a geometrical acceptance close to 4π combined with good energy and angular resolution in particular for neutral final states. After the energy upgrade of the Mainz Microtron (MAMI-C), the Crystal Ball and TAPS setup will be equipped with a frozen-spin polarized target filled with ^{1}H, or ^{2}H to perform new high precision, high statistics measurements of neutral meson production on the nucleon up to 1.5 GeV incident photon energies. In particular it provides a unique opportunity to investigate the GDH sum rule on a neutron target in the contributions by reactions $\gamma\mathbf{n} \to \pi^0 n$, $\gamma\mathbf{n} \to \pi^0\pi^0 n$ and $\gamma\mathbf{n} \to \eta n$.

1 Introduction

After the successful completion of a rich experimental program at Brookhaven National Laboratory the Crystal Ball, CB, photon spectrometer has been moved beginning of November 2003 to the Mainz Microtron Facility for a series of high precision experiments requiring high intensity, high quality, ultra-fine tagged, linearly and circularly polarized photon beams. The TAPS BaF_2 calorimeter [1] will be used in the measurements as a forward wall. The high granularity and large acceptance of the experimental setup allows the data to be simultaneously obtained for different final states over the full range of angles with good energy and angular resolution and high statistical accuracy.

Over the past years (1997-2002) the Crystal Ball detector has been used successfully in medium energy beams for nucleon and hyperon spectroscopy. The experiments have provided novel data on K^- and π^- induced reactions for kaon beams of 500-750 MeV/c and pion beams of 150 to 750 MeV/c as well as produced new upper limits for various η decay modes, see for example [2,3,4,5,6]. Here we use some of the K^- and π^- results to illustrate the extraordinary capabilities of the Crystal Ball.

2 MAMI-B

The Mainz Microtron is a unique facility which satisfies our beam demands. The maximum photon energy available with MAMI-B is E_γ^{max} =855 MeV. The energy upgraded machine (MAMI-C) will provide E_γ^{max} =1.5 GeV, which corresponds to $\sqrt{s}$ = 1.92 GeV. The resolution of the MAMI/Glasgow tagging facility [7] for bremsstrahlung photons is $\Delta E_\gamma = 2$ MeV for an incoming electron beam of 855 MeV. The resolution can be improved at least by factor of three using the tagger microscope. The microscope covers approximately 80 MeV of the photon bremsstrahlung spectrum. The maximum photon flux is $N_\gamma^{max} = 5 \times 10^5$ [s^{-1} MeV^{-1}], that is much higher than most other facilities in the world. The degree of photon polarization is 70% for linearly and 85% for circularly polarized photons.

3 MAMI-C

A Harmonic Double Sided Microtron (HDSM) is presently under construction to increase the end energy of the three staged cw Race-Track Microtron (RTM) cascade MAMI from 0.855 to 1.5 GeV. This new accelerator, scheduled to come into operation in 2004, consists mainly of two pairs of 90° bending magnets and two linear accelerators (see Fig. 1). Special features of the HDSM are the operation of the two linacs at different frequencies, 2.45 GHz and 4.90 GHz, for higher longitudinal stability, and a relatively strong field gradient in the bending magnets for the compensation of vertical edge defocusing. In this section the main design considerations and a short report of the status for construction is presented.

In order to extend the experimental possibilities at the Institute of Nuclear Physics at the University of Mainz the end energy of MAMI will be increased by a fourth stage to 1.5 GeV. The main prerequisites were that there should be no substantial degradation of the excellent beam quality and operational reliability of the RTM cascade (see Ta-

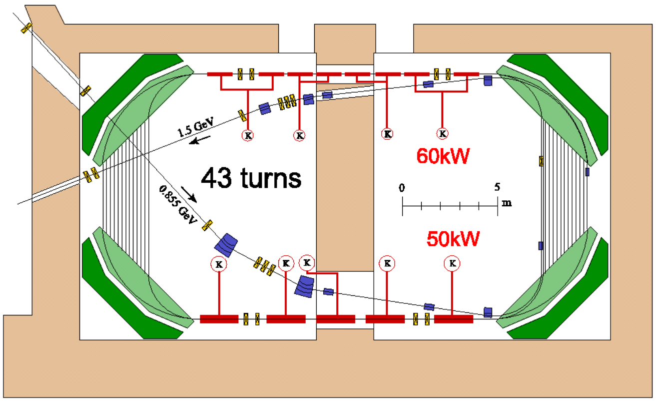

Fig. 1. General layout of HDSM

Table 1. Main parameters of RTM3 and HDSM

		RTM3	HDSM
General			
$E_{Inj.}$	MeV	180.2	855.5
$E_{Extr.}$	MeV	854.4	1507
turns	#	90	43
power consumption	kW	650	1500
RF system			**Linac: 1 / 2**
total energy gain	MeV	7.49	16.63 - 13.93
frequency	GHZ	2.449532	4.899 / 2.449
sections/klystrons	#	5/5	8/4 / 5/5
linac length	m	8.870	8.59 / 10.10
shunt-impedance	MΩ/m	67	78 / 68
dissipated power	kW/m	11.5	14.2 / 12.4
beam power	kW	67.4	65.2
Magnet system			
min./max. field	T	1.2842	0.95 - 1.53
min./max. gap	mm	100	85 - 138
min./max. radius	m	0.47 - 2.22	2.23 - 4.60
weight	to	900	1000
Beam parameters			
energy width	keV	13	110
hor. emittance	nm rad	7.8	9.2
vert. emittance	nm rad	0.5	0.4

ble 1), and that an existing experimental hall (29×15 m^2) should be used for the installation of the accelerator. At the beginning two different solutions were studied: a) a superconducting isochronous recirculator with only a few turns and b) a double sided microtron (DSM) with smaller energy gain and greater number of turns. Detailed calculations for solution b) showed that the emittance increase by quantum fluctuations from synchrotron radiation was only about a factor of 1.5 in both horizontal and longitudinal directions [8]. Therefore, and because of higher investment costs of solution a) it was decided to build a DSM. For more details on the design and status of the 1.5 GeV double sided microtron see [9].

4 Physical program

The first stage of our physical program at MAMI (MAMI B) is centered on the first measurement of the magnetic dipole moment of the $\Delta^+(1232)$ resonance. The magnetic dipole moment, μ_b, provides us with a simple way for testing the validity of the theoretical hadron description in the non-perturbative sector of QCD. This includes quark soliton models, the standard quark models, various effective Lagrangians and lattice QCD calculations. Our experimental technique takes advantage of the very short Δ lifetime by having the Δ radiatively decay to itself. This method has been successfully pioneered for the Δ^{++} using the reaction $\pi^+p \to \gamma'\Delta^{++} \to \gamma'\pi^+p$ [10]. We propose to determine $\mu_b[\Delta^+(1232)]$ using radiative π^0 photoproduction: $\gamma p \to \Delta^+ \to \gamma'\Delta^+ \to \gamma'\pi^0 p$. A first pilot experiment $\gamma p \to \gamma'\pi^0 p$ has been performed with the TAPS calorimeter at MAMI for energies $\sqrt{s} = 1221-1331$ MeV. Angular and energy differential cross section have been determined for all particles in the final state in three bins of the excitation energy [11]. The theoretical aspects have been dealt with in detail already by the theory groups at MAMI [12] and Tuebingen [13]. μ_b can be determined from the differential cross section $d\sigma^5/d\Omega_\gamma d\Omega_\pi dE_\gamma$ and from the asymmetry, Σ, for linearly polarized photons.

The broad spectrum of MAMI bremsstrahlung photons from $E_\gamma^{min} \approx$100 MeV to $E_\gamma^{max} \approx$1500 MeV together with the 4π acceptance of the experimental apparatus allows the simultaneous survey of π^0, $2\pi^0$, $3\pi^0$ and η production at all energies and for the full angular range. Such measurements will be perform with LH_2 and LD_2 targets using linearly and circularly polarized photon beams. A unique frozen spin target filled with ^{1}H, or ^{2}H will be used in the second stage of the experiment (MAMI-C). The target makes possible new high precision, high statistics measurements of the cross sections for the $\gamma\mathbf{N} \to \pi^0 N$ and $\gamma\mathbf{N} \to \pi^0\pi^0 N$ processes at incident photon energies up to 1.5 GeV. In particular it provides a unique opportunity to measure the partial contributions to the GDH sum rule on a neutron target in the reactions $\gamma\mathbf{n} \to \pi^0 n$ and $\gamma\mathbf{n} \to \pi^0\pi^0 n$. Our measurements will also provide new information on the photon coupling of low-mass baryon and hyperon resonances.

The production of $2\pi^0$'s on nuclei is interesting because of predicted medium modification effects. They have recently received much attention both, experimental and theoretical, see for example [6,14,15,16]. We plan to make new high statistics, high precision measurements of $2\pi^0$ production on complex nuclei with the Crystal Ball at Mainz. The data will be obtained simultaneously over the full range of incident photons energies up to 1.5 GeV. That will allow us to investigate in better details the possibility of chiral restoration in normal nuclear matter. It also enable us to make better estimate of the corrections due to the pion rescattering in nuclei.

An incomplete list of other possible measurements includes: (i) threshold photoproduction of π^0 and η at MAMI-B as well as η', ω and K_s^0 at MAMI-C with polarized and unpolarized beams and targets; (ii) measure-

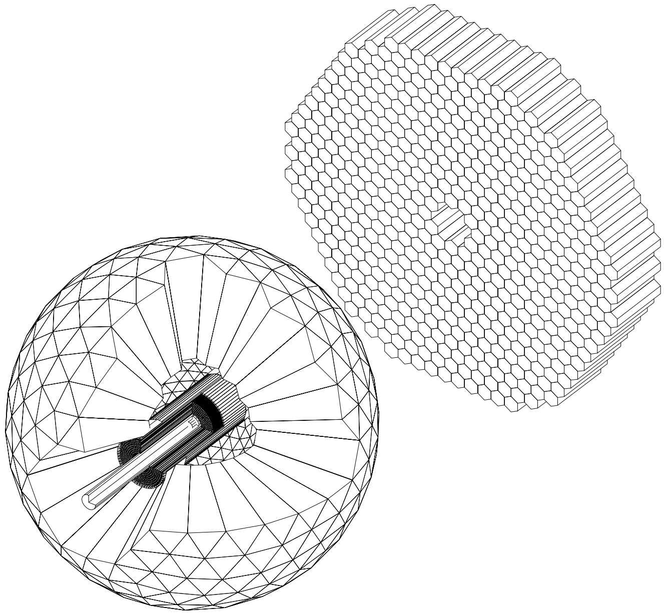

Fig. 2. The experimental apparatus proposed for the experimental program at MAMI. Some of the Crystal Ball crystals have been omitted in order to show the position of the cylindrical wire chamber and the target inside the Crystal Ball. The central detector, the Crystal Ball, TAPS as forward wall, the cylindrical wire chamber, and the liquid hydrogen target are shown

ments of the $N^*(1535)$ magnetic dipole moment using $\gamma p \to \gamma' \eta p$; (iii) a new measurement of the η mass.

The proposed experimental apparatus is shown in Fig. 2. The Crystal Ball with TAPS as the forward wall will be used for detection of photons and nucleons. In addition the polar and azimuthal angles of the outgoing proton for $\Theta_{lab} > 20°$ will be measured by the central tracker which is based on the DAPHNE cylindrical multiwire proportional chamber. The chamber will be inserted into the Crystal Ball beam cavity.

The Crystal Ball was build at SLAC and used in J/ψ measurements at SPEAR and b–quark physics at DESY [17]. The CB is constructed of 672 optically isolated NaI(Tl) crystals, 15.7 radiation lengths thick. The counters are arranged in a spherical shell with an inner radius of 25.3 cm and an outer radius of 66.0 cm. The hygroscopic NaI is housed in two hermetically sealed evacuated hemispheres. Each crystal is shaped like a truncated triangular pyramid, 40.6 cm high, pointing towards the center of the Ball. The sides on the inner end are 5.1 cm long and 12.7 cm on the far end. Electromagnetic showers in the spectrometer are measured with an energy resolution

$$\sigma_E/E \sim 1.7\%/(E\ (\mathrm{GeV}))^{0.4}\,;$$

the angular resolution for photon showers at energies of 0.05–0.5 GeV is $\sigma_\theta = 2°$–$3°$ in the polar angle and $\sigma_\phi = 2°/\sin\theta$ in the azimuthal angle.

High granularity and a large acceptance make the Crystal Ball a unique instrument for measuring reactions with multiphoton final states. The CB detects neutrons

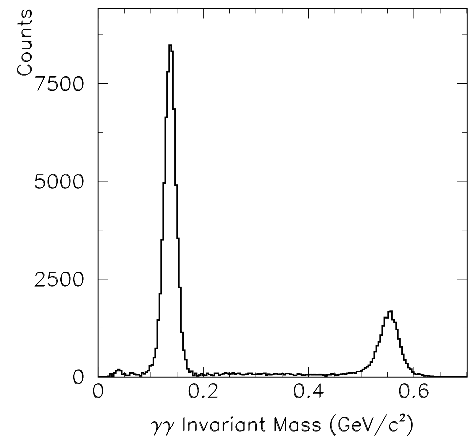

Fig. 3. Invariant mass of two photons obtained for a 1.8–cm–thick CH_2 target in a 750 MeV/c π^- beam. The normalized carbon and empty target spectra have been subtracted

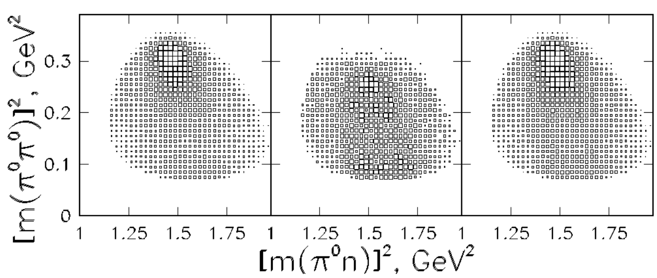

Fig. 4. Dalitz plots measured for $\pi^- p \to \pi^0\pi^0 n$. There are two entries for every event. **Left:** Only 4-cluster (*four photon*) events are used. **Center:** Only 5-cluster (*four photon and the neutron*) events are used. **Right**: Sum of 4- and 5-cluster events

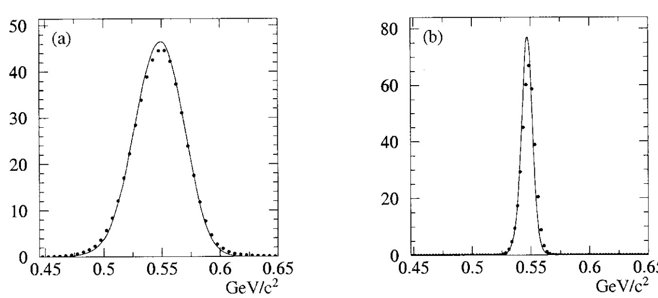

Fig. 5. a Invariant mass spectrum for the six clusters in $\pi^- p$ interactions at 720 MeV/c. **b** Invariant mass spectrum for the $3\pi^0$ for a constrained fit to the process $\pi^- p \to \eta n \to 3\pi^0 n \to 6\gamma n$, a 4C fit. The *dots* are our data and the *line* is the Monte Carlo showing excellent agreement

with an efficiency of $\approx 35\%$ at $E_n = 150$ MeV [4]. Figures 3, 4, and 5 show examples of our pion data for 2-cluster, 4-cluster, 5-cluster and 6-cluster events. The invariant mass of two photons exhibits two narrow peaks from $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ events, see Fig. 3. The small background under the peaks ($< 2\%$) comes from photon-neutron misidentification. Figures 4(Left) and 4(Center) show the Dalitz plots of the $2\pi^0 n$ final state from 4-cluster (four photon) and 5-cluster (four photon and a neutron) events. The sum of 4- and 5-cluster events is shown in

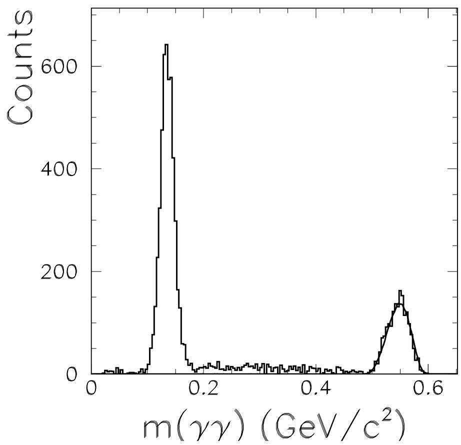

Fig. 6. The invariant mass of two photons in $K^- p \to \gamma\gamma\Lambda$ obtained with 750 MeV/c K^- beam. We have identified the π^0 that comes from Λ decay by its unique kinematics. The normalized empty target spectrum has been subtracted. The results of the Monte Carlo simulation are shown by the *smooth solid line*. The first peak is due to $K^- p \to \pi^0\Lambda$ and the second one to $K^- p \to \eta\Lambda$

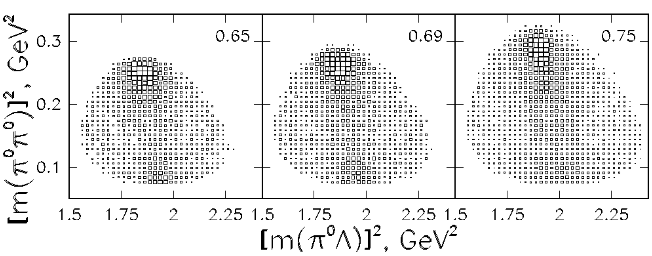

Fig. 7. Dalitz plots for $K^- p \to \pi^0\pi^0\Lambda$. Λ is detected via $\Lambda \to \pi^0 n$ decay

Fig. 4(Right). The CB acceptance for the sum is constant over the entire area of the Dalitz plot. Figure 5a shows the invariant mass of the 6γ satisfying a χ^2 test for the reaction $\pi^- p \to \eta n \to 6\gamma n$. The distribution peaks at the η mass and has $\sigma \approx 18.0$ MeV/c^2. The typical CB acceptance for the six photon final state is about 15%. The fact that the $\eta \to 6\gamma$ decay occurs via intermediate $3\pi^0$'s allows us to apply three additional constraints, namely the masses of the $3\pi^0$'s. Such constraints are useful to reduce the background and they improve the experimental resolution. The improved mass resolution when applying a constrained fit to the reaction $\pi^- p \to \eta n \to 3\pi^0 n$ is shown in Fig. 5b. The width of the η peak is $\sigma \approx 5.0$ MeV/c^2. The background under the peak is less than 1%.

The CB has been successfully used for extensive studies of hyperon production: the Λ is measured via $\Lambda \to \pi^0 n$, Σ^0 via $\Sigma^0 \to \Lambda\gamma$ and K_s^0 via $K_s^0 \to 2\pi^0$ decay. Λ and K_s^0 travel a few centimeters before decay. The distance between primary (production) vertex and decay vertex can be determined using the good energy and angular resolution of the detector. That allows the reliable identification of the π^0 from $\Lambda \to \pi^0 n$, see [2] for details. Figure 6 show the invariant mass of two photons from the $\gamma\gamma\Lambda$ final state. Most of the background comes from the $\gamma\gamma\Sigma$ final state and $K_s^0 \to \pi^0\pi^0$. Six-cluster events from $K^- p \to \pi^0\pi^0\Lambda$ are clearly detected. The Dalitz plot of the reaction is shown in Fig. 7 for three different momenta. The structure of the Dalitz plots looks remarkably similar to the ones from $\pi^- p \to \pi^0\pi^0 n$, see [18] for details. The process $K^- p \to \eta\Lambda$ followed by $\eta \to 3\pi^0$ decay is a source of 8-cluster events. The CB acceptance for such events is about 9% [2].

The unique features of the Crystal Ball detector demonstrated in the series of experiments in BNL will be substantially enhanced in Mainz by adding the TAPS forward wall and the central tracker. The Crystal Ball is scheduled to arrive to Mainz sometime in the fall of 2002. We are planning to start the data taking for the first round of experiments in early fall 2003. The first round will be finished by spring 2004 followed by the upgrade of MAMI and the tagger. The Crystal Ball collaboration is looking forward for the first experiment on the upgraded MAMI-C with the new tagger. The anticipated beginning date for the second stage of the experimental program is spring 2005.

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