Hadron physics with the Crystal Ball at MAMI

A. Starostin

Department of Physics and Astronomy
UCLA, box 1547, Los Angeles, CA, 90095-1547

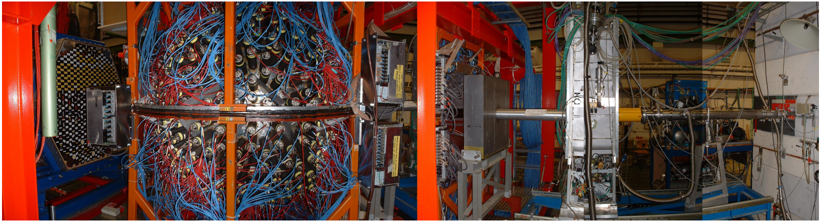
Meson08/Krakow, Poland, 6 – 10 June 2008

Outline

CB@MAMI Collaboration

- B. Nefkens, S. Prakhov, A. Starostin and I. Suarez: *UCLA, USA*
- J. Ahrens, H.J. Arends, A. Thomas, L. Tiator, D. von Harrach, Th. Walcher: *Uni. of Mainz, Germany*
- R. Beck, M. Lang, S. Schumann, and M. Unverzagt: *University of Bonn, Germany*
- S. Altieri, A. Braghieri, P. Pedroni, and T. Pinelli: *INFN Sezione di Pavia, Pavia, Italy*
- J.R.M. Annand, K. Livingston, I.J.D. MacGregor and G. Rosner: *Uni. of Glasgow, UK*
- W. Briscoe: *George Washington University, Washington, USA*
- S. Cherepnya, L. Fil'kov, and V. Kashevarow: *Lebedev Institute, Moscow, Russia*
- V. Bekrenev, S. Kruglov, A. Koulbardis and N. Kozlenko: *Petersburg Nuclear Physics Institute, Russia*
- B. Boillat, B. Krusche and F. Zehr: *Institut fur Physik University of Basel, Switzerland*
- R. Gregor, V. Metag, M. Kotulla, S. Lugert, R. Novotny, and M. Pfeiffer: *Giessen, Germany*
- D. Branford, K. Foehl, D. Glazier, C.M. Tarbert and D.P. Watts: *University of Edinburgh, Edinburgh, UK*
- V. Lisin, R. Kondratiev and A. Polonski: *Institute for Nuclear Research, Moscow, Russia*
- D. Hornidge: *Mount Allison University, Sackville, Canada*
- P. Grabmayr and T. Hehl: *Physikalisches Institut Universitat Tubingen, Germany*
- M. Manley: *Kent State University, Kent, USA*
- M. Korolija and I. Supek: *Rudjer Boskovic Institute, Zagreb, Croatia*
- D. Sober: *Catholic University, Washington DC*

Experimental Setup at MAMI



Detection System

Crystal Ball: spherical detector, 672 NaI crystals 16 r.l., geometrical acceptance ∼94%. Resolution: $\sigma_E/E \sim 1.7\%/(E\ (\mathrm{GeV}))^{0.4}$; $\sigma_\Theta \sim 2-3^\circ$.

TAPS: forward wall, 384 BaF crystals 12 r.l., excellent energy and TOF resolution, particle ID via pulse shape analysis, a veto counter in front of each crystal.

Tracker: MWPC – two layers, angular resolution 2°, PID detector – 24–elements barrel of plastic scintillators, particle ID based on dE/dx.

Beam and Targets

MAMI-B: high intensity, very stable beam of polarized electrons, $E_{max} = 883$ MeV.

MAMI-C: $E_{max} = 1.508$ GeV, first experiments started early 2007.

Tagger: provides high resolution photon beam with $E_{max}(\gamma) \approx 0.94 E_{max}(e^-)$.

Targets: Cryogenic liquid hydrogen, deuterium, ^{3}He, complex nuclear targets. Coming soon: Frozen–spin long. polarized, gas ^{3}He, ...

Magnetic Moments of Baryons

Nature of μ_b

- μ_b is due to quark spins and to the average of the quark currents
- μ_b is a fundamental characteristic of every baryon and a unique and elegant way for testing theoretical models

What is known?

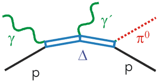
- Baryon octet ($\tau \geq 10^{-10}$ sec): μ_b well known – measured with spin precession techniques.
- Baryon decuplet ($\tau \leq 10^{-20}$ sec): μ_b unknown (except for $\Omega^-(1672)$).
- Radiative transition of resonances are sensitive for the μ_b. Proposed by Kondratyuk and Ponomarev (Yad. Fiz. 7 (1968) 11) for $\Delta^{++}(1232)$ and reaction $\pi^+ p \to \Delta^{++}\gamma' \to \pi^+\gamma' p$; measured by Nefkens *et al.* Phys. Rev. D 18 (1978) 3911.

Predictions for the value of the $\mu(\Delta^+(1232))$

Theory	Δ^+	References
LCQCD	2.2± 0.4	T.M. Aliev *et al.*, Phys. Rev. D **62**, 053012 (2000).
QCDSR	2.19± 0.50	B.L. Ioffe, Nucl. Phys. **B188**, 317 (1981); F.X. Lee, Phys. Rev. D (**57), 1801 (1998).**
Latt.	2.46± 0.31	D.R. Leinweber *et al.*, Phys. Rev. D **46**, 3067 (1992).
χPT	2.1± 0.2	M.N. Butler *et al.*, Phys. Rev. D **49**, 3459 (1994).
RQM	2.38	F. Schlumpf, Phys. Rev. D **48**, 4478 (1993).
NQM	2.73	K. Hikasa *et al.*, Phys. Rev. D **45**, S1 (1992).
χQSM	2.19	H.C. Kim *et al.*, Phys. Rev. D **57**, 2859 (1998).
χB	0.75	S.T. Hong and D.P. Min, nucl-th/9909004.

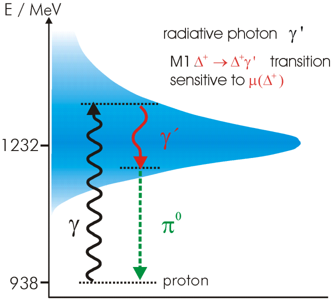
$\Delta^+(1232)$ Magnetic Moment

radiative pion photoproduction: $\gamma + p \rightarrow \Delta^+ + \gamma' \rightarrow \pi^0 + p + \gamma'$



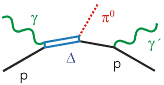
radiative photon γ'

M1 $\Delta^+ \rightarrow \Delta^+\gamma'$ transition
sensitive to $\mu(\Delta^+)$

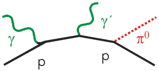


angular momentum, parity and time reversal
only M1 and M3 possible

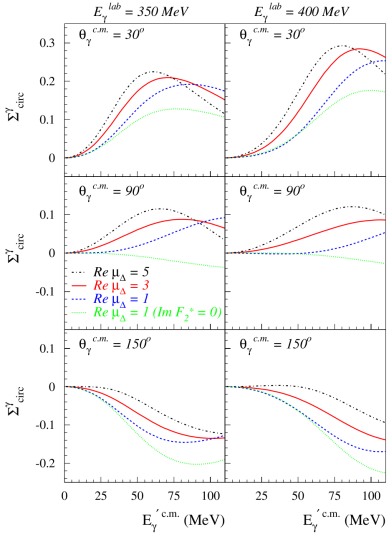
Problem :
Proton bremsstrahlung



Nonresonant contributions
small in Δ-resonance region



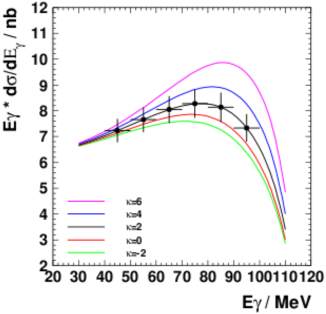
Theoretical predictions and experimental difficulties



- "Effective Lagrangian approach" (A.I Machavariani, A. Faeßler, and Buchmann, NP **A646** (1999) 631)
- "Dynamical models" (W.T Chiang, M. Vanderhaeghen, S.N. Yang, and D. Drechsel, PRC (2005) 015204)
- "Chiral effective field theory" (V. Pascalutsa and M. Vanderhaeghen PRD 77 (2008) 014027)

- To be sensitive, the differential cross section has to be measured to the accuracy of 5-10%
- Experimental backgrounds from $\gamma p \longrightarrow \pi^0 n$ (main) and $\gamma p \longrightarrow \pi^0 \pi^0 p$.

Magnetic Dipole Moment of $S_{11}(1535)$



JIAN LIU, JUN HE, AND Y. B. DONG

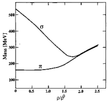
TABLE VI. Magnetic moments of the resonances with J = 1/2 (in units of nuclear magneton) in the different exchange models.

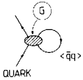
	OPE	OPsE	GBE	OGE
$\theta_{1/2^-}(^\circ)$[9]	25.5	23 ± 1	-27 ± 12	-32
$\mu_{1/2(S_{11}^+(1535))}(CQM)$	-0.5	$-0.4^{-0.0}_{+0.0}$	$1.7^{-0.6}_{+0.5}$	1.9
$\mu_{1/2(S_{11}^+(1535))}(\chi QM)$	-0.4	$-0.3^{+0.1}_{-0.0}$	$1.4^{-0.4}_{+0.4}$	1.6
$\mu_{1/2(S_{11}^0(1535))}(CQM)$	1.0	$0.9^{+0.0}_{-0.0}$	$-1.1^{+0.4}_{-0.3}$	-1.3
$\mu_{1/2(S_{11}^0(1535))}(\chi QM)$	0.9	$0.8^{+0.0}_{-0.0}$	$-0.9^{+0.4}_{-0.3}$	-1.0
$\mu_{1/2(S_{11}^+(1650))}(CQM)$	2.5	$2.4^{+0.0}_{-0.0}$	$0.3^{+0.6}_{-0.5}$	0.1
$\mu_{1/2(S_{11}^+(1650))}(\chi QM)$	1.9	$1.9^{+0.0}_{-0.0}$	$0.1^{+0.5}_{-0.3}$	0.0
$\mu_{1/2(S_{11}^0(1650))}(CQM)$	-1.3	$-1.2^{-0.0}_{+0.0}$	$0.8^{-0.4}_{+0.3}$	1.0
$\mu_{1/2(S_{11}^0(1650))}(\chi QM)$	-1.2	$-1.2^{-0.0}_{+0.1}$	$0.6^{+0.3}_{-0.4}$	0.7

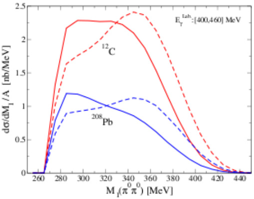
Predictions for the value of the $\mu(S_{11}(1535))$

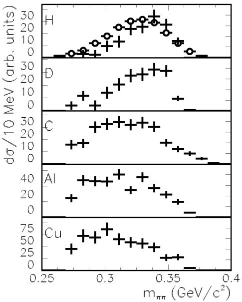
	$S_{11}^+(1535)$	$S_{11}^0(1535)$
CQM (W.-T. Chiang *et al.* NP A 723 (2003) 2005)	1.89	-1.28
χUM (T. Hyodo *et al.* nucl-th 0305023)	1.1	-0.25

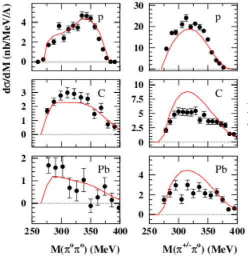
Medium Modification at Normal Nuclear Density







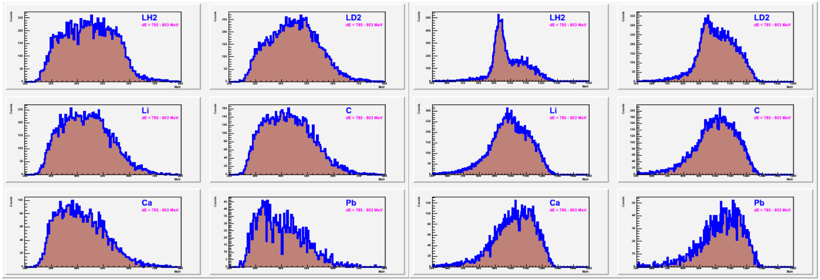


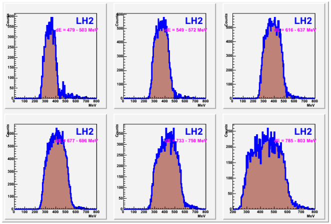


- In QCD hadrons are expected to change their mass in nuclear matter of normal density ρ_0.
- Effect was studied using production of short living particles ($f_0(600)$, $\rho()770$, *etc.*) inside nuclei.
- Rescattering of decays product inside the nuclei is a serious problem.

V. Bernard *et al.* PRL 59 (1987) 966; L. Roca *et al.* PL B541 (2002) 77; A. Starostin *et al.* PRL 85 (2000) 5539; J.G. Messchendorp *et al.* PRL 89 (2002) 222302.

$\pi\pi$ Invariant Mass on Complex Targets

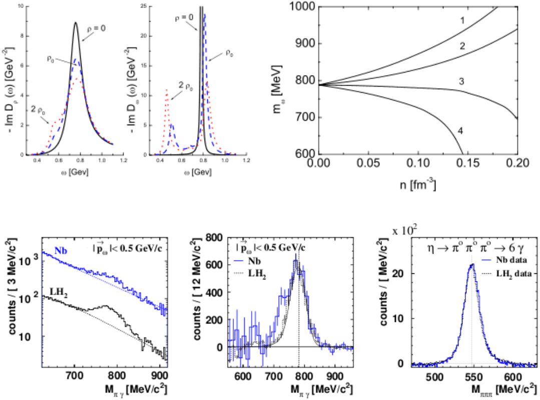




Experiment at MAMI-B

Significant statistics was collected for LH_2, C, and Pb.
Some data exist for LD_3, Li, Ca, and O
Currently experiment with liquid ^3He was completed.
Analysis of the data is in progress.

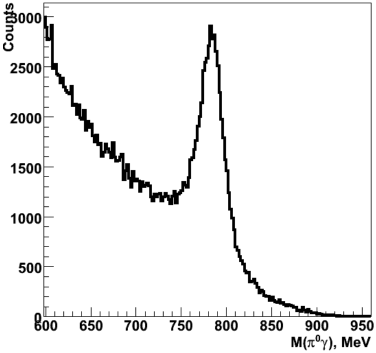
Measurement of the in–medium ω mass

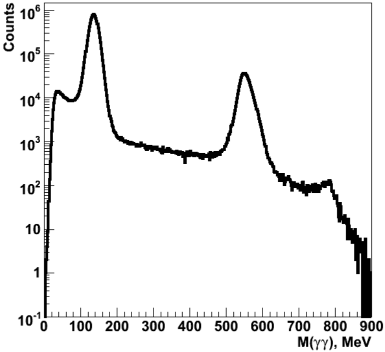


New MAMI-C proposal

Results of the TAPS experiment show effect of the nuclear media on ω mass. More statistics needed. CBTAPS@MAMI experiment was proposed and approved.
300 h worth of data were collected this April–May on *Nb* target. More data will be collected this summer.
M. Lutz *et al.* NP A706 (2002) 431; D. Trnka *et al.* PRL 94 (2005) 192303.

ω photoproduction at MAMI-C





ω were detected using $\omega \longrightarrow \pi^0\gamma$ and $\omega \longrightarrow e^+e^-$ decay modes. The $\omega \longrightarrow e^+e^-$ mode does not suffer from the pion rescattering inside the nuclei that is a largest correction while studying the medium effects.

Coherent and incoherent π^0 production from nuclei

- Give access to nuclear matter form factor
- Modeling structure of neutron stars
- ....

will be presented in details later today by D.Watts

Dalitz plot of $\eta \to 3\pi^0$

Slope parameter α

The density of the Dalitz plot is constant in QCD:

$$A(\eta) = \frac{m_u - m_d}{\sqrt{6}F^2} \times (\sqrt{1/2}\cos(\phi) - \sin(\phi))$$

(P. Di Vecchia *et al.*, Nucl. Phys. **B** 181 (1981) , 318).
The dependence gradient appears as a result of $\pi\pi$ interaction and can be calculated in χPT.

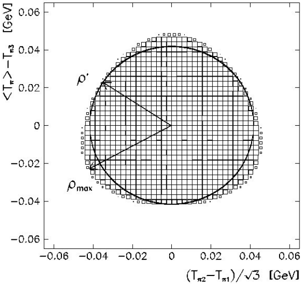
$$A(\eta \to 3\pi^0) \sim (m_u - m_d) \times (1 + \alpha z)$$

$$\Gamma(\eta \to 3\pi^0) \sim (m_u - m_d)^2 \times (1 + 2\alpha z)$$

$$z = 6\sum_{i=1}^{3}(E_i - m_\eta/3)^2/(m_\eta - m_{\pi^0})^2$$

Search for cusp in the $\pi^0\pi^0$ invariant mass

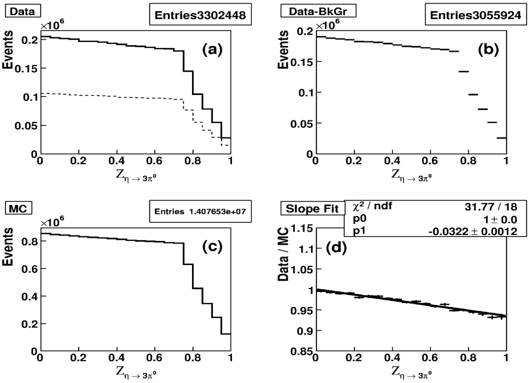
Cusp on the $\pi^0\pi^0$ invariant mass distribution expected at the opening of the $\pi^0\pi^0 \to \pi^+\pi^-$ channel. The cusp carries information on the s-wave $\pi\pi$ scattering length combination $a_0 - a_2$.



Current status on the experimental and theoretical study of the $\eta\to3\pi^0$ decay

- Experimental results for α:
  GAMS2000 (1984): -0.022±0.023
  CBarrel at LEAR (1998): -0.052±0.017±0.010
  CBall at AGS (2001): -0.031±0.004
  KLOE (prelim.2005): -0.013±0.004±0.005
  CELSIUS-WASA (2007): -0.026±0.010±0.010
  KLOE (prelim.2007): -0.027±0.004±0.005
- Predictions for α:
  J.Kambor et al. (1996): -0.007 or -0.0014
  B.Borasoy et al. (2005): -0.031±0.003
- no experimental results for the $m(\pi^0\pi^0)$ cusp in $\eta\to3\pi^0$
- J.Belina (2006): ~5% effect

Slope fit for the full data set
(3 runs: 04.07, 06.07, 07.07 ; 26.6M η's produced)



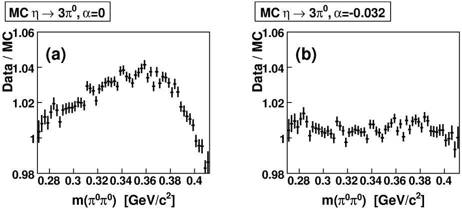
work by S. Prakhov, UCLA

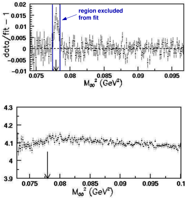
Summary of results for the $\eta \to 3\pi^0$ slope parameter depending on experimental conditions and selection cuts → α=-0.032±0.003

Test	Cuts	Statistics	α	χ^2/ndf
1	CL=2%	3.06M	-0.0322±0.0012	31.4/18
2	CL=5%	2.78M	-0.0326±0.0013	32.2/18
3	CL=10%	2.50M	-0.0329±0.0014	30.0/18
4	CL=20%	2.11M	-0.0326±0.0015	25.9/18
5	CL=2%, Eγ<1.1GeV	2.76M	-0.0320±0.0013	26.9/18
6	CL=2%, Eγ<0.9GeV	2.18M	-0.0321±0.0015	20.2/18
7	CL=2%, Ecb<0.42GeV	2.83M	-0.0316±0.0013	29.1/18
8	CL=2%, Ecb<0.47GeV	2.60M	-0.0319±0.0013	30.7/18
9	CL=2%, cosθ_η<0.	1.73M	-0.0334±0.0017	23.5/18
10	CL=2%, cosθ_η>0.	1.32M	-0.0312±0.0019	14.5/18
11	CL=2%, 7cl	2.39M	-0.0323±0.0014	26.4/18
12	CL=2%, 6cl	0.663M	-0.0292±0.0027	22.0/18

work by S. Prakhov, UCLA

Search for the cusp on the $\pi^0\pi^0$ Invariant Mass





Cusp is expected at the opening of $\pi^0\pi^0 \longrightarrow \pi^+\pi^-$. Magnitude is suppressed by the combinatorial background – all three $\pi^0\pi^0$ combinations are included.

top figure $K^+ \longrightarrow \pi^+\pi^0\pi^0$
bottom figure $K^0 \longrightarrow 3\pi^0$
presented by R. Wanke on MENU 2007.

Decay $\eta \to \pi^0\gamma\gamma$

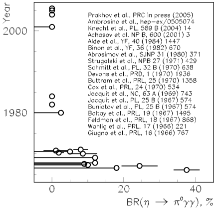
Test of higher-order χPT

- The leading order is forbidden because there is no direct $\gamma - \pi^0$, and $\gamma - \eta$ coupling.
- The tree diagram of the second order is forbidden because there is no direct $\gamma - \pi^0$, and $\gamma - \eta$ coupling.
- The loop diagram of the second order is suppressed because it violates G-parity.
- The third order is the first allowed term.

$\Gamma(\eta \to \pi^0\gamma\gamma) = 0.47 \pm 0.10\ \mathrm{eV}$ (E. Oset, J.R. Pelaez, and L. Roce, Phys. Rev. D, **67** (2003) 073013)

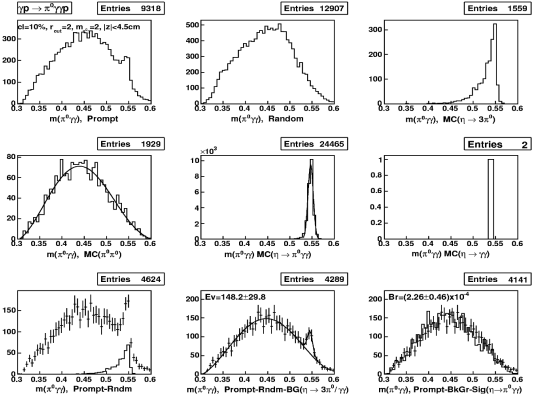
Experimental results for the width

CB@BNL: *BR*$(\eta \to \pi^0\gamma\gamma) = (3.5 \pm 0.7 \pm 0.6) \times 10^{-4}$
$\Gamma(\eta \to \pi^0\gamma\gamma) = (0.45 \pm 0.09 \pm 0.08)\ \mathrm{eV}$
(S.Prakhov *et al.*, Phys. Rev. C **72**, 025201 (2005).)
KLOE: *BR*$(eta \to \pi^0\gamma\gamma) = (0.84 \pm 0.27 \pm 0.14) \times 10^{-4}$
(F. Ambrosino *et al.*, arXiv:hep-ex/0505074, 25 May 2005.)



$\eta \to \pi^0\gamma\gamma$ from CB@MAMI-B

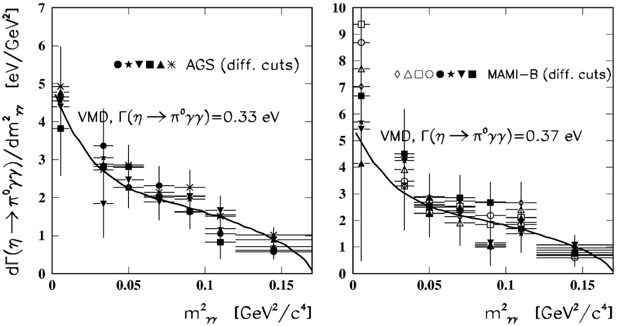
Example of the $\eta \to \pi^0\gamma\gamma$ analysis with the CB at MAMI-B



work by S. Prakhov, UCLA

$\eta \to \pi^0\gamma\gamma$ Matrix Element

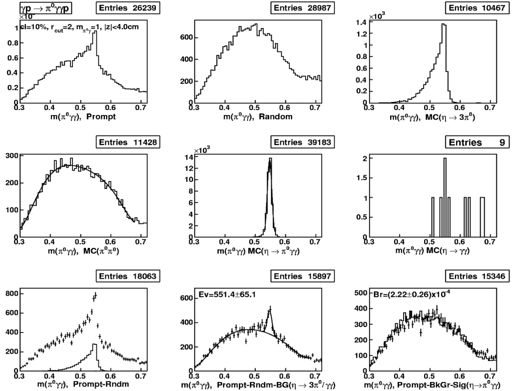
The CB (AGS and MAMI-B) results on the yield of $\eta \to \pi^0\gamma\gamma$ as a function of $m^2(\gamma\gamma)$ and comparison with the VMD prediction



Presented by S. Prakhov on MENU 2007 (to be published on the SLAC *econf* archive)

$\eta \rightarrow \pi^0\gamma\gamma$ from CB@MAMI-C

Preliminary analysis of $\eta\rightarrow\pi^0\gamma\gamma$ with the CB at MAMI-C
(data from April, June, July 2007)



work by S. Prakhov, UCLA

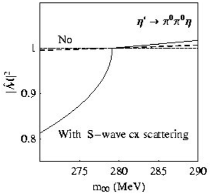
η and η' Decays at MAMI-C

η physics

- CB@MAMI will produce about 3 $\times$ 10^8 η within next a few years
- We will continue studying $\eta \to 3\pi^0$ Dalitz plot and $\eta \to \pi^0\gamma\gamma$
- More statistics will be collected for the $\eta \to e^+e^-\gamma$ decay (EM form-factor)
- We will improve on the upper limits for the *CP* and *C* forbidden decays, such as $\eta \to 4\pi^0$, $\eta \to \pi^0\gamma$, $\eta \to 2\pi^0\gamma$, $\eta \to 3\pi^0\gamma$, *etc*.

η' Decays at MAMI-C

- We will produce about 10^6 η' at MAMI-C
- The primary goal is $\eta' \to \eta\pi^0\pi^0$ Dalitz plot: slope parameter and the cusp on the $\pi^0\pi$ invariant mass
- New upper limits will be set for the *CP* and *C* forbidden η' decays: $\eta' \to 4\pi^0$, $\eta \to \pi^0 e^+e^-$, $\eta \to 3\gamma$.



Complete set of measurements

Usual symbol	Helicity representation	Transversity representation	Experiment required [a]	Type
$d\sigma/dt$	$\|N\|^2+\|S_1\|^2+\|S_2\|^2+\|D\|^2$	$\|b_1\|^2+\|b_2\|^2+\|b_3\|^2+\|b_4\|^2$	$\{-;-;-\}$	S
$\Sigma\, d\sigma/dt$	$2\mathrm{Re}(S_1^* S_2 - ND^*)$	$\|b_1\|^2+\|b_2\|^2-\|b_3\|^2-\|b_4\|^2$	$\{L(\frac{1}{2}\pi,0);-;-\}$ $\{-;y;y\}$	S
$T\, d\sigma/dt$	$2\mathrm{Im}(S_1N^* - S_2D^*)$	$\|b_1\|^2-\|b_2\|^2-\|b_3\|^2+\|b_4\|^2$	$\{-;y;-\}$ $\{L(\frac{1}{2}\pi,0);0;y\}$	S
$P\, d\sigma/dt$	$2\mathrm{Im}(S_2N^* - S_1D^*)$	$\|b_1\|^2-\|b_2\|^2+\|b_3\|^2-\|b_4\|^2$	$\{-;-;y\}$ $\{L(\frac{1}{2}\pi,0);y;-\}$	S
$G\, d\sigma/dt$	$-2\mathrm{Im}(S_1S_2^* + ND^*)$	$2\mathrm{Im}(b_1b_3^* + b_2b_4^*)$	$\{L(\pm\frac{1}{4}\pi);z;-\}$	BT
$H\, d\sigma/dt$	$-2\mathrm{Im}(S_1D^* + S_2N^*)$	$-2\mathrm{Re}(b_1b_3^* - b_2b_4^*)$	$\{L(\pm\frac{1}{4}\pi);x;-\}$	BT
$E\, d\sigma/dt$	$\|S_2\|^2-\|S_1\|^2-\|D\|^2+\|N\|^2$	$-2\mathrm{Re}(b_1b_3^* + b_2b_4^*)$	$\{c;z;-\}$	BT
$F\, d\sigma/dt$	$2\mathrm{Re}(S_2D^* + S_1N^*)$	$2\mathrm{Im}(b_1b_3^* - b_2b_4^*)$	$\{c;x;-\}$	BT
$O_x\, d\sigma/dt$	$-2\mathrm{Im}(S_2D^* + S_1N^*)$	$-2\mathrm{Re}(b_1b_4^* - b_2b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;x'\}$	BR
$O_z\, d\sigma/dt$	$-2\mathrm{Im}(S_2S_1^* + ND^*)$	$-2\mathrm{Im}(b_1b_4^* + b_2b_3^*)$	$\{L(\pm\frac{1}{4}\pi);-;z'\}$	BR
$C_x\, d\sigma/dt$	$-2\mathrm{Re}(S_2N^* + S_1D^*)$	$2\mathrm{Im}(b_1b_4^* - b_2b_3^*)$	$\{c;-;x'\}$	BR
$C_z\, d\sigma/dt$	$\|S_2\|^2-\|S_1\|^2-\|N\|^2+\|D\|^2$	$-2\mathrm{Re}(b_1b_4^* + b_2b_3^*)$	$\{c;-;z'\}$	BR
$T_x\, d\sigma/dt$	$2\mathrm{Re}(S_1S_2^* + ND^*)$	$2\mathrm{Re}(b_1b_2^* - b_3b_4^*)$	$\{-;x;x'\}$	TR
$T_z\, d\sigma/dt$	$2\mathrm{Re}(S_1N^* - S_2D^*)$	$2\mathrm{Im}(b_1b_2^* - b_3b_4^*)$	$\{-;x;z'\}$	TR
$L_x\, d\sigma/dt$	$2\mathrm{Re}(S_2N^* - S_1D^*)$	$2\mathrm{Im}(b_1b_2^* + b_3b_4^*)$	$\{-;z;x'\}$	TR
$L_z\, d\sigma/dt$	$\|S_1\|^2+\|S_2\|^2-\|N\|^2-\|D\|^2$	$2\mathrm{Re}(b_1b_2^* + b_3b_4^*)$	$\{-;z;z'\}$	TR

I.S. Barker, A. Donnachie, and J.K. Storrow, Nucl. Phys. **B95** (1975) 347.

- Lin. pol. of beam up to 60%, circ. pol. close to 100%
- Long. pol. “frozen–spin” target (will be available by end of this year)
- Long. pol. ^3He gas target (under construction)
- Nuclear recoil polarimeter (see talk by M. Sikora on this conference)
- Trans. pol. frozen–spin target (under consideration, can be available next year)

- beam asymmetry Σ, target asymmetry (T), recoil asymmetry (P)
- G, E, H, F
- O_x, O_z, C_x, C_z
- T_x, T_z, L_x, L_z

Summary

- The first round of the CBTAPS@MAMI experiments was completed in 2005. A large sample of data was collected using the beam of tagged polarized and unpolarized photons with the maximum beam energy up to 883 MeV.
- The data will be used to obtain the magnetic dipole moment of the $\Delta(1242)$, study medium modification effects, obtain new information on the properties of $P_{11}(1440)$ and $S_{11}(1535)$ and much more. Analysis of the data is in progress.
- Among other results, about 30 M η were produced. The sample will be used to determine the slope parameter of the $\eta \to 3\pi^0$ Dalitz plot, measure the branching ratio and determine the matrix element of the $\eta \to \pi^0\gamma\gamma$ decay, set new upper limits for C and CP forbidden η decays.
- The second set of experiments utilizes the upgraded MAMI-C 1.5 GeV beam. The program will continue most of the MAMI-B topics at higher energies. New experiments will be started as well, in particular measurements with polarized and double polarized observables.