Light meson physics with Crystal Ball/MAMI and at BES-III

Marc Unverzagt
Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, Germany
E-mail: unvemarc@kph.uni-mainz.de

Abstract.
Rare decays of light mesons like η, η', and ω offer excellent possibilities to study fundamental symmetries and symmetry-breaking patterns. Furthermore, electromagnetic transitions with vertices $P\gamma^*\gamma$ as in decays of light pseudoscalar mesons ($P$) or meson production in $e^+e^-$ collisions give insight into hadronic structure through transition form factors and produce additional constraints for the determination of the anomalous magnetic moment of the muon $(g-2)_\mu$. In this article, recent results on η and ω decays from the Crystal Ball at MAMI experiment as well as feasibility studies on transition form factors for the Crystal Ball and the BES–III at BEPC–II facility are presented.

1. Introduction
The decays of the light mesons provide unique information on the understanding of low-energy Quantum Chromo Dynamics (QCD). Since perturbative QCD cannot be applied in the low-energy region, other methods like lattice QCD, chiral perturbation theory ($\chi$PT) or model-dependent approaches are used. These can be tested by studying the different decay modes of the η and η' mesons. Moreover, many models and theories of hadronic interaction can be tested. One can also search for the violation of lepton–family number and place limits on the masses and couplings of many proposed lepto–quark families, see refs [1, 2, 3, 4, 5]. Decays of light mesons are also suitable to search for violations of C, CP, and CPT invariance [6].

Other studies that can be addressed with light meson decays are electromagnetic transition form factors. These form factors shed light on the intrinsic structure of hadrons. Furthermore, measurements of electromagnetic transition form factors of mesons are indirectly related to the Light–by–Light contribution, which is of increasing relevance for the Standard Model prediction of the anomalous magnetic moment of the muon. The high meson production rates achievable with the Crystal Ball/TAPS setup at MAMI (Mainz Microtron) provide a good opportunity for a valuable contribution to the Light–by–Light calculations.

Transition form factors of light mesons can also be studied in $e^+e^-$ scattering experiments in so–called $\gamma\gamma$–physics. This is done using the BES–III (Beijing Spectrometer) detector at the BEPC–II (Beijing Electron Positron Collider). These two different approaches are complementary, covering different momentum transfer regions. At MAMI this is $2m_l^2 < q^2 < m_P^2$ with $m_l$ a lepton mass, while at BEPC–II momentum transfers of $-10\text{GeV}^2 < q^2$ can be measured.
2. Experiments
The groups at the Johannes Gutenberg–University at Mainz, Germany, carry out measurements with two different experiments. At Mainz the accelerator MAMI together with the combined Crystal Ball/TAPS setup provides a unique environment to study symmetry–breaking patterns and transition form factors in meson decays. Furthermore, this experiment is ideal to study the lowest nucleon resonances and investigate the properties of light mesons. The goal of the BES–III detector at BEPC–II is to improve the knowledge of charmonium states and investigate D–meson decays. The mass of the τ lepton will also be measured very precisely. Another important topic at BEPC–II is γγ–physics. Since the two facilities work at different q^2 regions, many studies carried out at both experimental setups complement each other.

2.1. Crystal Ball at MAMI
The photoproduction facility at MAMI, with a maximum beam energy of 1604 MeV, together with the combined Crystal Ball/TAPS setup provides a perfect environment for studies of light meson decays. The high statistics available together with the good signal–to–background conditions makes investigations of η, η', and ω decays especially competitive at MAMI.

The electron accelerator MAMI consists of a cascade of three Race-Track-Microtrons (RTM) [7], and a fourth stage, a Harmonic-Double-Sided Microtron (HDSM) [8]. MAMI provides a very stable electron beam (energy drift δE < 100 keV) with a maximum energy of E_0 = 1604 MeV and an energy width of σ_e/E < 3·10^-5. High currents (110 μA) with electron polarisations up to 80 % can be achieved.

Within the A2 collaboration at MAMI, experiments are performed with a real photon beam. The photon beam for the production of light mesons is derived from the production of Bremsstrahlung photons during the passage of the MAMI electron beam through a thin radiator. The photon tagging spectrometer [9, 10] at Mainz (fig. 1) provides energy tagging of the photons through the relation E_γ = E_0 − E_{e−}, by detecting the post–radiating electron energy, E_{e−}. It can determine the photon energy with a resolution of 2 to 4 MeV depending on the incident beam energy, with a single–counter time resolution σ_t = 0.17 ns [11]. The maximum photon flux is 2.5·10^5 (s MeV)^{-1}. Photons can be tagged in the energy range from 5 to 93 % of the incoming electron energy E_0.

Since the η' photoproduction threshold is at E_{thr} ≈ 1447 MeV, most of the full photon energy range accessible at MAMI for η' production is not covered by the photon tagging spectrometer. Therefore, a new tagging device (End–Point Tagger) is currently being constructed. At the maximum electron beam energy, E_0 = 1604 MeV, photon energies between E_γ ≈ 1450 MeV and E_γ ≈ 1590 MeV can be tagged with this new device. To study the decays of the η' meson, the End–Point Tagger is essential for a clean trigger. The assembly of the End–Point Tagger is close to completion.

The central detector, surrounding the liquid hydrogen target (see fig. 2), is the Crystal Ball calorimeter (CB) [12, 13]. The CB is a highly segmented 672-element NaI(Tl), self triggering photon spectrometer. Each element is a 41 cm (15.7 radiation lengths) long truncated triangular pyramid. The CB has an energy resolution of ΔE/E = 0.020(E[GeV])^{0.36}, angular resolutions σ_θ of 2 – 3° and σ_φ of σ_θ/σ_φ for electromagnetic showers. The Crystal Ball is equipped with a barrel detector of 24 scintillator strips (50 cm length, 4 mm thickness at a radius of 6 cm around the photon beam line), which allows discrimination between charged and neutral particles, and offers the possibility to distinguish between different charged particles (PID).

At forward polar angles θ < 21° the TAPS detector [14, 15] provides acceptance for particle detection. Hence, the full detector system, as shown in fig. 2, is almost hermetic. The TAPS forward wall is composed of 384 BaF_2 elements, each 25 cm in length (12 radiation lengths) and hexagonal in cross section, with a diameter of 59 mm. Every TAPS element is covered by a 5 mm thick plastic veto scintillator. The single counter time resolution is σ_t = 0.2 ns. The energy
**Figure 1.** The photon tagging spectrometer at MAMI.

**Figure 2.** The Crystal Ball calorimeter with cut-away section showing the inner detectors and the TAPS forward wall.
resolution can be described by $\Delta E/E = 0.018 + 0.008/(E\,[\text{GeV}])^{0.5}$. The angular resolution in the polar angle is better than 1°, and in the azimuthal angle it improves with increasing $\theta$, being always better than $1/R$ radian, where $R$ is the distance in centimetres from the central point of the TAPS wall surface to the point on the surface where the particle trajectory meets the detector. The 2 inner rings of 18 BaF$_2$ elements have recently been replaced by 72 PbWO$_4$ crystals, each 20 cm in length (22 radiation lengths), see fig. 2. The higher granularity improves the rate capability as well as the angular resolution.

2.2. BES-III at BEPC-II

The BEPC-II electron–positron collider features high–statistics measurements in the center–of–mass energy range between 2 GeV and 4.2 GeV (so–called τ–charm–factory). It came into operation in 2009, and has reached a peak luminosity of $6 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$ [16]. The world’s largest data samples of $J/\psi$, $\psi'$ and $\psi(3770)$ have already been produced.

The BES–III detector comprises the main drift–chamber (MDC), a time–of–flight system (TOF), an electromagnetic calorimeter (EMC), and muon detectors, see fig. 3. The cylindrical MDC and the TOF system both cover polar angles of $18.2^\circ < \theta < 161.8^\circ$ and sit inside a magnetic field to measure the momentum of the reaction products. The MDC also contributes to particle identification through specific energy deposition of the particles. The EMC consists of 6300 Cs(Tl)–crystals and covers polar angles of $21.6^\circ < \theta < 158.4^\circ$. It can measure precisely the position (5 mm at $E = 1$ GeV) and the energy of leptons and photons (2.5 % at $E = 1$ GeV) between 20 MeV and 2 GeV [16].

Recently a new detector was installed 3.49 m downstream from the interaction point. Its purpose is to measure photons close to $\theta = 0^\circ$, Zero–Degree detector (ZDD), for measuring Initial–State–Radiation events. It consists of two lead bricks intermingled with scintillating fibers placed 5 mm above and below the beam axis. This detector will also improve the detection efficiency for $\gamma\gamma$–events.
3. Symmetry laws

Light mesons are fundamental excitations of the QCD ground state. Investigating their spectrum and interactions gives insight into the complex nature of the QCD vacuum and several competing mechanisms of symmetry breaking. In the low–energy region it is sufficient to consider only the three light quarks, \( u, d, \) and \( s \). The corresponding dynamical system exhibits gauge symmetry, and the discrete \( C, \ P, \) and \( T \) symmetries. Additionally it is subject to several approximate symmetries. Starting from the chiral symmetry for massless quarks, the interplay of three distinct symmetry–breaking patterns (explicit symmetry breaking due to finite quark masses, dynamical spontaneous symmetry breaking, and the \( U(1) \) axial anomaly) generates an extremely rich physics case.

The finite values of the quark masses lead to \( SU(3) \) flavour symmetry \( (m_u = m_d = m_s \neq 0) \). The fact that the \( s \) quark mass is much higher than the \( u \) and \( d \) quark masses \( (m_u = m_d \neq m_s) \) reduces the \( SU(3) \) flavour symmetry to \( SU(2) \) isospin symmetry. Isospin symmetry itself is also broken due to the different \( u \) and \( d \) quark masses \((m_u \neq m_d)\), and also due to their coupling the electromagnetic.

For the dynamical spontaneous symmetry breaking no rigorous mathematical proof is yet available. But there are clear indications for a breakdown of the global \( SU(3)_L \times SU(3)_R \times U(1)_V \times U(1)_A \) symmetry to \( SU(3)_V \) in the chiral limit. This gives rise to eight massless pseudoscalar Goldstone bosons, which are assigned to the pions, kaons and the \( \eta_8 \) state.

The \( U(1) \) anomaly is generated through quantum fluctuations that destroy the singlet axial–vector current conservation. In the large–\( N_C \) limit the anomaly disappears, and the singlet axial–vector current is restored. But it is assumed to be spontaneously broken in the large–\( N_C \) limit, giving rise to a ninth Goldstone boson, which is addressed with \( \eta_0 \).

The physical states, \( \eta \) and \( \eta' \), are an admixture of the two Goldstone boson states. This can be expressed by a single mixing angle, or in a more evolved parametrisation two mixing angles. Recently the KLOE collaboration published data on the \( \eta-\eta' \) mixing angle and a possible gluonium content to the \( \eta' \) [17, 18] determined from \( R = \Gamma(\phi \to \eta \gamma)/\Gamma(\phi \to \eta' \gamma) \). They found a non–zero gluonium content of the \( \eta' \), contrary to the theoretical calculation in [19].

In this context the \( \eta-\eta' \) system provides a unique tool for studying all three symmetry mechanisms simultaneously. By investigating decays like \( \eta/\eta' \to 3\pi^0 \), \( \eta \to \pi^0 \gamma \gamma \), \( \eta/\eta' \to 4\pi^0 \), \( \eta \to \pi^0 \pi^0 \gamma \gamma \), \( \eta \to \pi^+ \pi^- \gamma \), \( \eta' \to \eta \pi^0 \pi^0 \), \( \eta' \to \gamma \gamma \), and \( \eta' \to 3\gamma \) it might be possible to disentangle the various sources of symmetry breaking. In the near future all the reactions mentioned above will be investigated with the Crystal Ball at MAMI. Also, further studies dedicated to \( \omega \) decays (e.g. \( \omega \to \pi^0 \gamma, \omega \to \eta \gamma, \omega \to \pi^+ \pi^- \pi^0 \)) will be carried out.

In the remainder of this section the measurements and results from the Crystal Ball at MAMI experiment of two symmetry breaking meson decays are described. First the isospin breaking decay \( \eta \to 3\pi^0 \), then the branching ratios of three \( C \)–violating \( \omega \) decays are presented.

3.1. Isospin breaking in the \( \eta \to 3\pi^0 \) decay

The \( \eta \to 3\pi^0 \) decay violates isospin symmetry. Because electromagnetic contributions to the amplitude can be neglected [20, 21, 22], this decay occurs due to the isospin breaking part of the QCD Hamiltonian:

\[
H = \frac{1}{2}(m_u - m_d)(\bar{u}u - \bar{d}d).
\]

Hence, the amplitude is proportional to the mass difference \( m_u - m_d \) of the two lightest quarks \( u \) and \( d \). Calculations of the decay amplitude are usually based on the framework of \( \chi PT \). Thus, this measurement also provides a very important test for \( \chi PT \). The squared absolute value of the decay amplitude may be expanded around the centre of the Dalitz plot:

\[
|A(\eta \to 3\pi^0)|^2 = |N|^2(1 + 2\alpha z + \ldots),
\]

where \( \alpha \) is the Cabibbo–Kobayashi–Maskawa (CKM) matrix element (assumed to be zero for the purposes of this calculation).
where $N$ is a normalisation constant, which is equal to the amplitude that would apply, if the decay proceeded only according to the available phase space. The Dalitz plot parameter, $\alpha$, describes the pion energy dependence of the squared absolute value of the decay amplitude up to first order of the expansion. The parameter $z$ is given by

$$z = 6 \sum_{i=1}^{3} \left( \frac{E_i - m_\eta/3}{m_\eta - 3m_{\pi^0}} \right)^2.$$  \hspace{1cm} (3)

Here $E_i$ represents the pion energies in the $\eta$ rest frame.

At MAMI two new determinations of the Dalitz plot parameter, $\alpha$, from the $\eta \rightarrow 3\pi^0$ decay were performed using two different data sets with different electron beam energies, $E_0 = 883$ MeV [23] and $E_0 = 1508$ MeV [24], respectively. Thus, they can be considered as independent measurements. These results, with $1.8 \times 10^6$ and $3 \times 10^6$ events, represent the worlds two highest statistics measurements for the $\eta \rightarrow 3\pi^0$ decay. The two independent values for $\alpha$ from MAMI agree perfectly with each other and are consistent with other experiments (see fig. 4), [25] and references therein. Pure $\chi$PT calculations give the wrong sign for $\alpha$, which is fixed by the experiments to be negative. Dispersion calculations give the correct sign, but differ in the absolute value by several standard deviations.

Recently, a new study of rescattering effects in $\eta \rightarrow 3\pi$ decays was presented [25]. Using the modified non–relativistic effective field–theory, and matching the coupling constants involved to $\chi$PT at $O(p^4)$, the Dalitz plot parameter $\alpha = -0.025 \pm 0.005$ could be calculated. Not only did this study give a value in good agreement with experimental results, but it could also partly explain why $\chi$PT calculations up to $O(p^6)$ are not sufficient to produce an agreement with experimental results.

The main goal of these studies is the $u$ and $d$ quark mass ratio, which can be extracted from the partial width. For a reliable determination a full understanding of all effects on the Dalitz

### Figure 4.
Summary of the world data on the Dalitz Plot parameter. Taken from [25]. The grey shaded area is the PDG average [26].
Figure 5. Invariant mass spectra for the $\omega \rightarrow \pi^0 \gamma$, $\omega \rightarrow \eta \pi^0$, $\omega \rightarrow 3\pi^0$, and $\omega \rightarrow 2\pi^0$ decays (from upper left to lower right) measured with Crystal Ball at MAMI [28]. The crosses represent the data points. The solid histograms are the simulations. Dashed lines indicate the background contribution to the $\omega \rightarrow \pi^0 \gamma$ invariant mass spectrum, and the combined fit functions for the others.

plot is necessary. Here, experiments are now at the precision border to the appearance of new effects. For instance, a cusp effect due to the $\pi^+ \pi^- \rightarrow \pi^0 \pi^0 \pi^0$ rescattering reaction, similar to the one observed by the NA48 collaboration in $K^+ \rightarrow \pi^+ \pi^0 \pi^0$ [27], should also appear in the $\eta \rightarrow 3\pi^0$ decay. This charge exchange reaction also has an impact on the Dalitz plot parameter. According to [22] a 5\% effect on $\alpha$ should be visible. The statistics extracted from the two recent MAMI measurements [23, 24] did not show a significant indication for such a cusp effect.

3.2. C-violating $\omega$ decays
With the Crystal Ball at MAMI three C-violating $\omega$-decays were measured, and new upper limits were set [28]. The breaking of charge-conjugation symmetry is one of the three Sakharov criteria for explaining the excess of matter over antimatter in the known universe [29]. In strong and electromagnetic interactions C-symmetry should be conserved. Thus, any C-violation in such interactions would indicate physics beyond the Standard Model.

The three $\omega$-decay channels investigated at MAMI are $\omega \rightarrow \eta \pi^0$, $\omega \rightarrow 3\pi^0$, and $\omega \rightarrow 2\pi^0$. The branching ratios $BR(\omega \rightarrow \eta \pi^0) < 1 \cdot 10^{-3}$ [30] and $BR(\omega \rightarrow 3\pi^0) < 3 \cdot 10^{-4}$ [31] were already determined by the GAMS2000–collaboration. A branching ratio for the $\omega \rightarrow 2\pi^0$ decay has never been set before.

From the Crystal Ball data the upper limits of the branching ratios for these three decays were determined by comparing the count rates of the decays with the number of $\omega \rightarrow \pi^0 \gamma$ events. The 2008 PDG branching ratio $BR(\omega \rightarrow \pi^0 \gamma) = 0.0892$ [32] was used for this. The numbers of events were determined from fits of a combined function for the background and a
gaussian for the peak to the invariant mass spectra (see fig. 5). The measured branching ratios $BR(\omega \rightarrow \eta\pi^0) < 2 \cdot 10^{-4}$, $BR(\omega \rightarrow 3\pi^0) < 2 \cdot 10^{-4}$, and $BR(\omega \rightarrow 2\pi^0) < 2 \cdot 10^{-4}$ are all at the CL=90%. They are the world’s most precise values today.

4. Transition form factors

The study of electromagnetic decays and hadron-photon interactions provide the possibility to study the intrinsic structure of hadrons through photon interactions with the electric charges of the quarks. The transition form factors describe the electromagnetic structure at $P\gamma\gamma$ vertices. Since only one hadron is involved in these processes the corresponding transition form factor defines the electromagnetic properties of the pseudoscalar meson $P$. Apart from the above mentioned importance for hadron structure physics, these transition form factors provide additional constraints on the Light–by–Light hadronic contribution to the anomalous magnetic moment of the muon $(g-2)_\mu$.

There are several methods available to determine the transition form factors of neutral pseudoscalar mesons. Two of these will be presented here. Vertices of the kind $P\gamma\gamma$ can be investigated in decays of pseudoscalar mesons: $P \rightarrow \gamma^*\gamma \rightarrow e^+e^-\gamma$. The Crystal Ball setup at MAMI is well suited to detect such decays with high statistics. The momentum transfer of the virtual photon $q^2 = m^2_{e^+e^-}$ is in this case limited to $(2m_{e^-})^2 < q^2 < m^2_P$, thus it lies in the time–like region. For the corresponding decay into muons $P \rightarrow \mu^+\mu^-\gamma$ the range starts only at $(2m_\mu)^2$.

Another method to determine transition factors at $P\gamma\gamma$ vertices is through $e^+e^-$ collisions. The mesons are produced through the $e^+e^- \rightarrow e^+e^-\gamma^{(*)}\gamma^{(*)} \rightarrow e^+e^-P$ reaction. On the one hand, the momentum transfer of one of the two virtual photons in this reaction can be restricted to $q^2 \approx 0$ (see below), thus this photon can be considered as quasi–real. On the other hand, the momentum transfer of the second virtual photon lies in the negative region, the space–like region, limited by the accelerator energies. A program to extract space–like transition form factors from data measured with the BES-III detector at the BEPC–II collider in the range $-10$ GeV$^2 < q^2$ is underway.

In the following the result from the Crystal Ball at MAMI experiment for the transition form factor of the $\eta \rightarrow e^+e^-\gamma$ decay is described. Then a feasibility study for the transition form factor in the $\eta' \rightarrow e^+e^-\gamma$ decay that will be measured with the Crystal Ball in the near future will be presented. The last part of this section contains feasibility studies for the BES–III experiment at BEPC–II aiming to determine the transition form factors of $\pi^0$, $\eta$, and $\eta'$ in the space–like momentum transfer region.

4.1. Time–like transition form factors at MAMI

With the Crystal Ball/TAPS setup the Dalitz decay $\eta \rightarrow \gamma^*\gamma \rightarrow e^+e^-\gamma$ has been investigated [33]. The study of the electromagnetic transition form factors in such a decay not only gives insight into the intrinsic structure of hadrons, but is also important for validating hadronic models used in calculations of the hadronic Light–by–Light contribution to $a_\mu$.

From the amplitude of conversion $P \rightarrow \gamma^*\gamma \rightarrow l^+l^-\gamma$ decays of pseudoscalar mesons ($P$) the effective mass spectrum of the leptonic pair $(l^+l^-)$ normalised to the width of the corresponding radiative $P \rightarrow \gamma\gamma$ decay may be derived [34]:

$$\frac{d\Gamma(P \rightarrow l^+l^-\gamma)}{dq^2 \cdot \Gamma(P \rightarrow \gamma\gamma)} = |QED| \cdot |F(q^2)|^2.$$  \hspace{1cm} (4)

Here $|QED|$ stands for a pure QED term containing constants such as the fine structure constant, $\alpha$, the masses of the leptons and the pseudoscalar meson, and $F(q^2)$ is a normalised transition form factor.
Figure 6. Transition form factor for $\eta$–Dalitz decays. Red circles are MAMI data [33]. The black curve is a fit to the MAMI data. The open green circles show the SND results [35]. For comparison the NA60 data points on the $\mu^+\mu^-$ channel [36] are also plotted. The dashed green line is a calculation performed by [37].

To describe the effect of the transition form factor, one may use the vector meson dominance model (VMD). According to this model photon coupling to hadrons is mediated by a virtual vector meson ($V = \rho, \omega, \phi$). The transition form factor is usually parametrised in the VMD assumption by a one–pole approximation [34]

$$ F(q^2) = \frac{1}{1 - \frac{q^2}{\Lambda^2}}. $$

(5)

The information from experiments on the $\eta$ transition form factor is rather scarce. One result with 110 reconstructed $\eta \rightarrow e^+e^-\gamma$ events stems from the SND–collaboration [35]. With a value of $\Lambda^{-2} = (1.6 \pm 2.0)$ GeV$^{-2}$ the accuracy was insufficient to establish a deviation from QED calculations. The $\eta$ transition form factor may also be measured in $\eta \rightarrow \mu^+\mu^-\gamma$ decays. Recently, the NA60–collaboration performed such a measurement [36] and derived the very precise result ($\approx 9000$ events): $\Lambda^{-2} = (1.95 \pm 0.17_{\text{stat}} \pm 0.05_{\text{syst}})$ GeV$^{-2}$. Though, the statistics are sufficient to show deviations from QED calculations, and are well suited to test different models, the NA60 result suffers from two disadvantages. Due to choosing the $\mu^+\mu^-$ channel, the NA60 data points only start at dilepton masses above 200 MeV. Furthermore, the photon was not detected, and the form factor was deduced by unfolding the $\mu^+\mu^-$ invariant mass spectrum [33].

At MAMI the $\eta \rightarrow e^+e^-\gamma$ decay was studied [33]. In a sophisticated analysis 1345 events could be reconstructed. The overall efficiency in this analysis was only 2%. An improved tracking device could help to increase this number greatly. The statistics achieved with the experiment at MAMI are a factor of 10 higher compared to the SND result. The NA60 statistics are clearly superior, but by choosing the $e^+e^-$ channel the region below 200 MeV cold be reached.
Figure 7. Distribution of simulated $\eta' \rightarrow e^+ e^- \gamma$ events for the Crystal Ball experiment as a function of $q^2$. The red curve represents the shape of the probability distribution fed to the simulation program. It contains a one–pole approximation with $\Lambda^2 = 0.5883$ GeV$^2$ as a transition form factor.

at MAMI. The extracted $\eta$ transition form factor is shown in fig. 6 together with the SND und NA60 results. All measurements agree within the uncertainties. From the fit to the MAMI data points the value $\Lambda^{-2} = (1.92 \pm 0.35_{\text{stat}} \pm 0.13_{\text{syst}})$ GeV$^{-2}$ was deduced. In fig. 6 a theoretical calculation [37] is also shown which fits the MAMI data perfectly.

A feasibility study was carried out to probe a possible result from the Crystal Ball experiment for the transition form factor in the $\eta' \rightarrow e^+ e^- \gamma$ decay [38]. This decay is not well measured, and only an upper limit for the branching ratio exists ($BR(\eta' \rightarrow e^+ e^- \gamma) < 9 \cdot 10^{-4}$ at 90% CL) [26]. The simulation used realistic beam properties and the efficiency of 2% determined for the similar $\eta \rightarrow e^+ e^- \gamma$ decay described above [33]. As a result a distribution of the simulated events as a function of $q^2$ is shown in fig. 7. This study, using 600 h of beamtime, which corresponds to the production of roughly 18 million $\eta'$ mesons, means one might expect to extract 231 $\eta' \rightarrow e^+ e^- \gamma$ events. Such a measurement with the Crystal Ball at MAMI would allow the first determination of the transition form factor from $\eta' \rightarrow e^+ e^- \gamma$ decays.

4.2. Space–like transition form factors at BEPC–II
The experimental $\gamma \gamma$ physics program at BES–III for the measurement of pseudoscalar transition form factors will allow the region $Q^2 = -q^2 < 10$ GeV$^2$ to be covered. The investigations at BES-III will aim for an improved determination of the pseudoscalar transition form factors in the non–perturbative region below 3 GeV$^2$. Besides allowing for new testing grounds in this regime, such observables will serve as an important input to phenomenological calculations of the hadronic Light–by–Light contribution to $(g - 2)_\mu$. For the low $Q^2$ region, BES-III data will have a statistical precision significantly better than the CLEO experiment [39]. Below $Q^2 < 1.5$ GeV$^2$ this will be the first ever precision measurement.

In the region between perturbative and non–perturbative QCD up to 10 GeV$^2$, BES–III data will reach a similar precision to the CLEO results [39]. In view of the unexpected $Q^2$ dependence
of the BABAR results [40, 41] in the high $Q^2$ regime, a cross check of the overlap region between CLEO and BABAR will be provided.

To demonstrate the feasibility of the meson transition form factor measurements, studies were carried out for $e^+e^- \rightarrow e^+e^-P$ reactions detected with BES–III. These studies were made, assuming an integrated luminosity of 10 fb$^{-1}$. Presently, a data sample of 3 fb$^{-1}$ at $\sqrt{s} = 3.77$ GeV is already existing.

In fig. 8 the statistical accuracy for the $\gamma^*\gamma \rightarrow \pi^0$ transition form factor multiplied by $Q^2$ is shown, applying the so-called single-tag-method [42]. Taking into account the characteristics of the BES–III detector, this means that the beam electrons (or positrons) are simulated to be scattered in the fiducial polar angle area of the electromagnetic calorimeter, while the second beam particle is assumed to be scattered in forward direction. Since both the momentum of the scattered electron (positron) and the momentum of the neutral pion are fully reconstructed, specific cuts on the polar angle of the second (untagged) lepton can be applied. Through this one can assertain that the t-channel photon associated to this lepton is quasi-real. The form factor assumed in the simulation is a fit to the recent BABAR data [40]. The result of this feasibility study shows a similar accuracy to the CLEO data for $Q^2$ values above 5 GeV$^2$, while the accuracy will be unrivaled for lower $Q^2$ values.

Results from analogous studies [43] are presented for $\eta$ production in fig. 9, and for $\eta'$ production in fig. 10. At intermediate $Q^2$ values greater than 5 GeV$^2$, one observes a similar accuracy to previous measurements. Below 5 GeV$^2$, the $\eta$ and $\eta'$ transition form factors will be extracted with much higher precision at BES–III. Especially below 2 GeV$^2$ it will be the first precision measurement. The recently installed ZDD is ideally suited for detection of small angle leptons, and thus, will improve the extraction of the transition form factors significantly.
5. Summary
In this contribution results from the Crystal Ball at MAMI and BES–III at BEPC–II experiments were presented. At MAMI decays of the light mesons are studied to investigate the rich field of symmetries and symmetry-breaking patterns in low-energy QCD. As examples the measurements of the isospin-breaking $\eta \rightarrow 3\pi^0$, and three C-violating $\omega$ decays were described, which are currently the world’s most precise results. Furthermore, the determination of the transition form factor in the $\eta \rightarrow e^+e^-\gamma$ decay and a feasibility study for the $\eta' \rightarrow e^+e^-\gamma$ for an upcoming beamtime with the Crystal Ball at MAMI were shown. Transition form factors of light pseudoscalar mesons can also be measured with the BES–III detector at the $e^+e^-$ collider BEPC–II. With the results of feasibility studies the impact of this experiment on the $\pi^0$, $\eta$, and $\eta'$ transition form factors were demonstrated.

Acknowledgments
This work was supported by the German state Rhineland-Palatinate (EMG “Elementarkräfte und mathematische Grundlagen”), the Deutsche Forschungsgemeinschaft (SFB 443, SFB/TR 16), the DFG-RFBR (Grant No. 05-02-04014), European Community-Research Infrastructure Activity under the FP6 “Structuring the European Research Area programme” (HadronPhysics, Contract No. RII3-CT-2004-506078).

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Figure 10. Measured $\gamma^*\gamma \rightarrow \eta'$ transition form factors at CLEO [39] and BABAR [41] in comparison to the expected accuracy from a 10 fb$^{-1}$ data sample at BES–III [43].

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