MAMI C - Results and Perspectives

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Abstract. The Mainz Microtron accelerator MAMI C provides a high intensity, polarized electron beam with an energy up to 1.6 GeV. Together with polarized targets, recoil polarimeters and dedicated detector systems this beam is used to measure spin observables with a precision necessary to have a significant impact on our understanding of strong interactions in the low energy regime where perturbative QCD is not applicable. In this article, an overview over selected recent results is given.

1. Introduction

Electromagnetic probes can be used in a variety of ways and in a wide range of energies focussing on different aspects of hadron structure and QCD. Observables in lepton-nucleon scattering at high energy or momentum transfer can be interpreted perturbatively in terms of quark-gluon degrees of freedom. The complex, non-perturbative nature of hadron structure is parameterized by universal parton distribution functions. Below an energy scale of about 3 GeV the relevant degrees of freedom change to mesons and baryons, the bound states of QCD. A characteristic feature in this energy regime is the emergence of scales, e.g. the finite transverse size of hadrons and the appearance of discrete resonant states with definite quantum numbers. At MAMI the full potential of electroweak probes is explored in this interesting low energy regime.

2. MAMI C - accelerator and detector systems

The MAMI accelerator consists of four cascaded microtrons, an injector linac, a thermal source for unpolarized electrons and a laser-driven source for electrons with 80% spin polarization. High intensity beams (100 µA cw) with an energy spread of 30 keV and an emittance of 25 nm-rad are routinely achieved. The first 3 stages consist of race track microtrons which deliver beams up to 885 MeV (MAMI B). A fourth stage, the Harmonic Double-Sided Microtron (HDSM) [1], upgrading the maximum energy to 1.6 GeV, has gone into routine operation in February 2007.

The broad physics program at MAMI requires a similar broad range of sophisticated detector systems from high resolution magnetic spectrometers to large acceptance...
detectors for neutral particles. The largest experimental hall of the MAMI accelerator complex houses the spectrometer setup for electron scattering experiments operated by the A1 collaboration. The working horses of the setup are three high-resolution spectrometers with $\delta p/p \leq 10^{-4}$, a large solid angle acceptance of up to 28 msr, and a momentum acceptance of up to 25%. A proton recoil polarimeter gives, in combination with the polarized MAMI beam and a polarized Helium gas target, access to a broad variety of spin observables. A new kaon-spectrometer (KAOS/A1) covering high momenta with a moderate path length has recently been commissioned.

For experiments with circularly and linearly polarized real photons the Glasgow-Mainz bremsstrahlung tagging facility provides photons of known energy and flux. Since 2004, the Crystal Ball calorimeter, which was moved from BNL/AGS to Mainz, is the central part of a hermetic detector system for present and future experiments within the A2 collaboration at MAMI. The Crystal Ball consists of 672 NaI(Tl) crystals covering 93% of the full solid angle with an energy resolution of 1.7% for electromagnetic showers at 1 GeV. For charged particle tracking and identification two layers of coaxial multi-wire proportional chambers and a barrel of 24 scintillation counters surrounding the target were installed inside the Crystal Ball sphere. The forward angular range is covered by the TAPS calorimeter consisting of 384 BaF2 detectors and a Cerenkov detector. As spin degrees of freedom are essential the experimental setup is being complemented by polarized targets and a recoil polarimeter.

The A4 collaboration is using a setup of 1022 PbF$_2$ crystals that can be arranged to cover a solid angle of 0.6 sr at forward or backward angles. The A4 collaboration is measuring single spin asymmetries in elastic electron scattering. In case of longitudinally polarized electrons these asymmetries are parity violating and allow a flavor separation of the elastic nucleon form factors $G_E$ and $G_M$. Measurements with transverse electron spin determine the imaginary part of the two-photon exchange amplitude in elastic scattering.

3. Selected results

3.1. High precision determination of electric and magnetic form factors of the proton

The electric and magnetic form factors measured in elastic electron scattering off nucleons encode information about the spatial distribution of charge and magnetization. They provide benchmarks for our understanding of nucleon structure. An extensive measurement of the elastic $H(e, e')p$ reaction in the $Q^2$-region from 0.003 to 1 (GeV/c)$^2$ has been performed with the 3-spectrometer-setup of the A1 collaboration at MAMI. The data set consists of about 3000 overlapping cross section measurements with a high level of internal redundancy. The statistical errors are below 0.2 % and great effort has been invested in order to control the systematic errors to the 1 % level. Besides a classical Rosenbluth separation the electric and magnetic form factors of the proton were extracted by fits of a large variety of form factor models directly to the cross sections.
From these analyzes the following values for the electric and magnetic rms radii of the proton result [2]:

\[< r^2_E >^{1/2} = 0.875(5)_{\text{stat}}(4)_{\text{syst}}(6)_{\text{model}} \text{ fm}, \]

\[< r^2_M >^{1/2} = 0.777(13)_{\text{stat}}(9)_{\text{syst}}(7)_{\text{model}} \text{ fm}. \]  \hspace{1cm} (1)

The electric radius is in agreement with the CODATA [3] value of 0.8768(69) fm which is the result of a least-squares optimization of several fundamental constants to (mostly atomic) experimental data. It is dominated by Lamb shift measurements on hydrogen. However, from the very recent high-precision measurement of the Lamb shift in muonic hydrogen at PSI [9] a value which is about 5 standard deviations smaller has been extracted (see figure 1). This difference is still unexplained. The magnetic radius is smaller than results from previous fits, however, is in good agreement with results from hyperfine splitting in hydrogen.

### 3.2. Threshold pion photoproduction

Threshold pion photo-production has long been recognized as a fundamental process arising from the fact that the pion is a Nambu-Goldstone boson of QCD. Close to threshold, neutral pion photo-production is dominated by one s-wave, \( E_{0+} \), and three p-wave amplitudes. With this truncation, only a limited number of observables have to be measured for a complete description of the process. Cross section measurements of the \( \gamma p \rightarrow \pi^0 p \) reaction close to threshold have been carried out at Mainz [10, 11, 12] and Saskatoon[13]. The extracted values of the \( E_{0+} \) amplitude shows a strong energy dependence due to the unitary cusp at the opening of the \( \gamma p \rightarrow \pi^+ n \) reaction threshold. The experimental progress is paralleled by fundamental theoretical efforts. The most recent calculations in Heavy Baryon ChPT were performed to one loop [14]. Other recent
Figure 2. Preliminary energy dependence of the photon asymmetry $\Sigma$ at $\theta_{cm} = 90^\circ$ compared to different calculations (solid [17], dashed [15], long dashed [16]) and a pioneering work of Schmidt et al. (open square [12]).

Calculations start with the $O(p^3)$ chiral Lagrangian and use constraints from unitarity and causality to extend the radius of convergence from threshold up the energy region of the $\Delta(1232)$ resonance [15]. Experimentally, a separation of the $s$-wave amplitude $E_{0+}$ and the three $p$-wave combinations can be achieved by measuring the photon beam asymmetry

$$\Sigma = \frac{\sigma_\perp - \sigma_{\parallel}}{\sigma_\perp + \sigma_{\parallel}} \tag{3}$$

in addition to the differential cross section. Here $\sigma_\perp$ and $\sigma_{\parallel}$ denote the differential cross sections with the photon polarization vector perpendicular and parallel to the $p\pi^0$ reaction plane. This asymmetry has recently been measured with the Crystal-Ball TAPS calorimeter and the Glasgow tagging facility at MAMI. Figure 2 shows the preliminary results at $\theta_\pi = 90^\circ$ as function of the incoming photon energy. The new results are compared with a pioneering measurement at MAMI by Schmidt et al. in 2001 [12] and different theoretical predictions. In the near future these data will be analyzed within Heavy Baryon ChPT which will allow us to extract the low energy constants at $O(p^4)$. The measurement of any further observable will now provide stringent tests of our understanding of the underlying dynamics. In particular an observation of the time reversal odd observables, which involve transverse polarized targets, over a larger energy range are needed to understand quantitatively where ChPT calculations start to become less accurate. A new Mainz/Dubna polarized frozen-spin target with longitudinal and transverse polarization is fully operational at MAMI since the beginning of 2010. It provides proton polarization degrees of 90% and relaxation times of about 1000 hours. A series of data taking periods for $\pi^0$ and $\eta$ production as well
as for Compton scattering with transverse polarization is presently being carried out. An example for first preliminary results (from approximately 100 h of running time) of the double polarization observable $F$ (circularly polarized photons and transversely polarized protons) for $\pi^0$ production in the energy range of 300 to 1 GeV is shown in figure 3. This observable has never been measured before and will have significant impact on our understanding of meson photoproduction from threshold up to the resonance region.

3.3. Baryon Spectroscopy

A distinctive feature of hadronic reactions below 3 GeV are resonances with well defined quantum numbers. Usually, these resonances are interpreted within models as excitations of three constituent quarks bound in a QCD inspired confining potential. In contrast, there is an increasing number of publications claiming a dynamical origin of resonances due to the strong coupling of meson-baryon channels, thus a molecular nature of these phenomena. A clear interpretation of resonance phenomena is presently obstructed to a large extent by the model dependent analysis procedures. All resonances listed in the Particle Data Tables have been identified by partial wave analyzes and model dependent analyzes mainly in terms overlapping Breit-Wigner resonances sitting on a non resonant background. A sensitive check whether this hypothesis is correct requires the measurement of spin observables depending on interference terms between different

Figure 3. First preliminary data of the double polarization observable $F$ (see text) in $\pi^0$ production in the photon energy range of 300 MeV to 1 GeV.
partial wave amplitudes. At MAMI the energy region of the $S_{11}(1535)$ resonance is

![Graph showing partial wave amplitudes.](image)

Figure 4. Left: total cross section for the $\gamma p \rightarrow \eta p$ reaction measured with the Crystal Ball at MAMI [19] compared to previous results [20]. Right: Recoil polarization for $\eta$ electroproduction at $\Theta_\eta = 120^\circ$. Open point from [22], full point: new preliminary data [23].

presently studied in detail. It is known that the $S_{11}(1535)$ has a branching ratio of 50% into the $p\eta$ decay channel, whereas the $D_{13}(1520)$ couples only very weakly to this channel. Transverse asymmetries either using a transversely polarized target in the $\gamma\vec{p} \rightarrow p\eta$ reaction or the proton recoil polarization in the $p(e, e'\vec{p})\eta$ reaction are in particular sensitive to the interference between the $S_{11}$ and $D_{13}$ partial wave amplitudes. Previous data on the target asymmetry could not be explained by overlapping Breit-Wigner functions without changing the relative phase of these two resonances by hand [21]. At MAMI, the recoil polarization in the $p(e, e'\vec{p})\eta$ reaction has recently been measured by the A1 collaboration (see right hand side of figure 4). Also these data require a strong phase shift between the S- and D-waves, basically giving up the standard Breit-Wigner phase assignment. With the Crystal Ball detector at MAMI photoinduced $\eta$ production can be studied with an unprecedented accuracy (see left hand side of figure 4). The data span the photon energy range from 707 to 1402 MeV and the full angular range in the c.m. frame. The accumulation of $3 \times 10^6$ events via $\eta$-decay into $3 \pi^0$ allows a fine binning in energy (4 MeV) and angle (9 degrees). The present data agree well with previous measurements, but are markedly superior in terms of precision and energy resolution. First data with transversely polarized target are presently under analysis.

4. Conclusions

With the MAMI C accelerator in Mainz many highly significant experiments to unravel the structure and dynamics of hadrons in the low energy domain have started. They explore the full potential of electroweak probes to measure basic nucleon properties like (transverse) size, distribution of charge and magnetism, polarizabilities and excitation spectrum.
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