Recent results from ANKE, WASA-at-COSY, and PAX

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Abstract. The three complementary internal beam experiments ANKE, WASA, and PAX at the COoler-SYnchrotron COSY-Jülich offer unique and exciting opportunities for hadron physics with polarized and unpolarized hadronic probes. Due to the excellent properties of the COSY accelerator, which offers electron and stochastically cooled proton and deuteron beams with momenta up to 3.7 GeV/c, in combination with the high performance detection systems, a broad experimental program can be covered. One main emphasis of the studies at these facilities are measurements on symmetries in reactions and particle decays as well as high precision studies on particles and their properties. Furthermore, the availability of polarized beams and/or targets allows for investigations on hadronic reactions using the spin degree of freedom or studies towards polarized antiprotons. The experimental facilities will be presented and recent results will be discussed.

1. Introduction

The COoler SYnchrotron COSY [1] is located at the Forschungszentrum Jülich, Germany, and offers several target places for internal and external beam experiments. COSY itself allows for the storage and acceleration of proton and deuteron beams in a broad momentum range of $0.3 - 3.7$ GeV/c with high intensity. Due to the availability of stochastic and electron cooling devices, precision experiments with high beam momentum resolution are possible. Furthermore, polarized proton and deuteron beams can be provided at both the internal and external target places and enable in combination with the installed experimental facilities for a broad physics program.

One main filed of interest at COSY is the investigation of hadron-hadron interactions, such as nucleon-nucleon scattering, meson-nucleon and meson-nucleus interaction, and strangeness production. By using polarized target installations the spin degree of freedom can be considered in single and double polarized measurements, which is of high relevance for, e.g., the determination of production amplitudes or spin filtering experiments. Due to the available high luminosity important studies on symmetries and symmetry breaking can be performed, which allows for a deeper understanding of the Standard Model and possible physics beyond it. Furthermore, studies on more exotic particles have been performed, which recently resulted in exciting data on the d^* resonance. Details on this will be presented in an other contribution to this conference.

In this contribution recent results from the experimental facilities ANKE, WASA-at-COSY, and PAX will be presented, which are all located at internal COSY target positions. Due to their significantly different detector layouts, these three installations allow for complementary studies on the above listed topics.

2. Experiments

The ANKE magnetic spectrometer [2] is located at a straight section of the COSY ring. Two dipole magnets (D1, D3) deflect a proton or deuteron beam onto either a hydrogen cluster-jet target [3] or a polarized beam target and back onto the nominal orbit, respectively. A third dipole magnet (D2) is used to separate charged reaction products from the circulating beam. Positively charged reaction products with high momenta can be detected in a forward detection system, which is complemented by two side detectors for positively and negatively charged particles. Each of the detector systems is equipped with multiwire proportional chambers and scintillator hodoscopes. Close to the interaction point a set of segmented silicon strip detectors [4] can be placed for, e.g., the detection of low-momenta spectator particles.

The WASA-at-COSY facility is a close to 4π setup, which consists of a central detector to detect mesonic decay particles and a forward detector system to measure hadronic ejectiles. A pellet target provides a stream of frozen hydrogen or deuterium particles which are shot through the center of the central detector. The forward detector itself consists of an azimuthal-symmetric set of plastic scintillators of various thickness to measure the energy loss and total energy of forward scattered hadrons. Furthermore, these detectors provide precise timing information and positional reconstruction. A proportional chamber detector system further improves the charged track reconstruction. The central detector is equipped with a CsI(Na) calorimeter with 1012 elements, which measures signals from both photons and charged particles. A mini drift chamber is located inside of this calorimeter, which itself is surrounded by a plastic scintillator barrel to measure electrons and pions. Furthermore, a solenoid magnet inside of the calorimeter provides a field of 0.85 Tesla. By measuring the resulting curvature of charged tracks, both the charge and momentum of the ejectiles can be reconstructed. More details on the WASA-at-COSY detector can be found in [5].

The PAX experiment [6] consists of a polarized hydrogen gas target, which is installed at the PAX interaction point, and makes use of the ANKE facility for beam polarization. The PAX polarized target itself is equipped with a polarized atomic beam source, a storage cell, and a diagnostic system. The latter one contains a Breit-

Rabi polarimeter measuring the atomic (target) polarization and a targetgas analyzer determining the relative fraction of atoms and molecules. The beam polarization is measured via the ANKE experiment by detecting elastically scattered protons and deuterons off the ANKE cluster target.

3. Results

3.1. Studies towards polarized antiprotons

The preparation of polarized antiproton beams is of high interest for, e.g., investigations of Drell Yan processes in the scattering of polarized proton-antiproton beams. Such annihilation studies would allow for the first direct measurement of the transversity distribution of the valence quarks in the (anti)proton. However, although the preparation of polarized antiproton beams is discussed since more than two decades, up to now now no beams with sufficient polarization and intensity are available. Therefore, one of the aims of the PAX collaboration is the investigation of different methods to provide corresponding antiproton beams. In earlier measurements it could be shown that the spin-flip cross section in the $\vec{e}p$ scattering is much too low to transform an previously unpolarized antiproton beam into a polarized one [7]. Therefore, more detailed studies on the (anti)proton polarization via spin-filtering were performed. Main idea of this method is that a previously unpolarized (anti)proton beam is stored in a storage ring and interacts repeatedly with a polarized internal target beam. If the interaction cross section depends on the relative spin orientations of the target and beam particles, it can be written as

$$\sigma_{\text{total}} = \sigma_0 + \sigma_1(\vec{P} \cdot \vec{Q}) + \sigma_2(\vec{P} \cdot \hat{k})(\vec{Q} \cdot \hat{k}), \tag{1}$$

with P and Q as the beam and target spin orientations and k being parallel to the accelerator beam direction. Thus, a polarization build-up of the stored accelerator beam results due to spin-dependent beam life times in the presence of a polarized target. At PAX corresponding measurements on the cross section σ_1 have been performed successfully by using a transversely polarized hydrogen target beam and by measuring the accelerator proton beam polarization build-up at an kinetic energy of $T_p = 49.3$ MeV as function of time. A cross section of

$$|\sigma_1| = (23.4 \pm 3.9(\text{stat.}) \pm 1.9(\text{syst.}))\ \text{mb} \tag{2}$$

was determined which is well in line with calculations [7]. With this result it could be demonstrated that this method represents a viable way for a macroscopic antiproton polarization. Furthermore, the validity of corresponding polarization build-up calculations could be shown. Based on these results further investigations towards polarized antiprotons were proposed which consider longitudinal polarized target beams.

3.2. Measurement of analyzing powers in proton-proton and proton-deuteron scattering

One of the main topics of investigations at ANKE are studies on the short-range nucleon-nucleon interaction, which allow for a deeper understanding of this fundamental reaction type and which result, e.g., in important input parameters for phase shift analyses (SAID). In recent measurements new data on the proton analyzing power in the $\vec{p}p$ elastic scattering have been determined at ANKE at small angles of $\theta_{CM} < 30^\circ$ and at six different beam momenta between 796 MeV and 2.4 GeV [8]. It was found that the analyzing power results obtained at the lowest beam energy agree well with the already published data and also with the most recent partial wave solution at this energy. Contrary, the new data obtained at the higher energies were found to lie well above the predictions of the SAID SP07 [9] solution and also display a different angular dependence. Due to this finding an updated phase shift analysis was performed that uses the new precise ANKE data as well as previously available World data. This new analysis resulted in a much better description of these new measurements.

In further experiments data on the vector and tensor analysing powers, A_y and A_{yy}, of the charge exchange reaction $p\vec{d} \rightarrow n\{pp\}_s$ have been taken at ANKE at a beam energy of $T_p = 600$ MeV [10]. A selection of diprotons with a relative energy of less than 3 MeV ensured that the protons were in a relative $^1S_0$ state. Different to earlier measurements momentum transfers of $q > 160$ MeV/c could be accessed by analysing events where both protons entered the same silicon strip telescope close to the target. By this a new data base could be provided which extends the earlier results at $q < 140$ MeV/c [11]. It was found that these new data at higher momentum transfers agree nicely with the ones at lower momentum transfers. Furthermore, the new data are also consistent with impulse approximation predictions [12] based on the SAID SP07 solution and show only little sign evident for modifications due to multiple scatterings.

3.3. Measurements of η-meson decay branching ratios

Studies on rare meson decays allow for a deeper understanding of the low-energy QCD. Different to the high energy regime, at low energies the QCD coupling becomes asymptotically large and perturbative methods provide no longer accurate predictions. However, a good understanding of the strong interaction at low energies is essential for the understanding of the structure and dynamics of hadrons as well as the nature of confinement. In order to further develop the main theoretical approaches at low energies, i.e. lattice QCD and effective field theories including chiral perturbation theory, new precise measurements are highly needed. Therefore, detailed studies on η-meson decays with high statistics have been performed at the WASA-at-COSY installation. In detail 3×10^7 η-mesons produced in the $pd \rightarrow^3$ Heη reaction have been recorded at a beam energy of $T_p = 1$ GeV and branching ratios of the following decay channels have been investigated: $\eta \rightarrow \pi^+\pi^-\gamma$, $\eta \rightarrow e^+e^-\gamma$, $\eta \rightarrow \pi^+\pi^-e^+e^-$, and $\eta \rightarrow e^+e^-e^+e^-$. For these channels the preliminary branching ratios given in table 1 were determined. Although still preliminary, all determined branching ratios agree nicely with the PDG values with

Table 1. Preliminary branching ratios obtained at WASA-at-COSY

Channel	Brancing Ratio	PDG Value [13]
$\eta \to \pi^+\pi^-\gamma$	$(4.68 \pm 0.07(\text{stat./fit}) \pm 0.19(\text{syst.})) \times 10^{-2}$	$(4.22 \pm 0.08) \times 10^{-2}$
$\eta \to e^+e^-\gamma$	$(6.75 \pm 0.06(\text{stat./fit}) \pm 0.29(\text{syst.})) \times 10^{-3}$	$(6.9 \pm 0.4) \times 10^{-3}$
$\eta \to \pi^+\pi^-e^+e^-$	$(2.7 \pm 0.2(\text{stat.}) \pm 0.1(\text{syst.})) \times 10^{-4}$	$(2.68 \pm 0.11) \times 10^{-4}$
$\eta \to e^+e^-e^+e^-$	$(3.2 \pm 0.9(\text{stat.}) \pm 0.4(\text{syst.})) \times 10^{-5}$	$(2.40 \pm 0.22) \times 10^{-5}$

the exception of the $\eta \to e^+e^-e^+e^-$ channel. In order to further investigate this finding new studies are sheduled which will be based on a much richer data base from WASA-at-COSY. Here more than 5×10^9 η-mesons produced in the $pp \to pp\eta$ reaction are available and are currently under investigation.

3.4. $^3He - \eta$ production and final state interaction studies in pd collisions

The cross section of the $pd(dp) \to^3$ Heη reaction is known to show a very anomalous behaviour near threshold. In detail the cross section jumps to a plateau value already for $Q < 1$ MeV and remains almost constant for higher excess energies Q [14]. It was suggested that this effect is caused by a strong final state interaction (FSI) in the ^{3}He $- \eta$ system, which might lead to a quasi-bound η-nuclear state [15]. Fits to the most detailed data indicate the presence of a pole in the $\eta\,^3$He elastic amplitude for $|Q| < 0.5$ MeV [14], which is supported from the variation of the angular dependence of the cross section with Q [16]. In order to further investigate the nature of this finding, new data on the $\vec{d}p \to^3$ Heη reaction have been taken close to the production threshold. By using a tensor polarized deuteron beam, the analysing power T_{20} of this reaction could be measured [17] in small steps in excess energy up to $Q = 11$ MeV. It was found that T_{20} remains almost constant near threshold, which strongly supports that the rapid variation of the production amplitudes with energy is caused by an s-wave FSI that is common to the two possible different spin states in the entrance channel [17].

Different to the near-threshold region there are only limited cross section data available for the $pd \to^3$ Heη reaction at higher energies. In order to further investigate this reaction in the regime of higher excitation energies, total and differential cross section data have been determined using the WASA-at-COSY installation at excess energies of $Q = 48.8\,\text{MeV}$ and $Q = 59.8\,\text{MeV}$ [18]. The extracted angular distributions were found to show a strong anisotropy which is consistent with data at similar energies. However, the ratio of the newly determined total cross sections were found to be

$$\frac{\sigma_\eta(48.8\,\text{MeV})}{\sigma_\eta(59.8\,\text{MeV})} = 0.77 \pm 0.06. \tag{3}$$

In combination with previously available data from WASA/PROMICE [19] and ANKE [20], these new data might indicate an unexpected narrow cross section variation in the excess energy range of $Q = 20\,\text{MeV} - 60\,\text{MeV}$. In order to further investigate this surprising situation, new total and differential cross section data have been taken very recently at WASA-at-COSY at 15 different energies between $Q = 13.6\,\mathrm{MeV}$ and $Q = 80.9\,\mathrm{MeV}$ [21], which will allow for a more detailed investigation with high precision.

3.5. Charge symmetry breaking in the $dd \to^4 He\pi^0$ reaction

Charge symmetry breaking observables are highly suited to examine effects caused by quark masses on the nuclear level. In order to support the currently ongoing theoretical work on a consistent description of charge symmetry breaking within the framework of chiral perturbation theory, new data on the $dd \to^4 \mathrm{He}\pi^0$ reaction have been taken at WASA-at-COSY [22] at a beam momentum of $p_d = 1.2\,\mathrm{GeV/c}$, i.e. at an excess energy of $Q = 60\,\mathrm{MeV}$. Of high interest are studies on the development of the production amplitude as well as on the contribution of higher partial waves, i.e. p-wave. From these new data the total cross section was determined to be $\sigma_{\mathrm{tot}} = (118 \pm 18_{\mathrm{stat}} \pm 13_{\mathrm{sys}} \pm 8_{\mathrm{ext}})$. Considering already existing data taken much closer to threshold [23], the newly determined production amplitude might indicate the on-set of higher partial waves. However, for a final conclusion the analysis of a new WASA-at-COSY data set with much larger statistics has to be waited for.

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