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Internal Experiments at COSY–Jülich

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The COoler SYnchrotron COSY at the Forschungzentrum Jülich accelerates protons and deuterons up to momenta of 3.7 GeV/c. COSY is the machine for hadron spin physics on a world–wide scale. In combination with internal polarized Hydrogen and Deuterium targets, the availability of electron and stochastically cooled polarized proton and deuteron beams allows for precision measurements to be made. In this contribution selected recent results from the ongoing spin physics programme at the COSY ring using the internal ANKE facility are highlighted.

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1. Introduction

The COSY facility at Forschungszentrum Jülich (Germany) comprises sources for unpolarized and polarized beams, an injector cyclotron (JULIC) and the storage and cooler ring with a circumference of about 184 m [1] (see Fig. 1). It stores, accelerates and cools beams of protons and deuterons, which may be polarized, and provides them at internal target stations or extracts them for use at external targets and detectors. With a maximum beam momentum of 3.7 GeV/c, it is well suited for a wide range of hadron physics with hadronic probes – in fact it can be considered the hadron spin physics machine because of its possibilities to produce, accelerate, manipulate and use polarized beams and targets.

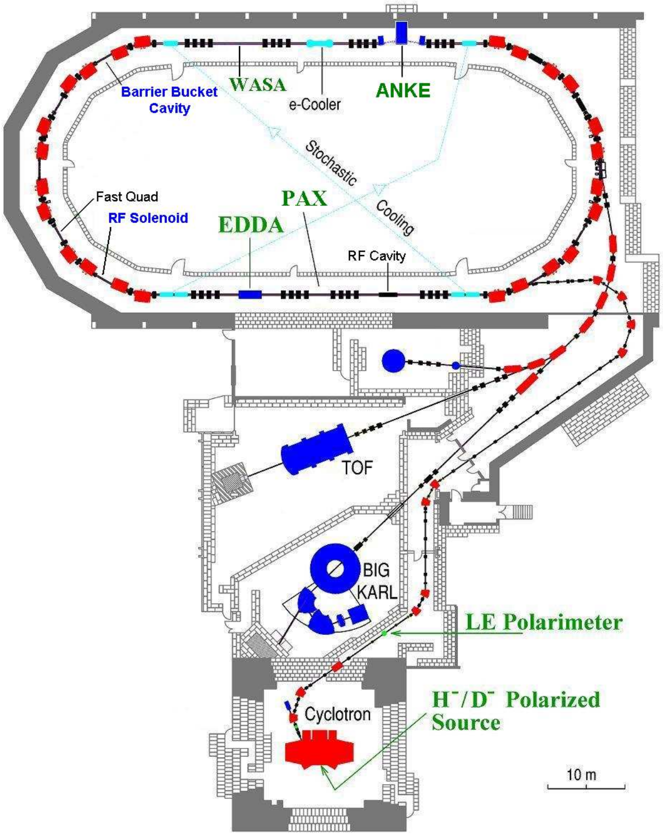

Figure 1: Floor plan of the COoler SYnchrotron COSY at Forschungszentrum Jülich (Germany). In addition to the injector cyclotron, the locations of the major detector facilities are indicated.

2. Experimental facilities - Internal Experiments

Different detection systems have been exploited or are still in use at COSY. While the first generation equipment (BIG KARL, COSY–11, EDDA) has been decommissioned during the recent past (EDDA [2] is, however, still in use as an internal polarimeter), and a second generation detector (PISA) has been transferred to CSR in Lanzhou (China), the third generation spectrometers ANKE, TOF and WASA are heavily used for hadron physics experiments. In addition, a new internal so called low-β section has been built and commissioned recently, which houses the PAX set-up.

Internal experiments are the unique possibility available at a storage ring like COSY: they allow measurements with thin gas targets very close to threshold, where the recoil energies are very small. They also permit experiments on neutrons via the use of deuterium and detection of the spectator proton.

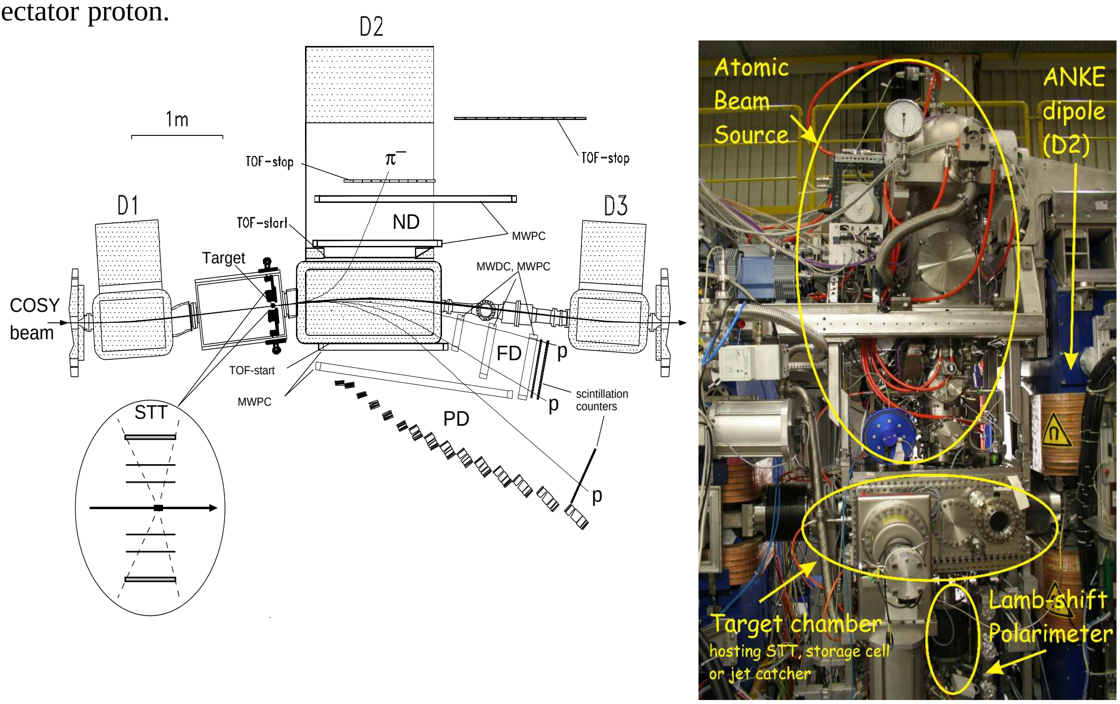

Figure 2: Left panel: top view of the ANKE setup at COSY. The positions of the dipole magnets D1, D2, D3, the cluster target spot, the Forward (FD), Positive (PD), Negative (ND) detector systems and the Silicon Tracking Telescope (STT), are shown. Right panel: photo of ANKE with the Polarized Internal Target (PIT) in front of the spectrometer dipole D2. The main components of the PIT system: Atomic Beam Source (ABS), Lamb–shift Polarimeter (LSP), and the target chamber hosting Storage Cell (SC) together with Silicon Tracking Telescope (STT) system are indicated.

2.1 The Magnetic Spectrometer ANKE

ANKE (Apparatus for Studies of Nucleon and Kaon Ejectiles) [3] is a large acceptance forward spectrometer in the COSY ring (see left panel of Fig. 2). The central dipole is movable to adjust the momenta of the detected particles independent of the beam momentum. Furthermore, ANKE has the capability to detect both positive and negative charged final state particles, and it uses gas targets and thin foil targets as well as a polarized internal target with a storage cell. Since summer 2005 ANKE is equipped with PIT located between the dipole magnets D1 and D2 (see right panel of Fig. 2)

The latter allows double–polarized experiments to be performed. The ANKE experimental program focuses on: (i) nucleon–nucleon scattering, in particular with the di–proton final states, (ii) deuteron breakup, also with di–protons, (iii) meson production without and with strangeness on nucleons and in proton–nuclear collisions.

2.2 The WASA Detector

WASA (Wide Angle Shower Apparatus) [4] is an internal 4π spectrometer for charged and neutral particles. It was originally set up at CELSIUS of TSL in Uppsala (Sweden), and transferred to COSY in 2005. After refurbishment it is in operation since early 2007. WASA comprises an electromagnetic spectrometer, a very thin superconducting solenoid, inner and forward tracking and energy–loss detectors and a frozen (hydrogen or deuterium) pellet target. The main emphasis of the WASA program is on symmetries in nuclear reactions and on pseudoscalar meson decays and search for and the investigation of symmetry breaking. There were several contributions from WASA collaboration to this conference proceedings, as an example see [5].

2.3 The Low-β Section for PAX

During the summer shut-down in 2010, a new internal target station has been set-up at COSY, which will be used for the PAX commissioning experiments on proton spinfiltering. This is the only viable method known to produce a beam of polarized antiprotons, after our precursor experiment [6] at COSY had shown that spin–flip from electrons (positrons) to protons (antiprotons) will not work. In order to set-up the equipment for spin–filtering with antiprotons with the goal in order to determine and optimize the method to produce an intense beam of polarized antiprotons for a possible future HESR-at-FAIR upgrade, a so called low–β section has been designed and constructed at COSY. This section houses: (i) magnetic quadrupole triplets, (ii) an atomic beam source (ABS) plus a Breit–Rabi polarimeter (BRP), (iii) an openable storage cell (SC), into which the polarized hydrogen or deuterium gas is injected and which is traversed by the COSY beam, and (iv) a silicon tracking detector system (STT), which is currently designed. (i) - (iii) have been commissioned in autumn 2010. With this set–up, proton spin–filtering [7] has been repeated in Septemebr 2011 and the analysis are in progress (see contribution to this conference proceedings prepared by Dieter Oellers).

3. Experimental Program at COSY

The hadron physics program at COSY can be summarized as spectroscopy, spin, and symmetry. Under the headline spectroscopy the foremost research object is the nucleon and its mutual interactions as well as its excited states (N^*'s and Δ's) and possible exotics. The role and manifestation of the strange quark is an issue studied in associated production of hyperons and strange mesons. Recently symmetries and their breaking have come into the focus of investigations, after the WASA detector has been brought to and installed at COSY. Finally medium modifications in the form of final state interactions or possible bound states are also being investigated. With proton and deuteron beams, isospin and polarization of beam and target are used as a tool, and photons serve as a selective (final state) probe.

4. Recent Highlights

In the following, a few selective examples of recent (ANKE) results are presented.

4.1 NN Scattering

A good understanding of the Nucleon–Nucleon interaction still remains one of the most important goals of nuclear and hadronic physics. Apart from their intrinsic importance for the study of nuclear forces, *NN* data are necessary ingredients in the modelling of meson production and other nuclear reactions at intermediate energies. It goes without saying therefore that any facility that could make significant contributions to this important database should do so.

The ANKE collaboration has embarked on a systematic programme to measure the differential cross section, analysing powers, and spin correlation coefficients of the $\vec{d}\vec{p} \to \{pp\}_s n$ deuteron charge–exchange breakup reaction [8]. The aim is to deduce the energy dependence of the spin–dependent *np* elastic amplitudes. By selecting the two final protons with low excitation energy, typically $E_{pp} < 3$ MeV, the emerging diproton is dominantly in the $^1S_0$ state. In impulse approximation the deuteron charge-exchange reaction can be considered as an $np \to pn$ scattering with a spectator proton.

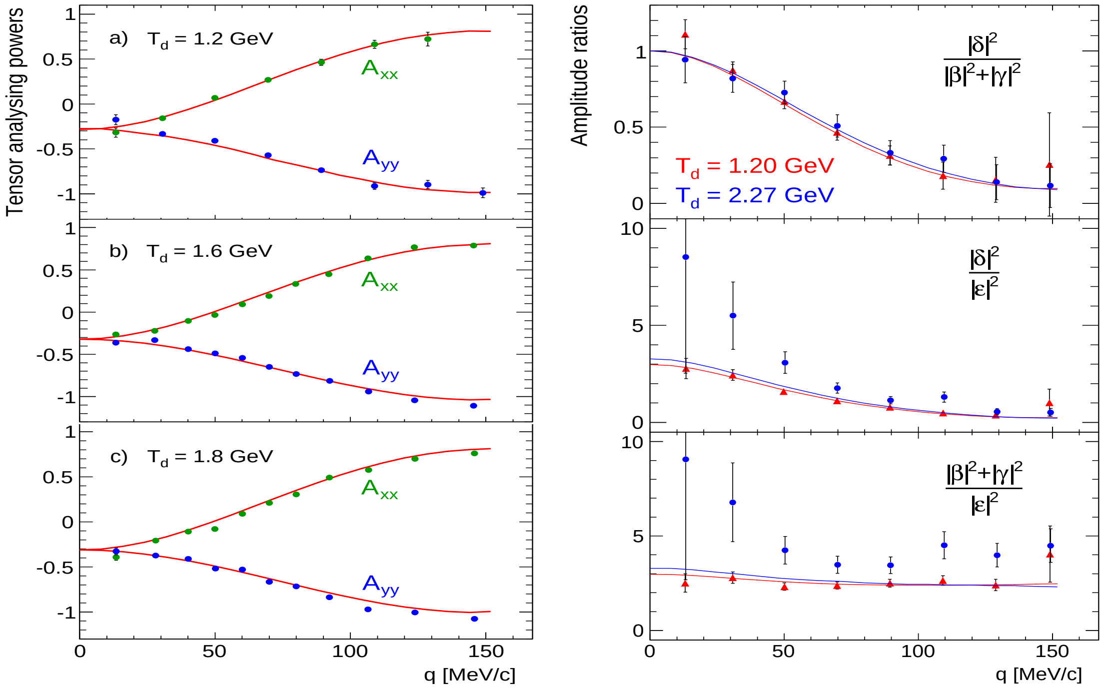

Figure 3: Left panel: Cartesian tensor analysing powers A_{xx} (green dots) and A_{yy} (blue dots) of the $\vec{d}p \to \{pp\}_s n$ reaction at beam energies of $T_d = 1.2, 1.6$, and 1.8 GeV for low diproton excitation energy, $E_{pp} < 3$ MeV. The solid red curves are results of an impulse approximation calculation, where the input *np* amplitudes were taken from the SAID program at the appropriate energies. Right panel: measured observable ratios as functions of q for two different beam energies. Solid lines are impulse approximation predictions.

The spin dependence of the *np* charge–exchange amplitude in the cm system can be displayed in terms of five scalar amplitudes as [9]:

$$\begin{aligned} f_{np} = {} & \alpha(q) + i\gamma(q)(\vec{\sigma}_1 + \vec{\sigma}_2)\cdot\vec{n} + \beta(q)(\vec{\sigma}_1\cdot\vec{n})(\vec{\sigma}_2\cdot\vec{n}) \\ & + \delta(q)(\vec{\sigma}_1\cdot\vec{m})(\vec{\sigma}_2\cdot\vec{m}) + \varepsilon(q)(\vec{\sigma}_1\cdot\vec{l})(\vec{\sigma}_2\cdot\vec{l}), \end{aligned}$$

where α is the spin–independent amplitude between the initial neutron and final proton, γ is a spin–orbit contribution, and β, δ, and ε are spin–spin terms. In the ${}^1S_0$ limit of the impulse approximation, the $\vec{d}\vec{p} \to \{pp\}_s n$ observables are directly related to the np spin–dependent amplitudes through:

$$\begin{aligned}
\frac{d^4\sigma}{dtd^3k} &= 13I\left\{S^-(k,q)\right\}^2 , \\
I &= |\beta|^2+|\gamma|^2+|\varepsilon|^2+|\delta|^2R^2 , \\
IA_y^d &= 0 ,\, IA_y^p \ = -2\mathrm{Im}(\beta^*\gamma) , \\
IA_{xx} &= |\beta|^2+|\gamma|^2+|\varepsilon|^2-2|\delta|^2R^2 , \\
IA_{yy} &= |\delta|^2R^2+|\varepsilon|^2-2|\beta|^2-2|\gamma|^2 , \\
IC_{y,y} &= -2\mathrm{Re}(\varepsilon^*\delta)R,\ IC_{x,x}=-2\mathrm{Re}(\varepsilon^*\beta),
\end{aligned}$$

where $R=\{S^+(k,q)/S^-(k,q)\}^2$ and $S^\pm$ are form factors that can be evaluated using low energy NN information. Here $\vec{k}$ is the pp relative momentum in the diproton and $\vec{q}$ the momentum transfer between the deuteron and diproton.

Although corrections due to final P- and higher pp waves have to be taken into account in the detailed analysis, it is clear that in the low E_{pp} limit a measurement of the differential cross section, A_{xx}, and A_{yy} would allow the extraction of $|\beta(q)|^2+|\gamma(q)|^2$, $|\delta(q)|^2$, and $|\varepsilon(q)|^2$ over a range of values of q.

For the above to be the realistic objectives, the methodology has to be checked in energy regions where the np amplitudes are reasonably well known. An extended paper [10] has recently been published with this in mind. The new ANKE results for the deuteron Cartesian tensor analysing powers A_{xx} and A_{yy} at three beam energies are shown in Fig. 3 as functions of the momentum transfer. The agreement between the experimental data and the impulse approximation predictions obtained using the reliable SAID np amplitudes [11] as input at T_n = 600, 800, and 900 MeV, is very encouraging. This success provides a motivation for repeating these measurements at higher energies where the np input is far less certain.

The deficiencies of the SAID input np amplitudes at 1.135 GeV can be shown more explicitly by forming the following combinations of the observables:

$$\begin{aligned}
(1-A_{yy})/(1+A_{xx}+A_{yy}) &\approx (|\beta|^2+|\gamma|^2)/|\varepsilon|^2 , \\
(1-A_{xx})/(1+A_{xx}+A_{yy}) &\approx |\delta|^2/|\varepsilon|^2 , \\
(1-A_{xx})/(1-A_{yy}) &\approx |\delta|^2/(|\beta|^2+|\gamma|^2) .
\end{aligned}$$

The variation of these quantities with q are presented in Fig. 3 (right panel) for the 1.2 and 2.27 GeV data. Whereas at the lower energy all the ratios are well described by the model, at the higher it is seen that it is only $|\delta|^2/(|\beta|^2+|\gamma|^2$ which is well understood. It seems that the SAID program currently overestimates the values of $|\varepsilon|$ at small q. This will become clearer when absolute values of the cross sections are extracted at 2.27 GeV.

The final goal is to go to even higher energies by using a proton beam (available up to 3 GeV at COSY) incident on a polarized deuterium target, $p\vec{d} \to \{pp\}_s n$. This could be very fruitful because so little is known about the spin dependence of the np charge exchange reaction much above 1 GeV.

It was shown at Saclay [12] that at $T_d = 2$ GeV the $\Delta(1232)$ isobar can be excited in the $\vec{d}p \to \{pp\}_s\Delta^0$ reaction and substantial tensor analysing powers were measured. In impulse approximation, these are also sensitive to a spin–transfer from the neutron to the proton in $np \to p\Delta^0$. The Δ^0 is seen clearly also in the ANKE charge-exchange breakup data at 1.6, 1.8, and 2.27 GeV. The missing-mass spectrum in the $dp \to \{pp\}_sX$ reaction measured at three beam energies is shown in Fig. 4 (left panel). The neutron peak that has been used in the analysis of the $dp \to \{pp\}_sn$ reaction is very clean, with almost no background. More details of the current analysis results can be found in [13].

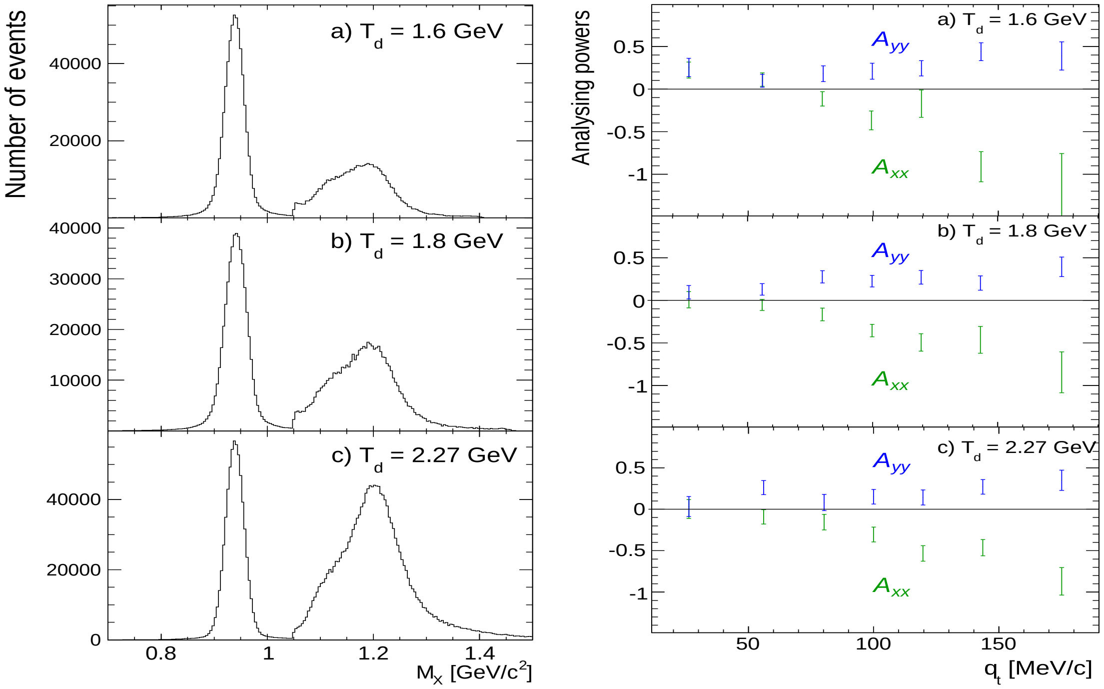

Figure 4: Left panel: The missing–mass M_x distribution for the reaction $\vec{d}p \to \{pp\}_sn$ at three deuteron beam energies. In addition to the neutron peak, one sees clear evidence for the excitation of the Δ^0 isobar. (The data in the high mass region have been scaled up by factor of eight.) Right panel: A_{xx} and A_{yy} tensor analysing powers at three deuteron beam energies. Higher mass region is used only.

Until the relative contributions of the two driving mechanisms (and their possible interferences) is sorted out, it is premature to compare the measured analysing power data with theory. However, one can assume that at high M_x the direct production dominates. We show only such data in Fig. 4 (right panel) as a function of the transverse momentum transfer q_t. In the forward direction, $q_t = 0$ and one must then have $A_{xx} = A_{yy}$ because there is no way of separating the x and y directions. The behaviour of both observables is similar at all three energies. However, it is important to note that the signs of the analysing powers are opposite to those of the $\vec{d}p \to \{pp\}_sn$ reaction shown in Fig. 3. These will prove to be valuable constraints on the modeling of the $pn \to \Delta^0p$ amplitudes, once we have sorted out the relative contributions of the two driving mechanisms.

4.2 Pion Production

A significant step forward in our understanding of pion reactions at low energies will be to establish that the same short–range $NN \to NN\pi$ vertex contributes to both p–wave pion production and to low energy three-nucleon scattering, where the identical operator plays an important role [14, 15]. Although there are extensive low energy data on pion production in the $pp \to d\pi^+$ reaction, the crucial physics of interest here is hidden in the much smaller cross sections associated with isospin $I = 1$ nucleon-nucleon final states. There is therefore a programme at the COSY-ANKE facility of the Forschungszentrum Jülich to perform a complete set of measurements on $NN \to \{pp\}_s\pi$ at low energy [8]. Here the $\{pp\}_s$ denotes a proton-proton system with very low excitation energy, E_{pp}. At ANKE we select events with $E_{pp} < 3$ MeV and, under these conditions, the diproton is overwhelmingly in the $^1S_0$ state with antiparallel spins. This simplifies enormously the spin structure and allows one to extract information on the production amplitudes without having to make measurements of the final proton polarizations.

As the first part of this larger programme, we report in these conference proceedings on a measurements of the cross section and proton analysing power in the $\vec{p}p \to \{pp\}_s\pi^{\circ}$ and $\vec{n}p \to \{pp\}_s\pi^-$ reactions [16].

4.3 η Mass Detrmination

The precise value of the mass of the η meson has been the subject of intense debate for several years. The situation seems to have been resolved with the publication of three experiments that obtained consistent results to high accuracy (for references see [17]). In all these new experiments the meson was cleanly identified through one of its decay modes.

It is, however, curious that experiments where the η meson is identified through a missing–mass peak in a hadronic production reaction have all reported a lower value for the mass, typically by about 0.5 MeV/c^2. This was the case for the $\pi^- p \to n\eta$ reaction, where the beam momentum was determined to high precision macroscopically using the floating wire technique [18]. In the two experiments where the $dp \to {}^3\mathrm{He}\,\eta$ reaction was studied [19, 20], the beam momentum was measured by studying other two–body reactions with known final masses. One concern is therefore whether the background under the η peak is slightly distorted by a strong coupling of, for example, $\eta\,^3\mathrm{He} \rightleftarrows \pi\pi\,^3\mathrm{He}$. Alternatively, perhaps the beam momenta were incorrectly calibrated, though this was done using different techniques for these experiments [18, 19, 20]. The situation can only be clarified through the performance of a more precise experiment.

The mass of the η meson has been measured at COSY–ANKE using pure kinematics by the determination of the production threshold of the $dp \to {}^3\mathrm{He}\,\eta$ reaction. Therefore a data set of final state momenta p_f and beam momenta p_d were measured with highest precision. The beam momentum was determined with a relative precision of $\Delta p/p < 6 \times 10^{-5}$ [(3100.0 ± 0.2) MeV/c] by using a polarized deuteron beam and inducing an artificial depolarizing resonance, which occurs at well–defined frequency [21]. The final state momentum above threshold was measured with an absolute precision of better than 0.32 MeV/c by studying the size of the momentum ellipse in the focal plane of the ANKE spectrometer. The preliminary value obtained, $m_\eta = (547.869 \pm 0.007 \pm 0.040)$ MeV/c^2, is consistent with other recent measurements where the meson was detected through its decay products. For more details see contribution [17].

5. Outlook - Snake concept

The physics case for longitudinally polarized protons is closely linked to the aspects outlined before. By means of a Siberian snake, the spin closed orbit at the location of the polarized target can be aligned along the direction of motion of the stored particles. The required field strengths that can be obtained with a solenoid together for the various experimental investigations [16, 22, 23, 24, 25] are listed in table 1. The snake is ordered and will be delivered during the next year.

Table 1: Required field integrals for the Siberian snake in the proposed experiments.

Purpose/Measurement	$\int B_z \cdot dl$ (Tm)
Determination of A_{xz} in $\vec{p}\vec{n} \to \{pp\}_s\pi^-$ at ANKE requires at $T_p = 353$ MeV	3.329
PAX at COSY requires at $T_p = 140$ MeV	1.994
PAX at AD requires at $T_p = 500$ MeV	4.090
$\vec{p}\vec{d}$ breakup studies in the range of $T_p = 30 - 50$ MeV require up to	1.165
$\lvert\vec{p}\rvert = p_z$ at the maximum possible proton beam energy of $T_p = 2880$ MeV	13.887

The concept is based on a fast ramping device that provides a field integral of 4.7 Tm, which can be either installed opposite the ANKE target location at the PAX interaction point. Installation of the snake at the ANKE target location allows one to provide longitudinal beam polarization in the straight section of COSY opposite the snake (see Fig. 1).

6. Summary

COSY is the only facility worldwide which provides polarized beams of protons and deuterons in the intermediate energy range for internal and external experiments. Together with existing and new detection systems, it is an indispensable facility for studies of hadron physics with hadronic probes. Its importance is further strengthened by the need to perform preparatory tests for the upcoming EDM measurements at COSY (see [22]).

Acknowledgments

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