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SPIN Physics at COSY: recent results and future plans

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The COSY facility at Forschungszentrum Jülich (Germany) comprises sources for unpolarized and polarized beams, an injector cyclotron (JULIC) and the cooler storage ring. It stores, accelerates and cools beams of protons and deuterons, and provides them for internal experiments and to external target stations. 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 combination with internal polarized hydrogen and deuterium targets, the availability of electron and stochastically cooled polarized beams (p,d), it allows for precision measurements. The major experimental facilities, used for the ongoing physics program, are ANKE and WASA (internal) and TOF (external). A new internal target station is in operation to investigate polarization build-up by spin-filtering (PAX). COSY is the machine which is also used for tests in conjunction with plans to build a dedicated storage ring for electric dipole moment (EDM) measurements of proton, deuteron and ^{3}He. To demonstrate the feasibility of a direct measurement of the charged particle EDMs in storage rings the JEDI collaboration (**J**ülich **E**lectric **D**ipole moment **I**nvestigations) has been formed.
In this contribution recent results from the ongoing spin physics program at COSY as well as future plans are summarized.

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1. Introduction

The COSY facility at Forschungszentrum Jülich comprises sources for unpolarized and polarized beams, an injector cyclotron (JULIC) and the storage and cooler ring[1] with a circumference of about 184 m (see Fig. 1). It stores, accelerates and cools beams of polarized/unpolarized protons and deuterons, 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. It can be considered the hadron spin physics machine because of its possibilities to produce, accelerate, manipulate and use polarized beams and targets.

The main focus at COSY is on the studies of the strong interaction in up, down,

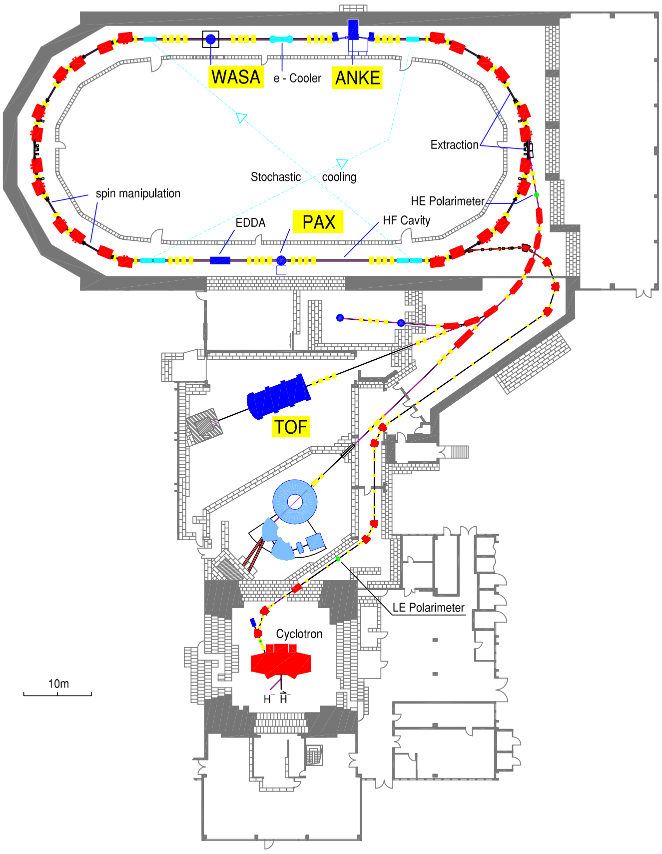

Fig. 1. Floor plan of the cooler synchrotron COSY. The locations of the major detector facilities are indicated.

and strange quark sector in their various topics of hadron structure and dynamics, as well as the symmetries and symmetry breaking processes. The aim is to study the properties and behaviour of hadrons in an energy range that resides between the nuclear and the high energy regime. The primary goal of the SPIN program at COSY[2] to carry out experiments aiming to extract the basic spin-dependent two-body scattering information via the study of 3-body final states. For this purpose the measurements are performed involving the polarized beams and targets (protons and deuterons), using the outstanding facilities available at COSY ring.

2. Experimental Facilities

Internal experiments are the unique possibility available at a storage ring like COSY: different detection systems like ANKE, WASA, and TOF, can be exploited for hadron physics experiments. In addition, a new internal so called low-beta section has been built and commissioned, which houses the PAX set-up. The upgraded

EDDA detection system as a polarimeter is exploited for the EDM investigations.

2.1. *The ANKE magnetic spectrometer*

ANKE (**A**pparatus for Studies of **N**ucleon and **K**aon **E**jectiles) is a large acceptance forward spectrometer installed in the COSY ring[3]. The central dipole is movable to adjust the momenta of the detected particles independent of the beam momentum. Detection systems for both positively and negatively charged particles include plastic scintillator counters for TOF measurements, multi-wire proportional chambers for tracking, and range telescopes for particle identification. The Forward Detector, comprising scintillator hodoscopes, and fast proportional chambers, is used to measure particles with high momenta, close to that of the circulating COSY beam.

Although strip and cluster-jet targets have been standard for use at ANKE, currently many experiments are using a polarized internal target (PIT) system[4]. One of the major advantages of doing experiments at a storage ring is that very low energy particles ejecting from the very thin targets can be detected in silicon tracking telescopes placed in the vacuum target chamber[5]. These are used to help in the measurement of elastic scattering, which is vital for luminosity and polarization calibrations. However, their most exciting use is for measuring the angles and energies of low energy protons (<10 MeV) that emerge as so-called spectators from the interactions of beam protons with the neutrons in the deuterium target.

2.2. *The 4π detector WASA*

WASA (**W**ide **A**ngle **S**hower **A**pparatus) is an internal 4π spectrometer for charged and neutral particles[6]. 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, on pseudo-scalar meson decays and the search for and the investigation of symmetry breaking.

2.3. *The low-β section for PAX*

A new internal target station, a so called low-β section, has been set-up at COSY which is used for the PAX (**P**olarized **A**ntiproton e**X**periments) experiments on proton spin-filtering[7]. 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 and built. With this set-up, spin-filtering experiment will be conducted at COSY with a longitudinally polarized proton beam.

3. Recent highlights from physics program at COSY

The hadron physics program at COSY can be summarized as spectroscopy, spin, and symmetry. Under the topic 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 tools, and photons serve as a selective (final state) probe. In the following, a few selective examples of recent results are presented.

3.1. *NN scattering*

The complete description of the NN interaction requires precise data as input to Phase Shift Analyses (PSA), from which the scattering amplitudes can be reconstructed. The PSA generally requires many independent observables and without polarization experiments it's goal can not be accomplished. Many of such experiments have been carried out for the *pp* system and as an example, the well-known EDDA experiment at COSY has produced a wealth of data for the *pp* elastic reaction. The amount of EDDA data on *pp*-scattering has reduced significantly the ambiguities in the phase shifts up to 2.1 GeV[8,9].

The ANKE spectrometer can provide precise data on the differential cross-section and spin observables in the energy range 1.0 to 2.8 GeV for center-of-mass angles $5^\circ < \theta_{cm} < 30^\circ$. One of the main tools here is the independent and accurate determination of the absolute luminosity. The technique relies on measuring the energy losses due to the electromagnetic interactions of the beam as it repeatedly passes through the target by studying the shift of the revolution frequency using the Schottky spectrum[10].

The experiment measuring the differential cross-sections ($d\sigma/d\Omega$) has been performed using an unpolarized proton beam at eight different beam energies, $T_p =$ 1.0, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, and 2.8 GeV, interacting with a hydrogen cluster-jet target[11]. The *pp* elastic events were identified by detecting one or both of the scattered protons in either the FD or STT system of ANKE. Detecting both protons provides valuable cross-checks between the two detection systems and significantly improves the accuracy and reliability of the measurements. The preliminary results of this experiment are presented in[12].

The proton analyzing power (A_y) in *pp* elastic scattering has also been measured at small angles at COSY-ANKE at 796 MeV and five other beam energies between 1.6 and 2.4 GeV using a polarized proton beam. The asymmetries obtained by detecting the fast proton in the ANKE forward detector or the slow recoil proton in a silicon tracking telescope are completely consistent. Although the analyzing power results agree well with the many published data at 796 MeV, and also with the most recent partial wave solution at this energy (SP07), the ANKE data at higher energies lie well above the predictions of this solution at small angles. An updated phase shift analysis that uses the ANKE results together with the World data leads to a much better description of these new measurements[13]. The details of this experiment are given in contribution talk of G. Macharashvili to this proceedings.

It was pointed out several years ago that the charge exchange of polarized deuterons on hydrogen, $dp \to \{pp\}_s n$, can furnish useful information on the spin dependence of elastic neutron-proton amplitudes near the backward center-of-mass direction provided that the final proton pair $\{pp\}_s$ is detected at very low excitation energy E_{pp}[14]. The most detailed studies of this reaction were undertaken by the ANKE collaboration at energies per nucleon of $T_N = 0.6$, 0.8, 0.9, and 1.135 GeV [15,16]. At the three lower energies the predictions of the impulse approximation model describe the data very well on the basis of np input taken from the SAID SP07 partial wave solution [17]. Deviations were, however, noted in the 2.27 GeV data [16] that were ascribed to an overestimate of the strength of the np spin-longitudinal amplitude at 1135 MeV.

To continue the studies at COSY to higher energies, where there is great uncertainty in the neutron-proton amplitudes, the experiments have to be carried out in inverse kinematics, with a proton beam incident on a polarized deuterium target. The study of the charge exchange at low momentum transfers would then require the measurement of two low energy protons recoiling from the target. The results of the first measurement for the $pd \to n\{pp\}_s$ charge-exchange at 600 MeV that extends the earlier deuteron beam data out to larger values of the momentum transfer q, are reported in[18].

Exclusive and kinematically complete high-statistics measurements of quasi-free polarized $\vec{n}p$ scattering have been performed by WASA collaboration in the energy range of the narrow resonance-like structure d^* with $I(J^P) = 0(3^+)$, $M \approx 2380$ MeV, and $\Gamma \approx 70$ MeV observed recently in the double-pionic fusion channels $pn \to d\pi^0\pi^0$ and $pn \to d\pi^+\pi^-$[19]. The experiment was carried out with the WASA detector setup at COSY having a polarized deuteron beam impinged on the hydrogen pellet target and utilizing the quasi-free process $\vec{d}p \to np + p_{spec}$. This allowed the np analyzing power (A_y) to be measured over a broad angular range. The obtained A_y angular distributions deviate systematically from the current SAID SP07 NN partial-wave solution. Incorporating the new A_y data into the SAID analysis produces a pole in the ${}^3D_3 - {}^3G_3$ waves in support of the d^* resonance hypothesis[20,21].

3.2. *Pion production*

Within the context of chiral perturbation theory, a significant step forward in our understanding of pion physics at low energies would be to establish that the same short ranged $NN \to NN\pi$ vertex contributes to p-wave production, to low energy three-nucleon scattering, to electroweak processes, and reactions involving photons. With this in mind, an extensive programme of near-threshold measurements of $NN \to \{pp\}_s\pi$ was conducted at the COSY-ANKE facility[2].

The missing term corresponds to an effective $NN \to NN\pi$ vertex, where the pion is in a p-wave and both initial and final NN pairs are in relative S waves. It was our aim to extract the relevant partial wave amplitudes in pion production from the experiment. This is a precondition for a reliable determination of the so called low energy contact term (LEC)[22]. The differential cross sections ($d\sigma/d\Omega$), analyzing powers (A_y), and the transverse spin correlations ($A_{x,x}$ and $A_{y,y}$), have been measured for $pp \to \{pp\}_s\pi^0$ and $np \to \{pp\}_s\pi^-$ reactions at 353 kinetic energy using the ANKE setup. The final results of this programme are summarized in[23,24,25,26].

3.3. *η-Meson production: $\eta - {}^3He$ FSI*

Studies on the $dp \to {}^3\mathrm{He}\,\eta$ reaction are motivated by the very anomalous results near threshold as well as by the poorly understood production mechanism[27]. It was suggested that the rapid jump of the total cross section as function of the excess energy Q is an effect of a surprisingly strong final state interaction (FSI) in the $\eta - {}^3He$ system that might lead to a quasi-bound eta-nuclear state[28]. Detailed studies on former measurements with unpolarized beams and targets show a pole in the $\eta - {}^3He$ elastic amplitude for $Q < 0.5$ MeV. This finding is supported by the analysis of the variation of the angular dependence of the cross section with the excess energy Q[29]. In order to further investigate this system new data with polarized deuteron beam have been taken close to the production threshold.

The deuteron tensor analyzing power t_{20} of the $dp \to {}^3\mathrm{He}\,\eta$ reaction has been measured at the COSY-ANKE facility in small steps in excess energy up to $Q =$ 11 MeV. Despite the square of the production amplitude varying by over a factor of five through this range, t_{20} shows little or no energy dependence. This is evidence that the final state interaction causing the energy variation is not influenced by the spin configuration in the entrance channel. The weak angular dependence observed for t_{20} provides useful insight into the amplitude structure near threshold[30].

3.4. *Polarization of antiprotons (test of the method with protons)*

The PAX Collaboration continues the program devoted to the study of viable methods to produce the first intense beam of polarized antiprotons for the future FAIR facility. In the past years, two milestones for the field have been accomplished through the experiments with protons at the COSY ring: in 2008 a dedicated experiment has ruled out the use of spin-flip as a viable way to polarize in situ a stored beam[31]. In 2011 a spin-filtering experiment with a transverse polarized hydrogen target has been successfully performed[32]. The measurement has definitely proven that spin-filtering can be used to polarize a stored beam in situ and confirmed that the theoretical understanding of the spin-filtering mechanism is in excellent agreement with the experimental results.

As a natural extension of this activity, the collaboration is now preparing the first ever spin-filtering test with longitudinal polarization. In order to determine corresponding term of the total cross section the polarization direction has to be longitudinal at the position of the polarized internal target. The preservation of a longitudinal stable direction for the beam polarization at the PAX interaction point requires the installation of a a dedicated solenoid (a so called *Siberian Snake*) on the opposite side of the ring, namely at the ANKE place. The snake is awaited at Jülich in early 2015. More details of the scheduled measurements by the PAX collaboration can be found elsewhere[33,34].

4. Future: EDM project

One of the great mysteries in physics is the dominance of matter over anti-matter in our Universe. The net baryon number is about 10^{-11}. In the Standard Model (SM) this ratio is expected to be on the order of 10^{-18}. New CP violating sources outside the realm of the SM are clearly needed to explain this discrepancy. Electric dipole moments (EDM) break parity (P), time-reversal (T) symmetry, and - via the CPT-theorem - charge-parity (CP) symmetry. EDM's of elementary particles are considered to be one of the most powerful tools to investigate CP violation beyond the SM and to find an explanation for the dominance of matter over anti-matter. Up to now experiments concentrated on neutral systems (neutrons, atoms, molecules). Storage rings offer the possibility to measure EDMs of charged particles by observing the influence of the EDM on the spin motion. For neutral systems this can be done in a quasi-static, localized setup. Charged particles, however, are accelerated by the electric field. Therefore, it has been suggested to utilize a storage ring for such a measurement.

Currently R&D work has started at COSY towards a dedicated storage ring for measuring electric dipole moments of charged hadrons. One major goal of the recent experiments was to increase the spin coherence time of the beam particles. For this purpose a time marking system using the EDDA detector as a polarimeter has been developed to monitor the horizontal spin precession - i.e. the in-plane polarization of a deuteron beam at 0.97 GeV/c. The set of obtained data have shown how the second-order effects from emittance and momentum spread of the beam affect the lifetime of the horizontal polarization of a bunched beam. It has been demonstrated that sextupole fields can be used to correct for these depolarizing sources and increase the spin coherence time up to hundreds of seconds. Further information on the method, the data analysis and the results on the spin coherence time can be found in refs.[35,36,37].

Another tool to be used for studying the effects of various ring elements (like solenoids, steerer and rf Wien filters) on the spin motion is the precise measurement of the spine tune. This has been successfully achieved with a precision close to

$\Delta\nu \approx 10^{-10}$ during 90 second beam storage. A corresponding publication is in preparation[38].

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