Physics Program at COSY-Jülich with Polarized Hadronic Probes

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Abstract. Hadron physics aims at a fundamental understanding of all particles and their interactions that are subject to the strong force. Experiments using hadronic probes could contribute to shed light on open questions on the structure of hadrons and their interaction as well as the symmetries of nature. The COoler SYnchrotron COSY at the Forschungszentrum Jülich accelerates protons and deuterons with momenta up to 3.7 GeV/*c*. The availability of both an electron cooler as well as a stochastic beam cooling system allows for precision measurements, using polarized proton and deuteron beams in combination with polarized Hydrogen or Deuterium targets.

This contribution summarizes the ongoing physics program at the COSY facility using ANKE, WASA and TOF detector systems with polarized hadronic probes, highlighting recent results and outlining the new developments.

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INTRODUCTION

Hadron physics aims at a fundamental understanding of all bound and resonant systems and their interactions that are subject to the strong force. Many aspects of the theory of the strong interactions (QCD) are not understood yet. It is one of the great challenges of contemporary physics to understand this key feature of QCD, the confinement of quarks and gluons. As a consequence of confinement information about quarks and gluons can only be obtained through investigations of hadronic systems – mesons, baryons, and possibly exotic states – their production, decays and interactions. Intriguing tests of QCD are possible with high precision experiments eventually involving polarization.

This contribution gives an overview of the ongoing physics program at the COSY facility with the emphasis on the polarization experiments using ANKE, WASA and TOF installations, as well as highlighting a few selective results.

EXPERIMENTAL TOOLS

The COoler SYynchrotron COSY–Jülich stores and accelerates both unpolarized and polarized proton and deuteron beams injected from the injector cyclotron JULIC after preacceleration up to momenta of 0.3 GeV/*c* for protons and 0.55 GeV/*c* for deuterons [1]. COSY subsequently accelerates those particles up to 3.7 GeV/*c*. It exploits electron cooling at injection energy and stochastic cooling between 0.8 GeV/*c* and the maximum momentum to provide precision beams for both internal and external targets. To preserve polarization during acceleration of polarized protons, well-established methods are being used. A fast tune jumping system has been developed to overcome intrinsic resonances. Polarization across imperfect resonances is preserved by the excitation of the vertical orbit using correcting dipoles to induce total spin flips. The polarization of the circulating beam in COSY can be monitored continuously during acceleration with the internal EDDA detector. The achieved polarization for protons is higher than 75% up to final momentum. Vector and tensor polarized deuterons are also routinely accelerated in COSY with polarizations up to 60% [2].

The Jülich Center for Hadron Physics (JCHP), recently established in Forschungszentrum Jülich (FZJ) [3], operates several experimental facilities for in-beam and external beam experiments, in cooperation with large international collaborations.

- **ANKE** (**A**pparatus for studies of **N**ucleon and **K**aon **E**jectiles), is a large acceptance forward magnetic spectrometer at an internal target station in the COSY ring [4]. The central dipole is movable to adjust the momentum of the detected particles independent of the beam momentum. Using deuterium cluster targets, reactions on the neuteron are tagged by detecting the low energy recoil proton in silicon strip detectors in vacuum next to the target. A Polarized Internal Target (PIT) system comprising with: an Atomic Beam Source (ABS), a Lamb–Shift Polarimeter (LSP), and a Storage Cell (SC) is in use at ANKE since 2005 [5].
- **TOF** (**T**ime–**O**f–**F**light), a non–magnetic spectrometer combining excellent tracking capability with large acceptance and full azimuthal symmetry allowing to measure complete Dalitz plots [6]. TOF is optimized for final states with strangeness. With the new straw tube tracking system, TOF will have a significantly improved mass resolution and reconstruction efficiency.
- **WASA** (**W**ide **A**ngle **S**hower **A**pparatus), an internal 4π spectrometer with large solid angle acceptance, is operated at the internal COSY beam [7]. WASA comprises an electromagnetic calorimeter, a very thin superconducting solenoid, inner and forward tracking detectors and a frozen–pellet target. Charge and neutral reaction products and their decay products can be measured exclusively.

In addition, the unique COSY capabilities are used by the **SPIN@COSY**- and the **dEDM**-collaborations to investigate spin-manipulations [8] and to prepare a dedicated EDM-storage ring experiment [9]. The **PAX** collaboration [10] is addressing the spin–filtering studies by accelerated proton beam and polarized targets.

EXPERIMENTAL PROGRAM AT COSY

Overview

The hadron physics program at COSY can be summarized to be focused around the issues of spectroscopy, spin, and symmetry. Under the headline spectroscopy the foremost research object is the nucleon an its mutual interactions as well as its excited states and possible exotics. The role and manifestation of the strange quark is an issue studied in associated production of hyperons and strange mesons. The symmetries expected in strong interactions, such as chiral symmetry and isospin, and their breaking have come into the focus of investigations. The 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. COSY research also provides a window into the future **FAIR** project [11] (Facility for Antiproton and Ion Research to be built at GSI, Darmstadt) with studies on spin manipulation and polarization build–up of protons (antiprotons) in polarized targets (PAX experiment [10]).

In the following chapters a few selective results will be presented.

NN–Interaction

An understanding of the *NN* interaction is fundamental to the whole of nuclear and hadronic physics. The database on proton–proton elastic scattering is enormous and the wealth of spin–dependent quantities measured by the EDDA collaboration [12] has allowed the extraction of *NN* phase shifts in the isospin $I = 1$ channel up to a beam energy of at least 2 GeV. The situation is far less advanced for the isoscalar channel where the much poorer neutron–proton data only permit the $I = 0$ phase shifts to be evaluated up to at most 1.3 GeV but with significant ambiguity above about 800 MeV.

The ANKE collaboration has embarked on a systematic program to measure the differential cross section and analyzing powers of the small momentum transfer deuteron charge–exchange $dp \to \{pp\}n$ breakup reaction up to the maximum energy at COSY of 1.15 GeV per nucleon, with the aim of deducing information on the *np* amplitudes. Higher energies per nucleon will be achieved through the use of a proton beam and deuterium target. Spin correlations will also be studied with a polarized beam and target. However, for these to be valid objectives, the methodology has to be checked in a region where the *np* amplitudes are reasonably well known.

The charge–exchange amplitude of the elementary $np \to pn$ scattering may be written in terms of five scalar amplitudes in the c.m. system as:

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

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 the spin–spin terms [13]. Impulse approximation applied to $dp \to \{pp\}_{^1S_0}n$ reaction leads to predictions for the differential cross section and deuteron spherical analyzing powers in such a form that allows in the $^1S_0$ limit to extract values of $|\beta(q)|^2 + |\gamma(q)|^2$, $|\delta(q)|^2$, and $|\varepsilon(q)|^2$ for small values of the momentum transfer $\vec{q}$ between the initial proton and final neutron. The variation of the cross section with momentum transfer can be found in Fig. 1 for $E_{pp} < 3$ MeV [13]. The impulse approximation describes well the dependence on this variable up to $q =$ 140 MeV/c. Our experimental values of the two tensor analyzing powers are shown in Fig. 1 as a function of the momentum transfer.

Although all the experimental data agree with the impulse approximation model one might invert the question. How well can one determine the amplitudes if there were no information available from the *np* phase shifts? Although the data reported here were

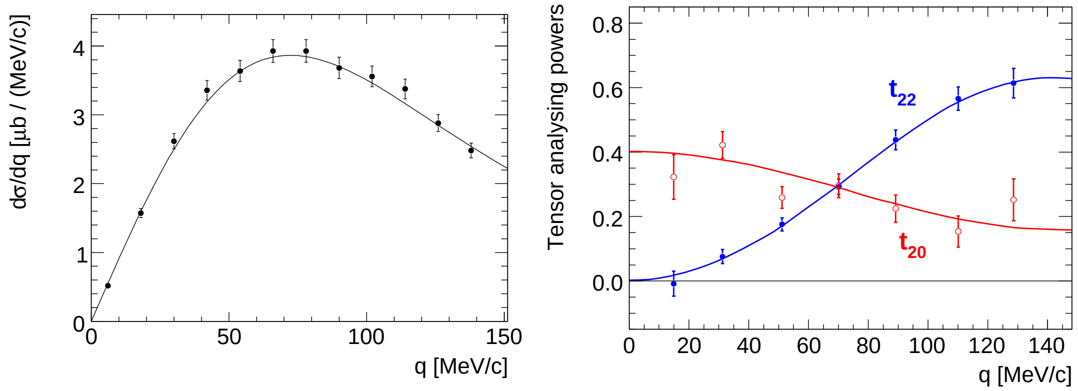

FIGURE 1. Left panel: Unpolarized differential cross section at $T_d = 1170$ MeV for the $dp \to \{pp\}n$ reaction of $E_{pp} < 3$ MeV. Right panel: Spherical tensor analyzing powers t_{20} (open symbols) and t_{22} (closed) for the $\vec{d}p \to \{pp\}n$ reaction at $T_d/2 = 585$ MeV for $E_{pp} < 1$ MeV. The solid curves are the impulse approximation predictions.

obtained over a short run, these are already sufficient to determine quite well the ratio of the $|\varepsilon(0)|/|\beta(0)|$ in the forward direction. The value obtained at the origin gives $t_{20} = 0.37 \pm 0.02$, where the error is purely statistical. The uncertainty introduced by the beam polarization would, however, contribute less than ± 0.01 to this. Since there is little or no dilution of the analyzing power by p-waves at $q = 0$, this result translates into an amplitude ratio of $|\varepsilon(0)|/|\beta(0)| = 0.61 \pm 0.03$, to be compared with SAID [14] value of 0.58. The proof–of–principle achieved in [13] for the method suggests that measurements at higher energies will provide useful information in regions where the existing np database is far less reliable.

Few Nucleon Systems with Diproton Final States

Properties of few nucleon systems have long been a subject of intensive theoretical and experimental study. A particularly important role in this study has been played by processes with the deuteron, a bound state of proton and neutron. In this respect, a particular interest arises for the investigation of the diproton, an unbound system of two protons with small excitation energy. The diproton, being the isospin partner of the deuteron, possesses different quantum numbers. Selection of the excitation energy of the proton pair $E_{pp} < 3$ MeV ensures dominance of the $^1S_0$ state of the diproton, which simplifies significantly the theoretical interpretation. The reactions with formation of a diproton involve transitions in the NN system, different from the case of the deuteron, and, in particular, the role of the Δ isobar is expected to be much suppressed because the S-wave ΔN intermediate state is forbidden. The diproton program at ANKE involves several experiments:

- Study of mesonless deuteron breakup $pd \to \{pp\}_s n$ in collinear kinematics: (i) at low momentum transfers (charge–exchange reaction) [13], and (ii) at high momentum transfers [15, 16].

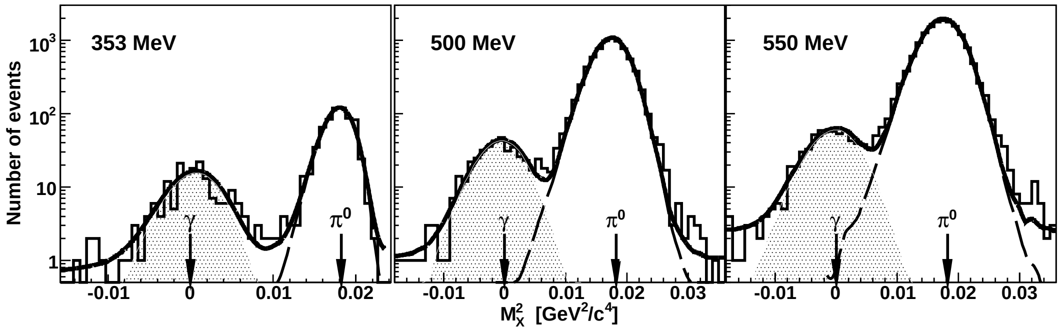

FIGURE 2. Missing-mass-squared for the $pp \to ppX$ reaction with $E_{pp} < 3$ MeV. The shaded area corresponds to the predicted γ peak, the dashed line to the π^0, and the solid to the sum of these and a straight line background.

- Study of meson production in $pN \to \{pp\}_s X$, where X can be : (i) a single pion [17], and (ii) the $(\pi\pi)$ system used to study ABC effect in $pp \to \{pp\}_s(2\pi)$ [18].
- Study of the inverse diproton photodisintegration $pp \to \{pp\}_s\gamma$.

The fundamental reaction $pp \to \{pp\}_s\gamma$ has been observed for proton beam energies of $T_p = 353, 500$, and 550 MeV [19]. This is equivalent to photodisintegration of a free $^1S_0$ diproton for photon energies $E_\gamma \approx T_p/2$. The events from this process produce a peak at $M_x^2 \approx 0$ in the experimental missing-mass spectra (Fig. 2).

The differential cross sections measured for c.m. angles $\theta_{pp}^{cm} < 20^\circ$ exhibit a steep increase with angle that is compatible with E1 and E2 multipole contributions [19]. The ratio of the measured cross sections to those of $np \to \gamma d$ is on the $10^{-3} - 10^{-2}$ level. The increase of the $pp \to \{pp\}_s\gamma$ cross section with T_p might reflect the influence of the $\Delta(1232)$ excitation. Further information on this process will be obtained within the planned measurement of the $pp \to \{pp\}_s\pi^0$ and the $pn \to \{pp\}_s\pi^-$ process with a polarized proton beam at ANKE [20].

Single pion production and the charge–exchange breakup reaction are the key double polarization experiments in the physics program at ANKE [21].

η–He Interaction and η–Mass Measurement

New and very precise data on the $dp \to {}^3\mathrm{He}\,\eta$ reaction near threshold [22, 23], taken at COSY, confirm the energy dependence of the total cross section found in earlier experiments, but with much finer steps in energy over an extended range. The observed variation of the total cross section and the angular distributions near threshold means that the both, the phase and magnitude of the S–wave amplitude, falls very rapidly with the η centre–of–mass momentum [24]. Such a behaviour is expected from a quasi–bound or virtual η^3He state. The interpretation can be investigated further through the measurements of $dp \to {}^3\mathrm{He}\,\eta$ analyzing powers and spin correlations, which will allow us to pursue the investigation without some of the simplifying assumptions which have been made in the current analysis. Such an experiment has been conducted at ANKE [25] and the analysis is in progress.

Using the experience gained in this investigation, it has been proposed to determine the mass of the η–meson in a precision measurement at COSY in a new and innovative way [26]. The experiment made use of a polarized deuteron beam incident on an unpolarized cluster jet target inside the COSY–ring. The reaction to be exploited was $\vec{d}p \rightarrow ^3\mathrm{He}\eta$, which has been identified by ^{3}He detection in the magnetic spectrometer ANKE and a missing–mass analysis. The techniques which have been employed are: (i) ramping of the deuteron beam energy across the η production threshold; (ii) ^{3}He identification with full acceptance over the full energy range; (iii) determination of the excess energy from kinematics ('radius method') [26]; and (iv) determination of the absolute deuteron beam momentum ('spin resonance method') [27]. All of these steps have been tested in previous experiments at COSY and have been shown to work. Taking the uncertainty limits, which have already been achieved, we expect the final uncertainty of the η–mass to be less than 50 keV/c^2, *i.e.* equivalent to or better than the best existing measurements.

Strangeness Production: The $\Lambda-$N Scattering Length

For systems with strangeness, there are still many open questions and it is not even clear if the kaon is more appropriately treated as a heavy or a light particle. To improve further our understanding of the dynamics of systems containing strangeness, better data are needed. The insights to be gained are relevant, not only for few–body physics, but also for the formation of hypernuclei, and might even be of significance for the structure of neutron stars. The hyperon–nucleon scattering lengths are obvious quantities of interest in this context.

The Jülich (IKP) theory group has developed a method to enable one to deduce a scattering length directly from data on a production reaction, such as $pp \rightarrow pK^+\Lambda$, in terms of an integral over the invariant Λp mass (m_X) distribution [28]. Using this method it can be seen that the inclusive Saclay $pp \rightarrow K^+X$ data [29], which had a mass resolution of 4 MeV, allow the extraction of a scattering length with an experimental uncertainty of only 0.2 fm. However, the actual value of the scattering length obtained in this way is not meaningful, since it represents the incoherent sum of the $^3S_1$ and the $^1S_0$ Λp final states with unknown relative weights. It is important to try to separate them.

The COSY-TOF detector has been designed particularly for the investigation of final states with strangeness. The detector combines excellent tracking capability with large acceptance and full azimuthal symmetry [6]. The tracking information, in particular close to the interaction point, allows to identify the production of strange hadrons with almost no background, based on the detection of the displaced decay vertices of Λ hyperons ($\Lambda \rightarrow p\pi^-$) and K_S mesons ($K_S \rightarrow \pi^+\pi^-$).

The available experimental data on Λp elastic scattering and on the Λp final state interaction in production reactions only allow to deduce the spin-averaged value of the Λp scattering length, with yet large uncertainty. COSY-TOF plans to measure the spin-triplet Λp scattering length by analysing the $\vec{p}p \rightarrow \Lambda pK^+$ reaction around 90° K^+ polar angle in the center-of-mass frame. The goal of the measurement is to achieve an accuracy below 0.3 fm, which is also the theoretical uncertainty of the method [28] to deduce the scattering length from production reactions.

The Λn triplet final state could be isolated unambiguously by measuring the unpolarized K^+ spectrum in the forward direction and this weighted with the incident spin correlation, obtained using a transversally polarized beam and target. This we will achieve by looking at the $\vec{p}\vec{d} \to p_{sp}K^+X$ reaction using the ANKE installation [21].

Symmetry and Symmetry Breaking

Symmetry and symmetry breaking patterns as well as the structure of hadrons are the primary focus of the WASA-at-COSY collaboration. One of the key experiments is a measurement of $\vec{d}d \to {}^4\mathrm{He}\,\pi^0$ to extract the P-wave contribution to the Charge Symmetry (CS) breaking amplitude [7]. In preparation of data taking with a polarized deuteron beam, the reaction has been measured with an unpolarized beam at a momentum of p_d = 1.2 GeV/c (T_d =351 MeV) to establish the so far unknown cross section, which can only be estimated based on data available at much lower excess energy and to demonstrate the separation of the helium isotopes after installation of the new forward tracking hodoscope [31]. Data analysis is presently in progress, and from first checks of the data a total statistics of 500 to 1000 events is expected for the CS breaking reaction.

Spin–Filtering Studies at COSY

An entirely new chapter in studies of hadron physics might unfold with the advent of a polarized antiproton beam provided an efficient method for polarizing antiprotons can be demonstrated. Polarized antiproton beams could be possibly employed e.g. at FAIR [11], and at the European Organization for Nuclear Research (CERN). There are major technological challenges to be met in order to produce beams of polarized antiprotons. Foremost is the question of how to polarize antiprotons effectively. The only viable method demonstrated so far that could yield a beam of polarized antiprotons is spin–filtering of a stored beam by selective loss and/or selective spin–flip through repetitive interaction with a polarized internal target. (The proof-of-principle experiment (FILTEX) has been carried out with protons at TSR, Heidelberg [32].) Although the FILTEX experiment clearly demonstrated that the spin–filtering technique works, a unique interpretation of the result is not available yet. In order to make spin–filtering a practicable method for polarizing antiprotons, preparatory experiments with protons and antiprotons are required. In order to accomplish this goal, a proper experimental setup and a theoretical structure have to be implemented to support a series of dedicated experimental investigations, which has recently started at COSY [33].

SUMMARY

COSY in combination with its complementary experimental facilities and polarized hadronic beams and targets provide unique opportunities to investigate a variety of aspects in hadron physics. The experience gained in undertaking polarization measurements will be put to good use for future developments at FAIR.

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