

PHYSICS PROGRAM AT COSY

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Abstract

The COoler SYnchrotron COSY at the Forschungszentrum Jülich accelerates protons and deuterons to momenta of up to $3.7 \text{ GeV}/c$. Experiments in the ring use the coasting beam, which can be produced with transverse polarization in excess of 80%. These experiments center around the production, interaction and decay of hadrons, mesons as well as baryons. This contribution summarizes the ongoing physics program at the COSY facility, highlighting recent results and detailing future developments and plans.

1 Introduction

Hadron physics with hadronic probes provides insight into the production, interaction and decay of hadrons. The search for missing states predicted in the scheme of constructing hadrons from elementary building blocks can shed light on quark interactions and selection rules. The symmetries expected in strong interactions, such as chiral symmetry and isospin, and their breaking are a matter of ongoing research. Mass modifications of mesons embedded in the nuclear medium may allow to understand chiral restoration and, thus, deepen the insight into the chiral symmetry concept.

The COoler SYnchrotron *COSY* [1] is designed for experimental research in this field of physics. It accelerates protons and deuterons to momenta of $3.7 \text{ GeV}/c$. Vector polarization of up to 80% can be achieved. Deuterons can also be tensor-polarized. In the past, a number of experiments addressed a broad range of topics at *COSY*. Results include the most complete set of observables in elastic proton-proton interactions between 500 and 2500 *MeV* beam energy [2] and many measurements on production of a variety of mesons in the pseudoscalar, vector and scalar sector very close to threshold and at higher excess energies (for a recent review, see [3]). Experiments at *COSY*

have access to the production of strangeness degrees of freedom, most commonly through associated production of hyperons and kaons.

The large experience gained in these studies has recently mounted in the formulation of a physics program that centers around three big experimental installations, the internal *ANKE* magnetic spectrometer, the external 4π *TOF* spectrometer and the *WASA* detector, which was successfully transferred from TSL in Uppsala to Jülich and has commenced operation recently after a period of refurbishing and upgrades to match the higher energies accessible at *COSY*. With *WASA*, explicit searches for isospin-violating processes have become feasible. Rare decays of η and η' will be investigated. These studies will be complemented by polarization physics using polarized beams and targets, and hyperon production experiments, which give access to the hyperon-nucleon interaction and baryon resonances. *COSY* research also provides a window into the *FAIR* future with studies on spin manipulation and polarization build-up of protons in polarized targets.

2 The COSY Facility

Figure 1 shows a schematic view of the experimental facility. Negative ions are accelerated to 40 *MeV* in the cyclotron and injected into *COSY* where electron cooling can be used to improve the phase space distribution of the beam before acceleration to the appropriate energy for a given experiment. At a circumference of 184 *m* *COSY* can store 10^{11} protons or deuterons. The coasting beam after acceleration has a typical momentum spread of $\Delta p/p \approx 10^{-4}$ and an emittance of better than π *mm mrad*.

When the beam is used at one of the internal target stations its emittance can be continuously controlled with stochastic cooling, which guarantees constant beam properties for an extended duration of beam-target interaction. In addition, *COSY* features slow extraction of beams with momenta up to 3.3 *GeV/c* for external experiments. This features provides continuous beams of 10^5 to 10^9 particles per second on target for up to 100 *s* or more depending on beam current. These beams can be polarized as well.

The figure also shows the experiments at *COSY*, some of which are phasing out (shaded entries) to be replaced by recent additions and massive upgrades of other detectors also shown. *PISA* was an experiment designed to study the interaction of high-energy protons with heavy targets and measure fragment isotopic distributions and differential cross sections. [4]. *EDDA* has been mentioned before. Here, an extensive data base of pp elastic scattering over the full *COSY* energy range was collected with very high statistics and

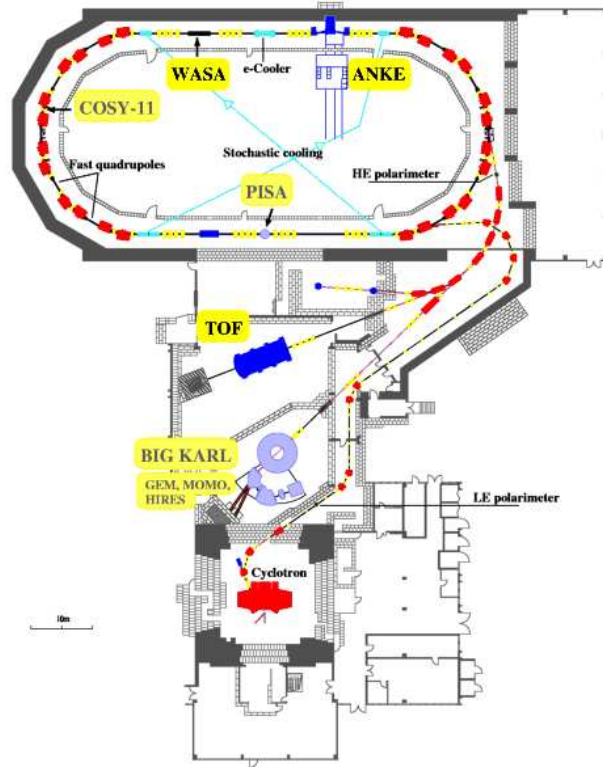


Figure 1: Schematic view of the *COSY* accelerator.

precision. Both polarized beam and polarized beam and target in combination were used to measure all differential observables that can be obtained with polarization degrees of freedom in the entrance channel [2]. These measurements have then been introduced into the SAID database and phase shift analysis [5] and caused a dramatic improvement of the reliability of this analysis. *EDDA* is still in use as a reliable polarization monitor for *COSY* beams, e.g. in the spin manipulation program of the "Spin at *COSY*" collaboration. *COSY - 11* used one of the *COSY* accelerator dipoles as an analyzing magnet by placing a gas jet target in front of the magnet. Reaction products have a smaller magnetic rigidity than the beam. Particles of positive charge therefore get deflected inward into the ring and can be detected with tracking and time-of-flight devices to determine particle species and velocity. Because of the limited acceptance *COSY - 11* was best suited for measurements only slightly above threshold. *COSY - 11* has produced detailed excitation functions for a number of reaction channels, in particular in the production of single mesons, e.g. $p\bar{p} \rightarrow pp\eta$, $pp \rightarrow pp\eta'$ [6]

and in dp interactions [7] and channels involving open strangeness such as $pp \rightarrow pKY$ [8] and also double-kaon production, $pp \rightarrow ppKK$ [9].

WASA at *COSY*, the *ANKE* magnetic spectrometer and the Time-of-flight experiment *COSY – TOF* will be described in some more detail later. The magnetic spectrometer *BIGKARL*, located at an external beam line, concludes the list of experiments in hadron physics at *COSY*. The large acceptance of the *BIGKARL* spectrometer and its excellent resolution has been used in a number of meson-production reactions where usually the mesons were detected in additional detectors that covered large solid angles, such as *MOMO*, a tracking detector covering polar angles up to 45° degrees and the *GEM* germanium wall that measured particle energies and energy loss in addition to the spatial information. Here, high-precision mass measurements for the η [10] and double-meson production in proton-deuteron fusion ($\pi^+\pi^-$ as well as K^+K^- [11], [12]) are among the highlights of the program.

3 Experiments at COSY

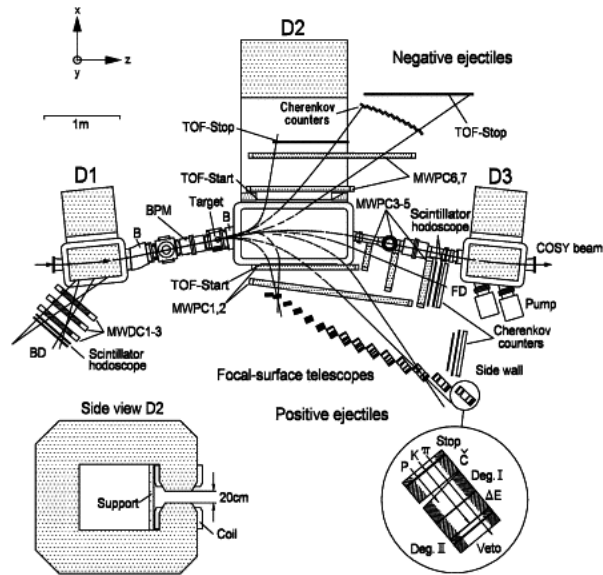
The ongoing physics program at *COSY* centers around three large experiments. These setups are complementary in their layout. Each of these will be discussed in some detail in the following.

The ANKE spectrometer

The *ANKE* magnetic spectrometer (cf. Fig. 2, from [13]) is a rather large-acceptance spectrometer featuring excellent momentum resolution. It is optimized for kaon identification. To this end, detectors inside the yoke allow detection of negatively charged particles. The detectors in the focal surface on the positive bending side are of $\Delta E - E$ type with absorbers inserted in order to identify kaons over a wide momentum range. The measurement of forward-going high-momentum particles is augmented by an array of silicon telescopes in the target region to measure recoil protons. This telescope can identify recoil protons from deuteron targets with good resolution, facilitating measurements on the neutron through recoil tagging. Apart from heavy foil targets, a cluster jet target and a polarized atomic beam target for protons and deuterons are available at *ANKE*. Exploiting these features, the *ANKE* collaboration performs experiments on three-body final states using polarized beams and targets. The focus here is on polarized nucleon-nucleon scattering also including np interactions and on investigations of meson-baryon and baryon-baryon final state interactions.

WASA at COSY

The *WASA* setup at *COSY* (cf. Fig. 3, see [14]) has a much larger geomet-

Figure 2: Schematic view of the *ANKE* spectrometer.

rical acceptance than the devices discussed so far. A very thin superconducting solenoid surrounding the target generates a magnetic field in which the momenta of charged particles are measured using a cylindrical tracker surrounded by a plastic scintillator barrel. In forward direction, a calorimeter with differential energy measurement and a set of tracking devices allows to measure particle ID and total energy as well as direction of charged particles with high accuracy. The central barrel of *WASA* is surrounded by a photon spectrometer with high granularity, which allows to measure photons from π and η decay as well as electrons with good spatial as well as energy resolution. The *WASA* setup is equipped with a hydrogen pellet target which permits operation at very high luminosity. Because of the large geometrical acceptance of *WASA*, rare final states can be searched for efficiently. The physics focus of *WASA* is the investigation of violation and breaking of basic symmetries through the measurement of exclusive final states. With the *WASA* detector, *COSY* becomes a factory for η and η' mesons, whose successive decay into a variety of channels can be studied.

COSY-TOF

The Time-of-Flight detector *COSY – TOF* (cf. Fig. 4) takes a very different approach which is optimized for the measurement of produced particles that subsequently decay in the region behind the target. The *COSY-TOF* spectrometer is located at an external *COSY* beamline. A small target cell

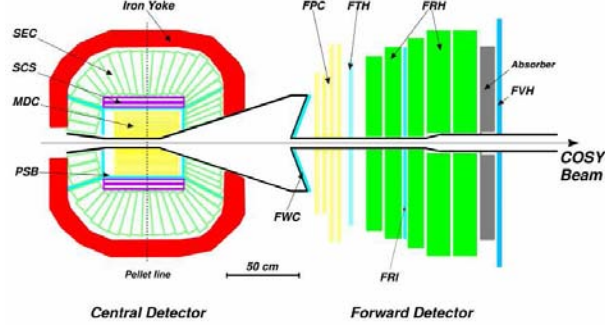


Figure 3: Schematic view of the WASA setup at COSY. (SEC: electromagnetic calorimeter; SCS, PSB, MDC: tracking and time-of-flight; FWC: forward window counter; FPC, FTH: tracking; FRH: range hodoscope; FVH: forward veto hodoscope.)

with a length of 4 mm only and a beam extension of less than 1 mm guarantee a very good definition of the primary reaction vertex. Reaction products are then detected in a series of position-sensitive detectors that define the particle tracks. (See inlay of 4, which shows the enlarged target region. The distance of the last two tracking layers is 10 cm.) Delayed decays in particular of neutral particles, e.g. $\Lambda \rightarrow \pi^+ p$ or $K_s \rightarrow \pi^+ \pi^-$, can be resolved by appropriate combinations of detector hits. The outer detector consists of a scintillator barrel and forward part. The barrel section with a length and diameter of about 3 m, respectively, is covered with 96 scintillator bars of 100 mm width and 15 mm thickness with double-sided photomultiplier read-out that allows a position resolution of ≈ 3 cm using mean timing and signal intensities on both sides. The forward part is made from two annular detectors consisting of three scintillator layers, one cut into wedges, one left- and one right-wound Archimedian spiral layer. The geometrical overlap of these three layers as seen from the target forms roughly triangular-shaped "pixels". Thus, a total of about 5000 individual subdetectors in the forward region is obtained, again yielding very good spatial and time-of-flight resolution of $\sigma_{ToF} \leq 250$ ps. The strength of this high-acceptance spectrometer with particle tracking and secondary-vertex recognition is the measurement of reactions involving strangeness production and reaction channels such as $pp \rightarrow pp\eta$ and $pp \rightarrow pp\omega, \omega \rightarrow \pi^+ \pi^- \pi^0$ where the number of charged particles in the exit channel allows efficient triggering and the complete exit

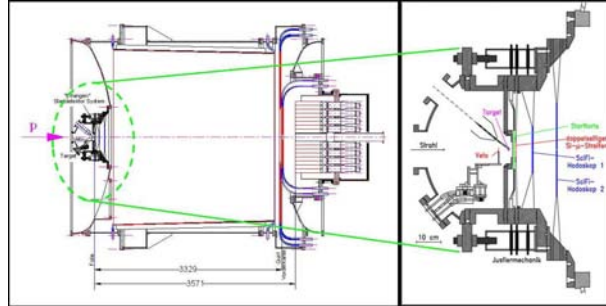


Figure 4: Schematic view of the *TOF* spectrometer at *COSY*.

channel kinematics can be reconstructed from the velocity vectors of the charged ejectiles.

4 Physics at *COSY*

Using hadronic probes, *COSY* experiments can help to shed light on open questions on the structure of hadrons and their interaction as well as the symmetries of nature and their breaking involved in the formation of hadrons from more fundamental building blocks, whose individual properties get lost in the process of making hadrons. This chapter will highlight some of the recent experiments that address specific questions in this context.

In 2003, a number of experiments claimed to have seen evidence for a manifestly exotic baryon resonance, the so-called Θ^+ with a quark structure $uudd\bar{s}$, a surprisingly low mass of $1540 \text{ MeV}/c^2$ and a width of less than 20 MeV in reactions involving very different beam-target combinations. The signal was seen in $\Theta^+ \rightarrow K^+n$ and $\Theta^+ \rightarrow K^0p$ decay; for a summary see [15]. Such a state had been predicted theoretically shortly before [16]. *COSY – TOF* was among the experiments reporting evidence. At *TOF* an indication from a signal was seen in exclusively reconstructed $pp \rightarrow pK_s\Sigma^+$ events at a beam momentum of $pc = 2.95 \text{ GeV}$ [17]. As in all other experiments, the indication was rather weak with only a few tens of events over significant "background", in this case meaning non-resonant reactions leading to the same exit channel. *COSY – TOF* has meanwhile repeated the measurement at $pc = 3.06 \text{ GeV}$ with an improved detector setup with increased detection efficiency, increase of the luminosity by a factor of five and exploitation of three independent strains of analysis which differ significantly in the weighting of employed observables and methods. The result

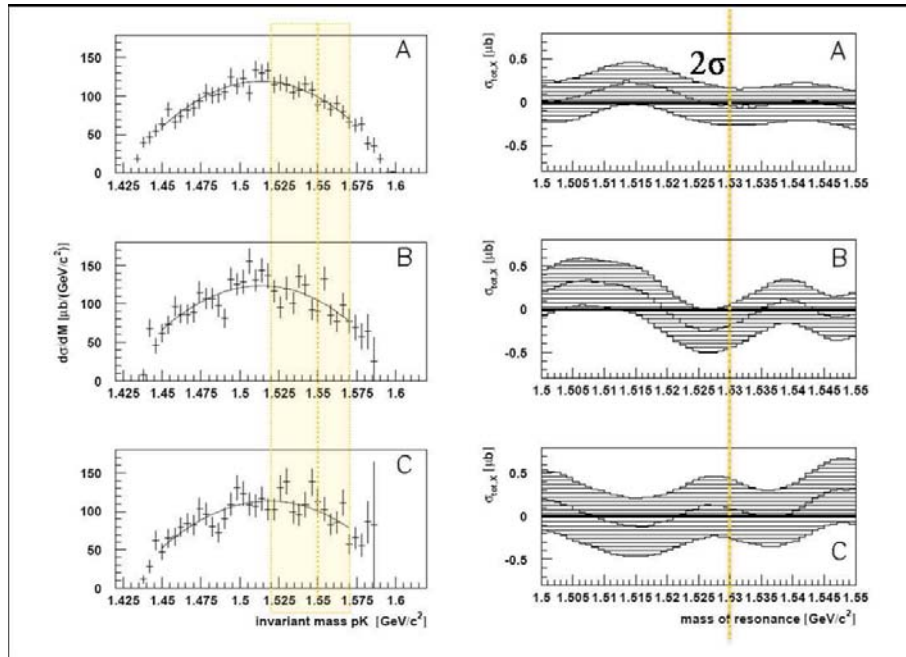


Figure 5: *COSY – TOF* result on the question of the existence of a Θ^+ resonance decaying into K^0p . The left column shows invariant mass spectra in the relevant two-body subsystem in the exit channel. The region of interest is shown by the overlaid shaded bar. The right column shows the average cross section determined for a possible structure in each invariant mass spectrum based on a smooth background parametrization over the full spectral range, and the shaded bar is the 2σ confidence interval from which an upper limit can be derived for each of the three analyses.

of this analysis as published in [18] is summarized in Figure 5. The left column of the figure shows invariant mass spectra in the Kp two-body subsystem. The region of interest for the Θ^+ is shown by the overlaid shaded bar. The right column in the figure shows the average cross section determined for a possible narrow structure in each invariant mass spectrum based on a smooth background parametrization over the full spectral range, and the shaded bar is the 2σ confidence interval from which an upper limit can be derived for each of the three analyses. In total, the upper cross section limit for a possible structure with a width compatible with the detector resolution was determined to be 150 nb (2σ). An additional upper cross section limit for Θ^+ production in $pp \rightarrow \Theta^+\pi^+\Lambda$ of $\sigma \leq 58 \text{ nb}$ was established at a beam momentum of $3.65 \text{ GeV}/c$ by *ANKE* [19].

ANKE has observed the much discussed $\Lambda(1405)$ [20] resonance via its decay into $\Sigma^0\pi^0$ [21]. Careful analysis of missing momenta and invariant masses in subsystems allowed discrimination of background from the $\Sigma(1385) \rightarrow \Lambda\pi^0$ channel which interferes with $\Lambda(1405)$ production in the charged decay channels ($\Sigma(1385)/\Lambda(1405) \rightarrow \Sigma^{+/-}\pi^{-/+}$) so that the line shape is distorted. The data show a rather symmetric Breit-Wigner-like shape compatible with old data [22] and a genuine resonance interpretation within the limited statistics available.

Apart from the search for exotics at *COSY – TOF*, a series of experiments has addressed hyperon production in various exit channels in pp collisions, also employing polarized beams. These measurements clearly indicate the contributions of decays of nucleon resonances with masses of around $1700 \text{ MeV}/c^2$ to the Dalitz plot, which due to the high acceptance of *TOF* is uniformly covered [23]. ω meson production in pp at the same energies also appears to involve resonances decaying to $p\omega$. Here, further data are needed to establish resonance excitation and discriminate contributions from different meson exchange currents [24]. *COSY – TOF* is currently undergoing a major upgrade in equipment. A straw tube tracker will replace the layered fiber hodoscopes in the start region, greatly increasing collection and reconstruction efficiency for strange decays. A new silicon detector will be used as a start and first tracking device [25].

Regular operation of *WASA* has commenced. A wealth of data on the decay of η and η' is to be expected in the near future [26]. First runs have been performed at the $pp \rightarrow pp\eta$ as well as the $pp \rightarrow pp\eta'$ reactions. A high-statistics sample on the decay $\eta \rightarrow 3\pi^0$ is already under investigation and compares favorably with data taken previously on the same channel with *WASA* at *CELSIUS* [27]. In the near future, investigations shall address the $\eta \rightarrow \pi^+\pi^-e^+e^-$ decay. The branching ratio of this decay has not been measured very precisely yet [28], but the decay allows a test of CP violation.

WASA at *COSY* will surpass the statistics of previous samples by orders of magnitude. Experiments on $dd \rightarrow \alpha\pi\pi, {}^3\text{He}n\pi^0$ as background to the very rare isospin violating $dd \rightarrow \alpha\pi^0$ process and on $pd \rightarrow {}^3\text{He}a_0/f_0$ in order to study the radiative decay of the scalar mesons will be performed in 2007.

The spin physics program at *ANKE* strives to provide detailed exclusive data on NN scattering, in particular np scattering, over the full *COSY* energy range. Data on $\vec{d}p \rightarrow (pp)_{1S_0}$ have recently been published [30], further measurements also using the polarized atomic beam target and the spectator detector are under preparation [31]. These double-polarization experiments together with detailed investigations on spin manipulation in *COSY* [32] have implications in the extended program of the facility for antiprotons and ion research *FAIR* at *GSI*, Darmstadt [33]. Here, an extension of the high-energy antiproton program at the *HESR* antiproton storage ring was proposed by the *PAX* collaboration [34] based on experience collected at *COSY* and other storage rings. *COSY* is also used for preparatory studies for the *HESR* and the *PANDA* experiment [35]. This includes conceptual studies for accelerator items such as stochastic cooling, a 2 MeV electron cooler, cavities and RF structures, magnets and diagnostics.

5 Summary and Conclusions

The ongoing physics program at *COSY* holds the potential to significantly contribute to our understanding of hadron physics in the light quark sector. With the commissioning of *WASA* at *COSY* a tool has become available that allows high-statistics studies aiming at very rare decays of η and η' , effectively turning *COSY* into a meson factory. These experiments touch upon fundamental questions such as symmetries and symmetry violation within and outside of the standard model.

Experiments on the structure and interaction of baryons and mesons will continue at *ANKE* and *COSY – TOF*. A quantitative analysis of the observed baryon states and an extension of the investigations toward polarization degrees of freedom and neutron interactions using deuteron beams or targets and spectator detection where applicable is envisaged. These experiments have a clear and direct perspective into the *FAIR* future.

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