

International Journal of Modern Physics A  
© World Scientific Publishing Company

## HADRON PHYSICS AT COSY

ALFONS KHOUKAZ

*Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Strasse 9,  
48149 Münster, Germany  
khoukaz@uni-muenster.de*

Received Day Month Year

Revised Day Month Year

One major focus of the physics studied at the COoler SYnchrotron COSY of the Forschungszentrum Jülich is the production of mesons and hyperons in the hadron-hadron scattering with the aim to investigate relevant production processes, interactions of the participating particles as well as symmetries and symmetry breaking. Due to the excellent experimental conditions at COSY also single- and double-polarization measurements can be performed with high reaction rates. This contribution gives an overview about the physics program which is currently under investigation at the three big COSY installations ANKE, COSY-TOF and WASA-at-COSY.

*Keywords:* Meson production; nucleon-nucleon interactions; hadronic decays.

PACS numbers: 13.60.Le, 13.75.Cs, 13.30.Eg

### 1. Introduction

Scattering experiments using nucleons or light nuclei are an important tool to investigate the production of hadrons as well as their interactions and their decays. With the COoler SYnchrotron COSY a powerful accelerator and storage ring is available at the Forschungszentrum Jülich, which provides proton and deuteron beams 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 a high energy resolution of the beam which is needed for precision measurements especially close to the production thresholds. Furthermore, a polarized ion source enables to perform experiments with proton beams with a polarization of up to 80% as well as with vector and tensor polarized deuterons.

The beam energy available at COSY allows for studies on a variety of mesons in the pseudoscalar, vector and scalar sector up to a mass of  $m \sim 1 \text{ GeV}/c^2$ . The production of strangeness degrees of freedom is accessible e.g. via the associated production of hyperons and kaons.

From 2007 on the major experimental facilities at COSY are the internal magnetic spectrometer ANKE, the external  $4\pi$  TOF spectrometer as well as the recently installed WASA-at-COSY detector. At these installations a rich physics program

2 *Alfons Khoukaz*

is addressed, covering e.g. studies on the structure of hadronic states and investigations on rare and very rare meson decays, which allow to test fundamental symmetries. Furthermore, measurements on the isospin dependence of the interaction of (polarized) hadron systems, e.g. nucleon-nucleon or nucleon-hyperon, are performed as well as investigations on meson-nucleus systems with respect to possible meson-nucleus bound states.

## 2. The Accelerator Facility COSY

The cooler synchrotron COSY with a circumference of 183.5 m is a storage ring for protons and deuterons. Negatively charged ions, accelerated by a cyclotron to a kinetic energy of 40 MeV, are injected into the COSY ring and can be accelerated to beam momenta ranging from 300 to 3700 MeV/c. A polarized ion source at the cyclotron allows for the usage of polarized proton and deuteron beams with a polarization of up to 80%. In case of deuterons both vector and tensor polarized beams can be provided. The maximum number of stored particles (single injection) amounts to  $1 \cdot 10^{11}$  protons and deuterons in case of unpolarized beams and  $1 \cdot 10^{10}$  protons and  $6 \cdot 10^9$  deuterons for polarized beams<sup>1</sup>. Important for the quality of the data obtained in scattering experiments is the momentum resolution of the stored beam. Therefore, COSY can make use of electron cooling for injection energies as well as of stochastic cooling, designed for beam momenta above 1.5 GeV/c. Both cooling devices allow for a transverse and longitudinal cooling and enable for a beam momentum resolution of  $\Delta p/p \leq 5 \cdot 10^{-5}$ . Additionally, by using a polarized beam in combination with a spin resonance method<sup>2</sup>, the absolute beam momentum can be determined with a precision of  $\Delta p/p \sim 3 \cdot 10^{-5}$ . The emittance of the COSY beams amounts to  $\epsilon = 1 \pi$  mm mrad.

## 3. Experimental Facilities at COSY

The stored beam can either be used directly for internal beam experiments or can be extracted and directed to external beam experiments. Currently, three big experimental facilities are operated at COSY, namely the internal experiments ANKE and WASA-at-COSY as well as the external beam experiment COSY-TOF, which in the following will be described in more detail.

### 3.1. The ANKE Facility

The internal experiment ANKE (see Fig. 1) is a magnetic spectrometer which consists of three dipole magnets, acting as a chicane for the circulating COSY beam<sup>3</sup>. The detector arrangement is ideally suited for the detection and identification of positively and negatively charged ejectiles with a high momentum resolution. The geometrical acceptance amounts to almost  $4\pi$  for charged ejectiles originating from reaction channels close to their production thresholds. Due to the special detector design of the setup for positively charged particles, an excellent identification of

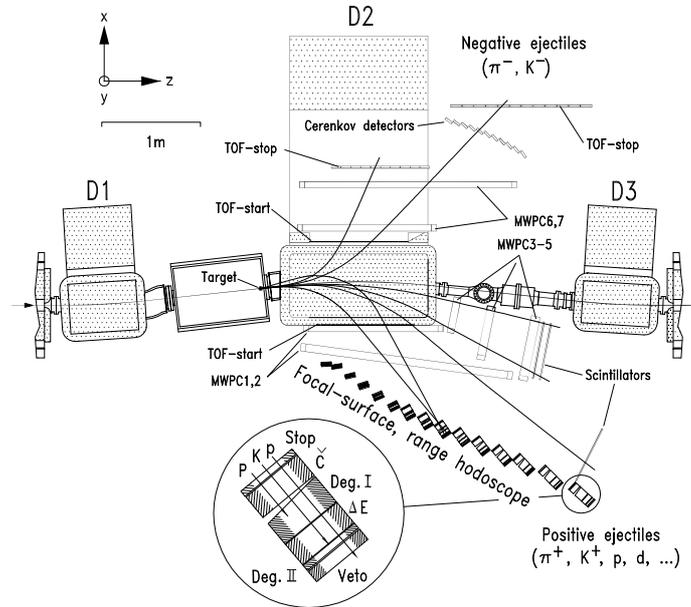


Fig. 1. A schematic illustration of the ANKE spectrometer at the internal COSY beam.

charged kaons is possible. Depending on the reaction type to be investigated, ANKE can make use of three different types of internal targets: A hydrogen/deuterium cluster-jet, a solid state C/Cu/Au foil target as well as a polarized H-/D-atomic beam source.

### 3.2. The COSY-TOF Facility

COSY-TOF is a non-magnetic “geometry” spectrometer with a flexible modular design<sup>4</sup>. The large vacuum barrel (see Fig. 2) is operated as an external beam experiment and has a high acceptance and good particle tracking for charged ejectiles. The extracted (un)polarized COSY-beam is directed onto a liquid H<sub>2</sub>/D<sub>2</sub> target with an intensity of  $I = 10^7 \dots 5 \cdot 10^7$ /s. A silicon micro-strip detector is placed close to the interaction region and allows for a delayed vertex detection, e.g. from hyperon decay products. Due to the large scale of the vacuum barrel the momenta of the registered particles can be reconstructed and particle identification can be performed using the time-of-flight method.

### 3.3. The WASA-at-COSY Facility

The WASA-at-COSY facility<sup>5</sup> (see Fig. 3) is based on the WASA experimental setup, which was formerly operated at the CELSIUS storage ring in Uppsala. After the modification and installation at COSY, the first commissioning run took place in 2007 at COSY. Similar to ANKE, WASA-at-COSY is an internal beam experiment

4 *Alfons Khoukaz*

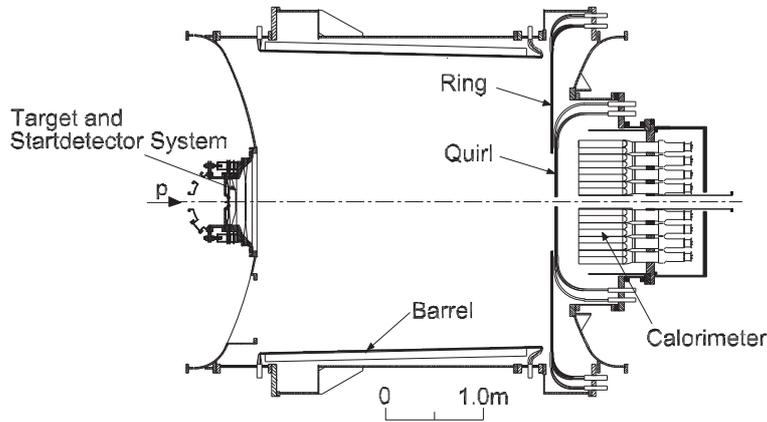


Fig. 2. A schematic illustration of the external beam experiment COSY-TOF.

which is located at a straight section of COSY. The detection system consists of two parts: The central detector and the forward detector. The forward detection system allows to detect charged ejectiles. The central detector with an almost  $4\pi$  geometry contains an highly granulated electromagnetic calorimeter, which allows for the detection of both neutral and charged ejectiles. Due to this it is possible to detect decay particles including e.g. photons from  $\eta$  or  $\eta'$  mesons. Additionally, a superconducting solenoidal field allows for the charge and momentum determination of charged ejectiles. At WASA-at-COSY a pellet target is used, providing frozen hydrogen/deuterium spheres with a diameter of  $d \sim 25 \mu\text{m}$ .

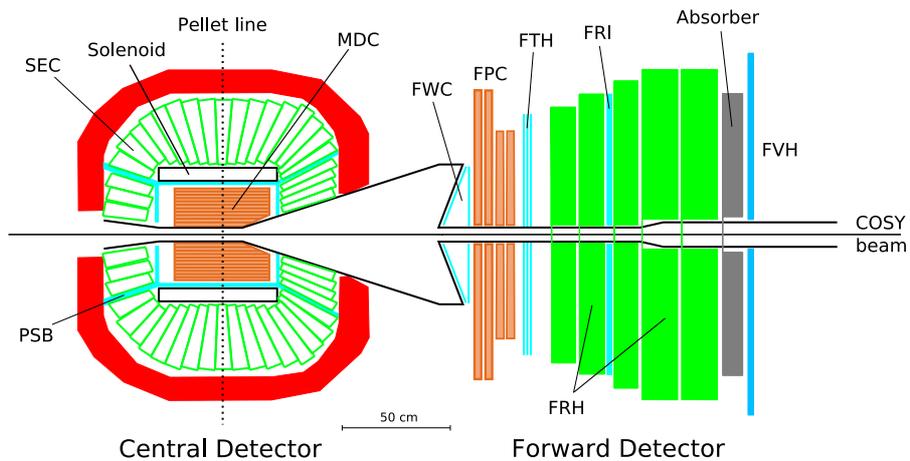


Fig. 3. A schematic illustration of the WASA-at-COSY installation at the internal COSY beam.

#### 4. Physics at COSY

At the different and complementary experimental facilities at COSY a rich variety of experiments using hadronic probes are performed since many years, resulting in a wealth of new and important information. Main focus is set on the structure and interaction of particles as well as on the relevant processes involved in the production of particles. In this section an overview about the physics program will be given by presenting selected results from different exemplary measurements.

Of fundamental interest is information about the nucleon-nucleon scattering amplitudes. However, different to the proton-proton case the situation for the neutron-proton interaction is highly unsatisfactorily. Therefore, an extensive measurement program on the reaction  $\vec{d} + \vec{p} \rightarrow (pp)_{s\text{-wave}} + n$  has been started at the ANKE facility, to gain information about the spin-dependent charge exchange amplitudes  $np \rightarrow pn$ . First measurements using a polarized deuteron beam and an unpolarized proton target already resulted in tensor analyzing powers  $A_{xx}$  and  $A_{yy}$  (see Fig. 4) which agree well with predictions from the SAID database<sup>6</sup>. In a next step

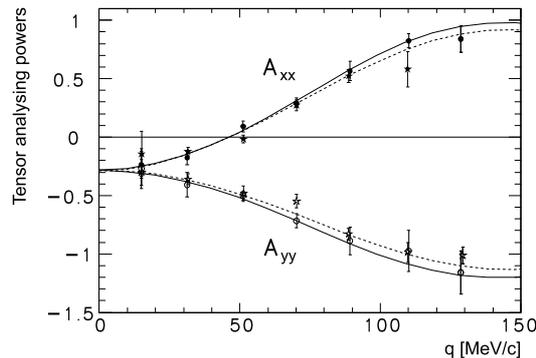


Fig. 4. Tensor analyzing powers for the reaction  $\vec{d} + p \rightarrow (pp)_{s\text{-wave}} + n$  as function of the momentum transfer  $q$ . The solid lines represent predictions from the SAID data base.

double polarization measurements have been prepared and are scheduled to be performed at ANKE in the very near future. These experiments will in addition gain information about spin-correlation coefficients.

Detailed studies on the vector meson production  $pp \rightarrow ppV$  have been performed at both ANKE and COSY-TOF, resulting in total and differential cross sections for both the  $\omega$ - and  $\Phi$ -meson production from threshold up to excess energies of  $Q \sim 200$  MeV<sup>7-9</sup>. The data gain information about the violation of the OZI-rule which was observed to be  $R_{\Phi/\omega} \sim 7 \cdot R_{OZI}$  at  $Q=93$  MeV. At ANKE the produced  $\Phi$ -mesons are identified by the detection of the decay particles, i.e. the charged kaon pair  $K^+K^-$ . This allows to investigate in addition the non-resonant kaon pair production  $pp \rightarrow ppK^+K^-$  in detail. Both at ANKE and at the former experiment COSY-11, which was situated at an arc section of COSY, the kaon-proton invariant

mass distributions  $K^\pm p$  have been compared, resulting in a clear enhancement of the  $pK^-$  system (see Fig. 5) for low relative momenta<sup>10,11</sup>. The results can be explained well by a strong  $pK^-$  final state interaction and a comparatively weak interaction of the final  $pK^+$  pair.

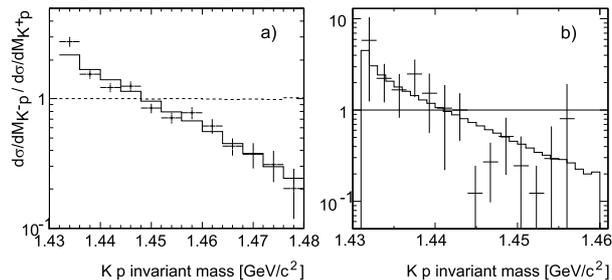


Fig. 5. Ratio of the kaon-proton invariant mass  $R_{pK^-/pK^+}$  as function of the proton-kaon invariant mass, obtained at (a) ANKE and (b) COSY-11.

Studies on the hyperon production in nucleon-nucleon interactions gain valuable information about relevant production mechanism and hyperon-nucleon final state interactions. During the last years a very rich data base on total cross sections of the  $\Lambda$  and  $\Sigma^0$  hyperon production in proton-proton collisions has been collected<sup>12–18</sup>. To disentangle contributions from possible final state interactions and reaction mechanism via the excitation of nucleonic resonances, high statistics differential cross sections have been determined recently for the hyperon production channel  $pp \rightarrow pK^+\Lambda$  at different excess energies using the COSY-TOF installation. Depending on the beam momentum contributions of the nucleonic resonances  $N^*(1650)$ ,  $N^*(1710)$  and  $N^*(1720)$  with different relative strengths have been extracted from the Dalitz plot, which is covered uniformly at COSY-TOF due to the high acceptance of the detection system<sup>18</sup>. For the near future partial wave analyses are foreseen by studies using a polarized COSY beam at COSY-TOF.

A very challenging task is to identify signals from the  $\Lambda(1405)$  hyperon production in proton-proton collisions and to separate them from the nearby lying  $\Sigma^0(1385)$  hyperon resonance. This  $\Lambda$ -resonance is of high interest since its structure is still discussed controversially. Recently, it was succeeded at the ANKE facility to reveal a method to extract a clean signal from the  $\Lambda(1405)$  hyperon through its  $\Sigma^0\pi^0$  decay<sup>19</sup>. Further measurements at COSY with high statistics are planned e.g. for detailed investigations on the lineshape of this hyperon, which will gain further information on the nature of this particle.

An interesting field in meson physics is the search for possible bound states consisting of mesons and nuclei. The anomalous energy dependence found for the  $dp \rightarrow {}^3\text{He}\eta$  reaction suggests that the strong  $\eta^3\text{He}$  final state interaction might lead to the formation of a new state of matter in the form of an  $\eta^3\text{He}$  quasi-bound state<sup>20</sup>.

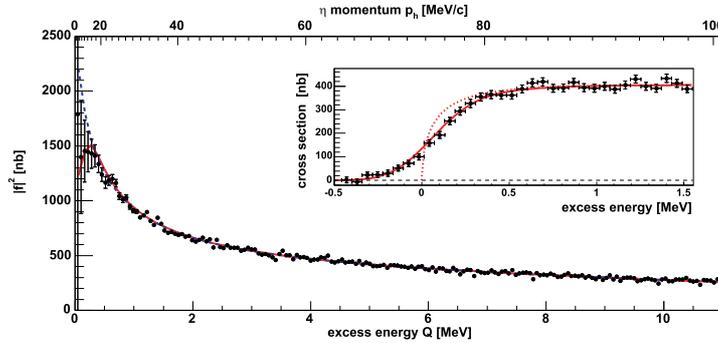


Fig. 6. Scattering amplitude squared  $|f|^2$  and total cross section (inlay) as function of the excess energy  $Q$  for the  $dp \rightarrow {}^3\text{He}\eta$  reaction close to threshold. The solid line represents a fit to the data considering the  $\eta^3\text{He}$  final state interaction as well as the finite width of the COSY beam. The dashed line represents the expectation for a measurement without beam smearing effects.

At ANKE data have been obtained for this reaction channel with unprecedented precision<sup>21</sup> (see Fig. 6). The very rapid rise of the obtained total cross sections and the levelling-off indicates the existence of a pole in the production amplitude within one MeV of  $Q=0$ . Fits to the data suggest that the scattering length has an enormous real part<sup>21</sup>. Further measurements using polarized beams/targets are on the way to investigate the spin dependence of the scattering amplitudes. In addition, this reaction channel is used for a high-precision measurement on the  $\eta$ -meson mass at ANKE<sup>22</sup>.

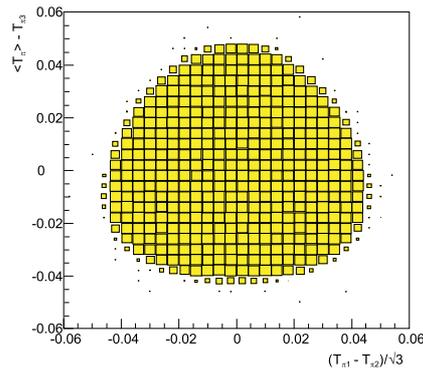


Fig. 7. Dalitz plot of the  $\eta \rightarrow \pi^0\pi^0\pi^0$  decay obtained at the WASA-at-COSY facility.

In 2007 the newly installed WASA-at-COSY facility was set into operation at COSY. One main subject of the planned measurements will be the investigation of rare decays of  $\eta$ - and  $\eta'$ -mesons to study symmetries and symmetry breaking in QCD. By measuring e.g. the forbidden  $\eta$ -decays into  $4\pi^0$ ,  $\pi^+\pi^-e^+e^-$ ,  $\pi^0e^+e^-$  and

8 *Alfons Khoukaz*

$3\pi^0\gamma$ , information about C- and CP-violation will be gained. With a luminosity above  $L = 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  and a close to  $4\pi$  geometrical acceptance, the future results are expected to exceed the currently available data by orders of magnitude<sup>5</sup>. Already during a first commissioning run high statistic data have been gained on the  $\eta \rightarrow \pi^0\pi^0\pi^0$  decay, studied in the  $pp \rightarrow pp\eta$  reaction. The extracted data with more than  $10^5$   $\eta \rightarrow 3\pi^0$  events (see Fig. 7) result in a preliminary slope parameter  $\alpha$  of the Dalitz plot which compares well with results from other installations.

## 5. Summary

The COoler SYnchrotron COSY in combination with the complementary experimental facilities allows to investigate a rich variety of aspects in hadron physics. The precision of the stored beam and the availability of both polarized beams and targets offers the possibility to investigate production processes and hadron interactions with highest quality at the installations ANKE, WASA-at-COSY and COSY-TOF. With the now routinely running WASA-at-COSY installation the physics case at COSY got enriched by the possibility to study symmetries and symmetry breaking within and outside the Standard Model.

For more details on the COSY physics program see for example Ref. 23.

## References

1. D. Prasuhn, private communication (2008).
2. R. Gebel, R. Maier, D. Prasuhn, H. Stockhorst, private communication (2007).
3. S. Barsov et al. (ANKE Collaboration), *Nucl. Instr. Meth.* **A462**, 364 (2001).
4. A. Böhm et al. (TOF Collaboration), *Nucl. Instr. Meth.* **A443**, 238 (2000).
5. WASA-at-COSY Collaboration, B. Hoistad, J. Ritman et al., Proposal for WASA at COSY (2004); arXiv: nucl-ex/0411038v1.
6. D. Chiladze et al., *Phys. Lett.* **B637**, 170 (2006).
7. M. Hartmann et al., *Phys. Rev. Lett.* **96**, 242301 (2006).
8. M. Abdel-Bary et al., *Phys. Lett.* **B647**, 351 (2007).
9. S. Barsov et al., *Eur. Phys. J.* **A31**, 95 (2007).
10. P. Winter et al., *Phys. Lett.* **B635**, 23 (2006).
11. Y. Maeda et al., *Phys. Rev.* **C77**, 015204 (2008).
12. J. Balewski et al., *Phys. Lett.* **B388**, 859 (1996).
13. J. Balewski et al., *Phys. Lett.* **B420**, 211 (1998).
14. J. Balewski et al., *Eur. Phys. J.* **A2**, 99 (1998).
15. R. Bilger et al., *Phys. Lett.* **B420**, 217 (1998).
16. S. Sewerin et al., *Phys. Rev. Lett.* **83**, 682 (1999).
17. P. Kowina et al., *Eur. Phys. J.* **A22**, 293 (2004).
18. S. Abdel-Samad et al., *Phys. Lett.* **B632**, 27 (2006).
19. I. Zychor et al., *Phys. Lett.* **B660**, 167 (2008).
20. C. Wilkin, *Phys. Rev.* **C47**, R938 (1993).
21. T. Mersmann et al., *Phys. Rev. Lett.* **98**, 242301 (2007).
22. A. Khoukaz, *Precision measurement of the  $\eta$  mass at COSY*, COSY Proposal+Beam Request #187 (2007).
23. Annual report of the Institute of Nuclear Physics (IKP), Forschungszentrum Jülich: [www.fz-juelich.de/ikp/publications/AR2007/en/contents.shtml](http://www.fz-juelich.de/ikp/publications/AR2007/en/contents.shtml).