COSY: Achievements and Ramp-up Towards FAIR

Frank Goldenbaum, IKP, FZ-Jülich, Germany
FZJ: from COSY to HESR at FAIR

PoF 2: Hadron physics at COSY (ANKE, TOF, WASA and PAX)
PoF 3: COSY required as essential test facility – and EDM machine
Introduction: Physics Case and Tools

COSY: Non-perturbative QCD in the (u,d,s) sector

Structure of hadrons
- nucleon, hyperons, mesons

Dynamics & interactions
- nucleon-nucleon, meson-nucleon, hyperon-nucleon
- meson-nucleus, medium effects

Symmetries and symmetry breaking
- chiral symmetry
- isospin & charge symmetry in reactions
- discrete symmetries in meson decays

COSY (COoler SYnchrotron):
- external and internal experiments, polarized beams & polarized targets
COSY Facility

**COSY:**
- Circumference: 183 m
- Beam momentum: 0.3 - 3.7 GeV/c
- Electron and stochastic cooling
- (Un-)polarized proton and deuteron beams

**Detectors:**
- **ANKE:** magnetic spectrometer, polarized targets
- **PAX:** polarized targets
- **TOF:** time-of-flight spectrometer
- **WASA:** electromagnetic calorimeter, pellet target
ANKE Result: Nucleon-Nucleon (NN) Scattering

Single polarized $pp$ elastic scattering: analyzing power $A_y$

- **ANKE**: dedicated facility for forward region ($5^\circ$ – $30^\circ$); precision data
- Significant change in quantitative description of short-distance NN interaction
- Ongoing: double polarized measurements (np system)

SAID (partial wave analysis) description of NN world data without new ANKE results
TOF Result: Hyperon Production

Production mechanism (nucleon resonances, hyperon polarization)
Hyperon-nucleon interaction and \((p\Lambda - N\Sigma)\) channel coupling

- **TOF**: provides full phase space coverage
- Impact on nuclear strangeness production and hypernuclei
- Ongoing: spin-resolved hyperon-nucleon scattering lengths

\[
pp \rightarrow pK^+\Lambda \\
p_{\text{beam}} = 2.95 \text{ GeV/c}
\]
**WASA Result: Exotic NN Resonance? Dibaryon**

**ABC effect** in double-pion fusion reactions

Isospin dependence ($I = 0,1$)

**New:** impact on elastic np-scattering

- **WASA:** structure (at 2.37GeV, 70MeV width) in isoscalar ($I=0$) channel
- Origin of structure: 6 quark bound state? Quantum numbers: $I(J^P)=0(3^+)$
- Ongoing: Partial wave analysis (SAID), quantum numbers

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CERN Courier, 54, 6, (2014)
PAX Result: Spin Filtering; Goal: Pol. Antiprotons

Polarization build-up by spin filtering in storage rings
Tests with **protons at COSY**
New: low-\(\beta\) section, intense polarized target, precision polarimetry

**Transverse build-up**

**Energy dependence**

- **PAX**: spin filtering works and is well understood in NN scattering
- Preparations for spin-filtering with **antiprotons** at CERN/AD (or FAIR)
- Ongoing: longitudinal build-up with protons at COSY (Siberian snake needed)
COSY Facility: Developments Related to HESR

Barrier Bucket Cavity
mean energy loss compensation

Stochastic Cooling
(prototyp pick-up tank 1.5-15 GeV/c)

Pellet Target
beam-target interaction

Residual Gas Profile Monitor

e-Cooler
100 kV

e-Cooler (2 MV; 2013)

Test bench for accelerator components and operation
**Example: 2 MV Electron Cooler for HESR**

Joint development with Budker Institute (BINP, Russia), **injection cooler** for HESR, milestone towards 8 MV cooler

Parameters demonstrated so far:
- Voltage up to 1.5 MV (5 bar SF6)
- Cooling at 900 kV / 300 mA (1.8 GeV p)

- Electron cooling achieved for 1.8 GeV protons
- Ongoing: commissioning for full COSY energy range (3 GeV)
COSY Facility: Developments for PANDA

Pre-assembly of major PANDA components in Jülich
COSY Facility: User Activities for FAIR

PANDA:

- Straw-tube tracker  
  Cracow, Frascati, Pavia, Ferrara, Bucharest, Jülich
- Micro-vertex detector  
  Giessen, Turin, Jülich
- Calibration detector for luminosity monitor  
  Jülich, Lanzhou
- Disk DIRC  
  Erlangen, Tübingen, Giessen, Jülich
- Radiation hardness of high purity Ge-detector  
  Mainz (HIM)

CBM/Hades:

- Tracking detectors, diamond detectors  
  München, Frankfurt, Darmstadt, Kolkata, Wuppertal

NuSTAR:

- Cherenkov, Time Projection Chamber  
  Giessen, Kyoto

Phase-out of hadron physics program at COSY
Use of COSY as accelerator and detector test facility
Summary and Outlook

Successful physics program at COSY during PoF 2
spin physics and fundamental symmetries
close cooperation with in-house theory group

COSY vital test facility for FAIR
accelerator and detector components and operation

COSY ideal starting place for EDM searches
(not subject of this presentation)
Spare slides…
COSY Accelerator

- Energy range
  - 0.045 – 2.8 GeV (p)
  - 0.023 – 2.3 GeV (d)
  - (momentum 3.7 GeV/c)

- Cooling (transverse & longitudinal)
  - 2 methods:
    - electron, stochastic
    - $\Delta p/p \leq 5 \times 10^{-5}$

- Polarization
  - p, d beams & targets

- Beams
  - internal, extracted

- Experiments, detectors
  - ANKE, TOF, WASA, PAX

- ~ 340 users, 15 countries
COSY Beam Parameter

**beam quality:**

- without cooling: \( \Delta p/p \sim 2 \cdot 10^{-4} \)
- electron cooling: \( \Delta p/p \leq 5 \cdot 10^{-5} \) \( p_p < 0.5 \text{ GeV/c} \)
- stochastic cooling: \( \Delta p/p \leq 5 \cdot 10^{-5} \) \( p_p > 1.5 \text{ GeV/c} \)

\[ \varepsilon = \pi \text{ mm mrad} \ 1 \text{mmØ} \cdot 0.18^\circ \]

**beam intensities (cooled):**

- protons, unpolarized: \( 1 \cdot 10^{11} \)
- protons, polarized: \( 1 \cdot 10^{10} \)
- deuterons, unpolarized: \( 1 \cdot 10^{11} \)
- deuterons, polarized: \( 6 \cdot 10^{9} \) (by stacking)

**extracted beam:**

- \( 10^5 ... 10^9 \) protons/s in spill
- slow extraction: \( 10 \text{ s} ... > 10 \text{ min spill, quasi-DC beam} \)
- \( 10(5) \text{ s inter-spill (un)cooled} \)
- fast extraction: \( 2 \cdot 10^9 \) protons in 200 ns, every 15 s
### Main machine parameter

- **Momentum range**: 1.5 to 15 GeV/c
- **Circumference**: 575 m
- **Magnetic bending power**: 50 Tm
- **Dipole ramp**: 25 mT/s
- **Acceleration rate**: 0.2 (GeV/c)/s
- **Geometrical acceptances for $\beta_t = 2$ m**
  - horizontal: 4.9 mm mrad
  - vertical: 5.7 mm mrad
- **Momentum acceptance**: $\pm 2.5 \times 10^{-3}$
Pre-Assembly of PANDA components in Jülich

- high rate in-beam tests of individual detector components in the COSY-TOF area
- Mechanical integration of “full” PANDA in the COSY test-hall
- Infrastructure available:
  - M&E Workshop capacity
  - staging space for detectors
  - (limited) clean room space
  - office space available
- Transport to and setup in Darmstadt 2017
ANKE Spectrometer: Apparatus

Main features:
- Excellent Kaon identification (Positive and Negative)
- Di-proton ($\{pp\}_s$) selection by Forward Detector (FD)
- Low energy proton (spectator) detection (STT)
- Polarized (unpolarized) dense targets (PIT)
- Openable storage cell (SC)
ANKE: Scientific Program

Since 2005 ANKE has been equipped with a Polarized Internal Target (PIT) and embarked to measure the spin dependence of many polarized reactions

Nucleon-nucleon interaction
pp- and np-amplitudes, nuclear forces, di-proton system in $^1S_0$-state \( \{pp\}_s \)

Meson production
NN\(\pi\) amplitudes (PWA), extension of ChPT to the NN→NN\(\pi\) process via measuring all observables in \(pp \rightarrow \{pp\}_s \pi^0\) and \(np \rightarrow \{pp\}_s \pi^-\)

Meson-nucleus interaction
\(\eta\)-\(^3\)He interaction (FSI), \(\eta\)-mesic \(^3\)He, precision \(\eta\)-mass determination

Strangeness degree of freedom
YN interaction, \(\Lambda\)N scattering lengths, separation of spin-singlet (\(a_s\)) and spin triplet (\(a_t\)) \(\Lambda\)p production amplitudes, SU(3) symmetry

Summary of recent results: Nuclear Physics News (NuPECC, issue 3, 2013)
ANKE: Examples of Analyses

pp elastic: recoil slow proton detection (STT)

Mean = 938 MeV
σ = 8 MeV

Reaction identification (FD)

Target polarization (PIT)

dp→dp_{sp}π^0

Spin “down”

Unpolarized

Spin “up”

Q_y ≈ 80%
ANKE: Scientific Output

50 scientific papers (since spin program started in 2005)

Topics:

• NN-interaction (HEPI Tbilisi, IKP)
• Deuteron breakup at large momentum transfer (JINR Dubna, IKP)
• Complete measurement for NN → NNπ (JINR, Erlangen, IKP)
• High energy bremsstrahlung (JINR, IKP)
• Two-pion production (JINR, Münster, IKP)
• The η-meson production (Münster, IKP)
• Vector meson (φ, ω) production (RCNP, PNPI Gatchina, IKP)
• Medium modifications (ITEP Moscow, IKP)
• Kaon-pair production (PNPI, IKP)
• Hyperon production (PNPI, IKP)

Very strong collaboration groups!
NN Scattering: Motivation (pp)

Data distribution plots (SAID)

\[A_y (pp)\]

\[d\sigma/d\Omega (pp)\]
**NN Scattering: Motivation (pn)**

Data distribution plots (SAID)

- $A_y (np)$
- $\frac{d\sigma}{d\Omega} (np)$
- NP charge-exchange
- NP forward
**Fit of the Dalitz plot for 2.95 GeV/c (Isobar Model*)**

- Fit of the Model to extract resonance strength
- Study at different beam momenta


**Fit properties**

\( p\Lambda - N\Sigma \) cusp as a resonance with a 30 MeV width

\[ N^*(1650) / N^*(1720) \approx 2/1 \]
Hyperon Production at 2.7 GeV/c

Production mechanism (nucleon resonances, hyperon polarization)
Hyperon-nucleon interaction and \((p\Lambda - N\Sigma)\) channel coupling

No significant observation of \(p\Lambda - N\Sigma\) coupled channel effect
pΛ Effective Scattering Length


Result from Fit and Likelihood analysis

\[ a = (-1.343 \pm 0.016) \text{ fm} \]

- Ongoing: Spin-resolved hyperon-nucleon scattering length
Λ Polarization

- Λ Polarization changes strongly between the two beam momenta
- Ongoing: Theoretical description for understanding
PAX: Experimental setup for Spin-filtering

Spin flipper
(better systematics)

Polarization analysis at ANKE

Spin filtering with PAX target

pd elastic scattering

Spin filtering with PAX target
PAX: Theoretical predictions for $\bar{p}$ polarization


Spin-dependent part of $p\bar{p}$ interaction cross section and Nijmegen potential

V.F. Dmitriev$^{a,b}$, A.I. Milstein$^{a,b}$, S.G. Salnikov$^{a,b}$

transverse ($\approx \sigma_1$)  
longitudinal: ($\approx (\sigma_1 + \sigma_2)$)

Lab acceptance angles  
(10, 20, 30 mrad)

$P_\perp$  
$P_\parallel$  

$T_{\text{lab}}$ (MeV)

$-0.20$  
$-0.40$
Spin filtering using a longitudinally polarized target

\[ \sigma_{tot} = \sigma_0 + \sigma_1 \vec{P} \cdot \vec{Q} + \sigma_2 (\vec{P} \cdot \vec{k}) (\vec{Q} \cdot \vec{k}) \]

- Should allow for flexible use at two locations (ANKE and PAX)
- Fast ramping (< 30 s)
- Cryogen-free system

<table>
<thead>
<tr>
<th>Reaction</th>
<th>B-dl (Tm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(pn \rightarrow {pp}_s\pi^-) at 353 MeV</td>
<td>3.329</td>
</tr>
<tr>
<td>PAX at COSY (140 MeV)</td>
<td>1.994</td>
</tr>
<tr>
<td>PAX at AD (500 MeV)</td>
<td>4.090</td>
</tr>
<tr>
<td>(T_{\text{max}}) at COSY (2.88 GeV)</td>
<td>13.887</td>
</tr>
</tbody>
</table>
PAX: Publications

F. Rathmann et al.
A Method to polarize stored antiprotons to a high degree

V. Barone et al. (PAX collaboration), Proposal to FAIR QCD-PAC
Antiproton-proton scattering experiments with polarization

D. Oellers et al.
Polarizing a stored proton beam by spin flip?

C. Barschel et al. (PAX collaboration), CERN-SPSC-2009-012 (2009)
Measurement of the Spin-Dependence of the p anti-p Interaction at the AD-Ring

P. Lenisa and F. Rathmann
CERN Cour., 50N6, 21 (2010)
PAX promotes beams of polarized antiprotons

W. Augustiniak et al.
Polarization of a stored beam by spin-filtering

P. Lenisa and F. Rathmann
Perspectives for polarized antiprotons
WASA: Setup

- Solenoid
- Pellet line
- Tracking Detectors
- TOF Detector
- EM Calorimeter
- Thin Plastic Scintillators
- Range Hodoscope

COSY beam
WASA: Physics Program

Symmetries and symmetry breaking in $\eta$ decays
  chiral symmetry, C and CP tests

Structure of mesons
  transition form factors in $\pi$, $\eta$ and $\omega$ Dalitz decays

Physics beyond the Standard Model
  dark photon search in $\pi^0 \rightarrow e^+ e^- \gamma$

Nucleon-nucleon interaction, meson-nucleon interaction
  ABC effect in $pN \rightarrow d\pi\pi$, $pd \rightarrow ^3He \pi\pi$, $dd \rightarrow ^4He \pi\pi$

Quark mass effects
  Charge symmetry breaking in $dd \rightarrow ^4He \pi^0$

Meson-nucleus interactions
  $\eta$-mesic $^3He$ and $^4He$
WASA: ABC Resonance

\[ \sigma \, [\text{mb}] \]

- Proton-neutron → Dπ^0π^0
- Resonance model
- \( I(J^p) = 0(3^+) \)

- Roper resonance
- t-channel ΔΔ

\[ d\sigma/dM_{\pi\pi} \] [μb/bin] on \( M_{\pi\pi} \) [GeV]

- “ABC effect” \( M_{\pi\pi} \) on \( M_{\pi\pi} \) [GeV]

- \( \Delta \)
- \( \pi^0 \)
- Δ

Frank Goldenbaum

COSY: Achievements and Ramp-up Towards FAIR
WASA: References

Measurement of the pn → ppπ0π− reaction in search for the recently observed resonance structure in dπ0π0 and dπ+π− systems  
*Phys. Rev. C 88 (2013) 055208*

Search for a dark photon in the π0 → e+e−γ decay  

Investigation of the dd → 3He n π0 reaction with the FZ Jülich WASA-at-COSY facility  
*Phys. Rev. C 88 (2013) 014004*

Isospin Decomposition of the Basic Double-Pionic Fusion in the region of the ABC Effect  

Search for eta-mesic 4He with the WASA-at-COSY detector  
*Phys.Rev. C87 (2013) 035204*

Abashian-Booth-Crowe resonance structure in the double pionic fusion to 4He  
*Phys.Rev. C86 (2012) 032201*

Exclusive Measurement of the η → π+π− gamma Decay  

Experimental Investigation of π0π0 Production in Proton-Proton Collisions at Tp = 1400 MeV  

ABC Effect in Basic Double-Pionic Fusion --- Observation of a new resonance?  
*Phys.Rev.Lett. 106 (2011) 242302*

Measurement of the η → 3π0 Dalitz Plot Distribution with the WASA Detector at COSY  
Calibration detector for Luminosity monitor
Goal is to determine parameter $\sigma_{\text{tot}}, \rho$ and $b$ for PANDA luminosity monitor

- Forward tracking detector to measure scattered beam particles
- Recoil detector to measure energy and angle of recoil protons
- Large $t$ range, 0.0008-0.1 GeV$^2$, measurement
- Coincidence for background suppression

Antiproton-proton elastic scattering measurement
Large t-range measurement at HESR?

- Forward scattering measurement (e.g. polar angle 4.6-8 mrad ~ t range of 0.0008-0.0025 GeV²@6.2GeV/c)
- Recoils measurement (e.g. recoil angle 1.0° -11.5° ~ t range of 0.0008-0.1 GeV²@6.2GeV/c)

Dedicated day-one experiment at HESR
Standing

COSY is the storage ring facility for polarized beams and hadron physics worldwide.

IKP scientists have widely acknowledged experience in:
- storage rings
- polarized beams
- polarized targets
- spin physics

Balance

Operation of COSY and construction of HESR was mastered during PoF 2.

Building of HESR and work for the EDM project can well be handled during PoF 3.

Potential

The physics case for charged particle EDM searches is outstanding ("must-do" experiment).

COSY is the ideal starting point for the storage ring EDM project; FZJ provides an excellent environment; staging is the approach of choice.

Matter and the Universe, Topic 2, FZJ