QCD Physics at FAIR -

FAIR - Facility for Antiproton and Ion Research

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Workshop on QCD in Nuclear and Hadronic Physics, CCLRC Daresbury Laboratory
FAIR: Facility for Antiproton and Ion Research
FAIR Will Probe the Intensity Frontier With Secondary Beams

**Primary Beams**

- $10^{12}$/s; 1.5 GeV/u; $^{238}$U$^{28+}$
  - Factor 100-1000 over present in intensity
  - x10 faster ramping (0.3 Hz $\rightarrow$ 3 Hz)
  - x10 space charge ($^{238}$U$^{73+} \rightarrow ^{238}$U$^{28+}$)

- $10^{10}$/s $^{238}$U$^{73+}$ up to 35 GeV/u

- $3 \times 10^{13}$/s 30 GeV protons
  - 75 MeV Linac
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**Primary Beams**
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- $3 \times 10^{13}/s$ 30 GeV protons

**Secondary Beams**
- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- Antiprotons 3 (0) - 30 GeV

**Storage and Cooler Rings**
- Radioactive beams
- $10^{11}$ stored and cooled 1 - 15 GeV/c antiprotons

Technical Challenges include: Storage rings and high energy electron cooling
Strong QCD

QCD Lagrangian

\[ L_{\text{QCD}} = -\frac{1}{4} F^{(a)}_{\mu\nu} F^{(a)\mu\nu} + i \sum_q \bar{\psi}_q \gamma^\mu (D_\mu)_i^j \psi_q^j - \sum m_q \bar{\psi}_q^i \psi_q^i , \]

Running coupling const.
- Perturbative at high \( Q^2 \)
  high precision tests
- New phenomena at low \( Q^2 \)
  - Broken symmetries
  - Confinement

How do hadrons become the effective degrees of freedom as \( Q^2 \) decreases?
QCD Physics at FAIR

• Compressed Baryonic Matter (CBM)

• „High Energy“ Antiprotons (PANDA)

• Polarized Antiprotons (PAX)

• Stopped Antiprotons (FLAIR)
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States of strongly interacting matter

- Baryons
- Hadrons
- Partons

Compression + heating = quark-gluon plasma (pion production)

Neutron stars
Early universe

- Quark-hybrid star
- Hyperon star
- Absolutely stable strange quark matter
- Strange star
- Nucleon star

Neutron star with pion condensate

Fe
$10^6$ g/cm$^3$
$10^{11}$ g/cm$^3$
$10^{14}$ g/cm$^3$

R $\sim$ 10 km
M $\sim$ 1.4 $M_\odot$
Mapping the QCD phase diagram with heavy-ion collisions

Critical endpoint:
Z. Fodor, S. Katz, hep-lat/0402006
S. Ejiri et al., hep-lat/0312006
"Trajectories" (3 fluid hydro)

Pb+Pb, central collision

Hadron gas EOS
V. Toneev, Y. Ivanov et al.
nucl-th/0309008
U+U 23 GeV/A

t=-17.14 fm/c

UrQMD Frankfurt/M
Diagnostic probes

U+U 23 AGeV

charm

φ, Ξ, Ω

ρ → e⁺ e⁻

K, π, Λ, η

decay γ

resonance decays

prompt γ

thermal γ
CBM physics topics and observables

- In-medium modifications of hadrons
  - onset of chiral symmetry restoration at high $\rho_B$
    - measure: $\rho, \omega, \phi \rightarrow e^+e^-$
      - open charm (D mesons)

- Strangeness in matter (strange matter?)
  - enhanced strangeness production?
    - measure: $K, \Lambda, \Sigma, \Xi, \Omega$

- Indications for deconfinement at high $\rho_B$
  - anomalous charmonium suppression?
    - measure: $J/\psi, D$

- Critical point
  - event-by-event fluctuations

- Color superconductivity
  - precursor effects?
The critical point

Event-by-event analysis by NA49: 5% most central Pb+Pb collisions at 158 AGeV

Above $T_c$: no phase boundary

At the critical point:
Large density fluctuations,
critical opalescence
Fluctuations on the Lattice

Lattice QCD:
maximal baryon number density fluctuations at $T_C$ for $\mu_q = T_C$ ($\mu_B \approx 500 \text{ MeV}$)
Experimental challenges

Central Au+Au collision at 25 AGeV: URQMD + GEANT4

160 p
400 $\pi^-$
400 $\pi^+$
44 K$^+$
13 K$^-$

- $10^7$ Au+Au reactions/sec (beam intensities up to $10^9$ ions/sec, 1 % interaction target)
- determination of (displaced) vertices with high resolution ($\approx 30 \mu$m)
- identification of electrons and hadrons
The CBM Experiment

- Radiation hard Silicon (pixel/strip) Tracking System in a magnetic dipole field
- Electron detectors: RICH & TRD & ECAL: pion suppression better $10^4$
- Hadron identification: TOF-RPC
- Measurement of photons, $\pi$, $\eta$, and muons: electromagn. calorimeter (ECAL)
- High speed data acquisition and trigger system
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Charmonium:  
Quark confining potential

Search for Exotic Hadrons  
Glueballs  
Hybrids

Charm Production in pbar A  
Charmonium
Charmonium – the Positronium of QCD

- Positronium
- Charmonium

![Diagram showing levels and masses of charmonium states](image-url)
Why Antiprotons?

- e+e- annihilation via virtual photon: only states with $J^{pc} = 1-$

- In pp̅ annihilation all mesons can be formed

- Resolution of the mass and width is only limited by the beam momentum resolution
Why Antiprotons?

- $e^+e^-$ annihilation via virtual photon: only states with $J_{\text{pc}} = 1$.

- In $pp$ annihilation all mesons can be formed.

- Resolution of the mass and width is only limited by the beam momentum resolution.

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<th>CM Energy</th>
<th>Beam Resonance</th>
<th>Cross Section</th>
<th>Ion Intensity</th>
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<td>0.97</td>
<td>$\bar{p}p \rightarrow \chi_{1,2}$</td>
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<tr>
<td>1.03</td>
<td>$\gamma \rightarrow \gamma J/\psi$</td>
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by the beam momentum resolution.
High Resolution

- Crystal Ball: typical resolution $\sim 10$ MeV
- Fermilab: 240 keV

$\Rightarrow \Delta p/p < 10^{-4}$ needed
Open Questions

\( \eta_c \left( 1^1S_0 \right) \)

experimental error on \( M > 1 \) MeV
\( \Gamma \) hard to understand in simple quark models

\( \eta'_c \left( 2^1S_0 \right) \)

Crystal Ball result way off
study of hadronic decays

\( h_c \left( 1^P_1 \right) \)

Spin dependence of \( \bar{Q}Q \) potential
Compare to triplet \( P \)-States
LQCD \( \leftrightarrow \) NRQCD

\[
M_{cog} = \frac{M(\chi_0) + 3M(\chi_1) + 5M(\chi_2)}{9}
\]
Open Questions

States above the DD threshold

Higher vector states not confirmed $\Psi(3S), \Psi(4S)$
Expected location of 1st radial excitation of P wave states
Expected location of narrow D wave states
Only $\Psi(3770)$ seen
Sensitive to long range Spin-dependent potential
Glueballs

Self interaction between gluons

⇒ Construction of color-neutral hadrons with gluons possible

exotic glueballs don’t mix with mesons (qq)

0⁻, 0⁺⁻, 1⁺, 2⁺⁻, 3⁺,...
Prediction in QCD:

Collective gluon excitation

(Gluons contribute to quantum numbers)

Ground state:
$J^{PC} = 1^{-+}$ (spin exotic)
Partial Wave Analysis

Partial wave analysis as important tool

Example of $1^{-+}$ (CB@LEAR)
\[
\bar{p}d \rightarrow X(1^{-+})+\pi+p, \ X \rightarrow \eta \pi
\]

Strength $\sim q\bar{q}$ States!

Signal in production but not in formation is interesting!
Hadron Properties at Finite Density

Mass splittings because charge conjugation symmetry broken at \( n_B \neq 0 \)

Overall attraction of Kaons due to scalar interaction: KN sigma term

Mass splitting due to vector interaction: Weinberg-Tomozawa

\[ K^-(s\bar{u}) : \frac{m_s}{m_u} \approx 40 \]
\[ D^+(c\bar{d}) : \frac{m_c}{m_d} \approx 200 \implies \text{Quark atom} \]
J/Ψ Absorption in Nuclei

J/Ψ absorption cross section in nuclear matter
\( \bar{p} + A \rightarrow J/Ψ + (A-1) \)
The time like FF remains about a factor 2 above the space like. These differences should vanish in pQCD, thus the asymptotic behavior has not yet been reached at these large values of $|q^2|$. (HESR up to $s \sim 25$ GeV$^2$)
Strange Baryons in Nuclear Fields

Hypernuclei open a 3rd dimension (strangeness) in the nuclear chart

- Double-hypernuclei: very little data
- Baryon-baryon interactions: $\Lambda$-N only short ranged (no $1\pi$ exchange due to isospin) $\Lambda-\Lambda$ impossible in scattering reactions

$\Xi^{-}$

$p\rightarrow 3$ GeV/c

secondary target

$\Xi^{-}p\rightarrow\Lambda uud\Rightarrow\Lambda uds\Lambda uds$
HESR: High Energy Storage Ring

Beam Momentum: 1.5 - 15 GeV/c

High Intensity Mode:
Luminosity: $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ (2x10$^7$Hz)
$\delta p/p$ (st. cooling) $\sim 10^{-4}$

High Resolution Mode:
Luminosity: $2 \times 10^{31}$ cm$^{-2}$s$^{-1}$
$\delta p/p$ (e- cooling) $\sim 10^{-5}$
Dimuon Spectrum in $\bar{p}+\text{Cu}$

- Beam momentum “on resonance”
- Full background simulations (result scaled up)
- Muons from $J/\Psi$ have high $P_t$
- $J/\Psi$ has low $P_t$ (coplanar)
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Central Physics Issue

Transversity distribution of the nucleon:

- last leading-twist missing piece of the QCD description of the partonic structure of the nucleon
- directly accessible uniquely via the double transverse spin asymmetry $A_{TT}$ in the Drell-Yan production of lepton pairs
- theoretical expectations for $A_{TT}$ in DY, 30-40%
  - transversely polarized antiprotons
  - transversely polarized proton target
- definitive observation of $h_1^q(x,Q^2)$ of the proton for the valence quarks
Leading Twist Distribution Functions

Probabilistic interpretation in helicity base:

\[ f_1(x) \]

\[ g_1(x) \]

\[ h_1(x) \]

\[ q(x) \text{ spin averaged (well known)} \]

\[ \Delta q(x) \text{ helicity diff. (known)} \]

No probabilistic interpretation in the helicity base (off diagonal)

Transversity base

\[
\begin{align*}
    u_\uparrow &= 1/\sqrt{2}(u_R + u_L) \\
    u_\downarrow &= 1/\sqrt{2}(u_R - u_L)
\end{align*}
\]

\[ h_\perp \text{ helicity flip (unknown)} \]
Transversity in Drell-Yan processes

Polarized Antiproton Beam → Polarized Proton Target
(both transversely polarized)

\[ Q^2 = M^2 \]

\[ \bar{p} \]
\[ p \]

\[ A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2) h_1^\bar{q}(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2) \bar{q}(x_2, M^2)} \]

\[ q = u, \bar{u}, d, \bar{d}, \ldots \]

M invariant Mass of lepton pair
\( A_{TT} \) for PAX kinematic conditions

**RHIC:** \( \tau = x_1 x_2 = M^2/s \sim 10^{-3} \)
→ Exploration of the sea quark content (polarizations small!)
   \( A_{TT} \) very small (~ 1 %)

**PAX:** \( M^2 \sim 10 \text{ GeV}^2, s \sim 30-50 \text{ GeV}^2, \tau = x_1 x_2 = M^2/s \sim 0.2-0.3 \)
→ Exploration of valence quarks \( (h_1^q(x,Q^2) \text{ large}) \)

\[
A_{TT}/a_{TT} > 0.3
\]
Models predict \( |h_1^u| >> |h_1^d| \)

\[
A_{TT} = \hat{a}_{TT} = \frac{h_1^u(x_1, M^2) h_1^u(x_1, M^2)}{u(x_1, M^2) u(x_1, M^2)}
\]

(\( \bar{q}^p = q^p = q \))

Main contribution to Drell-Yan events at PAX from \( x_1 \sim x_2 \sim \sqrt{\tau} \):
deduction of \( x \)-dependence of \( h_1^u(x, M^2) \)

Similar predictions by Efremov et al.
Other Physics Topics

- Single-Spin Asymmetries
- Electromagnetic Form Factors
- Hard Scattering Effects
- Soft Scattering
  - Low-\(t\) Physics
  - Total Cross Section
  - pbar-p interaction
Polarization Buildup: Optimum Interaction Time

Statistical error of a double polarization observable ($A_{TT}$)

$$\delta_{A_{TT}} = \frac{1}{P \cdot Q \cdot \sqrt{N}}$$

Measuring time $t$ to achieve a certain error

$$\delta_{A_{TT}} \sim \text{FOM} = P^2 \cdot I$$

Optimum time for Polarization Buildup given by maximum of FOM($t$)

$$t_{filter} = 2 \cdot t_{beam}$$
Beam Polarization

$\Psi_{acc} = 50$ mrad

EM only

Filter Test: $T = 23$ MeV  
$\Psi_{acc} = 4.4$ mrad

Buildup in HESR (800 MeV)

F. Rathmann et al., PRL 94, 014801 (2005)
• CSR (green)  Cooler Storage Ring
   unpol. Pbar beam (pol. target) at 3.5 GeV/c

• APR (blue) Anti-Proton-Polarizer
   double spin measurements at 3.5 GeV/c

• Asymmetric collider
   15 GeV/c pbar on 3.5 GeV/c protons  (both polarized)
Conceptual Detector Design

Polarized Antiproton Experiments

Forward detector
Scintillation hodoscope

$P \ 3.5 \text{ GeV/c}$

Drift chambers
Silicon detector

$\bar{P} \ 15 \text{ GeV/c}$
Vacuum pipe

EM calorimeter
Magnet coils
Expected precision of the $h_1$ measurement

One year of data taking at 50 % efficiency (180 days), $A_{TT}/a_{TT} = 0.3$

$$A_{TT}(x, \bar{x}) = \hat{a}_{TT} \frac{h_1(x)}{u(x)} \frac{h_1(\bar{x})}{u(\bar{x})}$$

Collider mode: $5 \cdot 10^{30}$ cm$^{-2}$s$^{-1}$

Fixed Target: $2.7 \cdot 10^{31}$ cm$^{-2}$s$^{-1}$
Yerevan Physics Institute, Yerevan, Armenia
Department of Subatomic and Radiation Physics, University of Gent, Belgium
University of Science & Technology of China, Beijing, P.R. China
Department of Physics, Beijing, P.R. China
Centre de Physique Theorique, Ecole Polytechnique, Palaiseau, France
High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
Nuclear Physics Department, Tbilisi State University, Tbilisi, Georgia
Forschungszentrum Julich, Institut für Kernphysik Julich, Germany
Institut für Theoretische Physik II, Ruhr Universität Bochum, Germany
Helmholtz-Institut für Strahlen- und Kernphysik, Bonn, Germany
Physikalisches Institut, Universität Erlangen-Nürnberg, Germany
Department of Mathematics, University of Dublin, Dublin, Ireland
University del Piemonte Orientale and INFN, Alessandria, Italy
Dipartimento di Fisica, Universita di Cagliari and INFN, Cagliari, Italy
Istituto Nazionale di Fisica Nucleare, Ferrara, Italy
Dipartimento di Fisica Teorica, Universita di Torino and INFN, Torino, Italy
Istituto Nazionale di Fisica Nucleare, Frascati, Italy
Dipartimento di Fisica, Universita di Lecce and INFN, Lecce, Italy
Unternehmensberatung und Service Büra (USB), Gerlinde Schultes & Partner GbR, Langenberndorf, Germany
Soltan Institute for Nuclear Studies, Warsaw, Poland
Petersburg Nuclear Physics Institute, Gatchina, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
Lebedev Physical Institute, Moscow, Russia
Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Russia
Dzhelepov Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, Dubna, Russia
Laboratory of Particle Physics, Joint Institute for Nuclear Research, Dubna, Russia
Budker Institute for Nuclear Physics, Novosibirsk, Russia
High Energy Physics Institute, Protvino, Russia
Institute of Experimental Physics, Slovak Academy of Sciences and P.J. Safarik University, Faculty of Science, Kosice, Slovakia
Department of Radiation Sciences, Nuclear Physics Division, Uppsala University, Uppsala, Sweden
Collider Accelerator Department, Brookhaven National Laboratory, USA
RIKEN BNL Research Center, Brookhaven National Laboratory, USA
University of Wisconsin, Madison, USA
Department of Physics, University of Virginia, Virginia, USA
Summary

- FAIR is approved, $\bar{p}$ beam expected 2013
- Highly compressed baryonic matter
- Charmonium (D) spectroscopy
- QCD exotics
- Polarized antiprotons for transversity