Hadron Experiments in the Framework of Medium Energy Physics

Topical KHuK-Meeting
GSI, 19.10.2001
Klaus Peters
Ruhr-Universität Bochum
Open problems

- Confinement
  - $qq(\bar{q})$-Potential, ...
- Gluonic Degrees of Freedom
  - glueballs and hybrids, ...
- Origin of Mass
  - chiral aspects, ...
- Others
One for all

CHARM-PHYSICS

- Confinement
- Gluonic DoF
- Origin of Mass
- Others

- no direct complication due to light quarks
- narrow states
- non-pertubative effects tend to be "smaller corrections" to the pertubative results
- transition between the two worlds
Light Mesons are complicated

- naive quark-antiquark-picture is wrong for light mesons

- “leading” meson-term is only the simplest of many Fock-states

- exception:
  - narrow states (small mixing of states)
  - exotic quantum numbers (reduce density of states)

\[
\sum_i (q\bar{q})_i \sum_j g_j
\]
Further Options

- Experiments with open charm production are suitable to address other questions in addition:
  - mixing and CP-violation in the charm-sector
  - rare charm-decays
  - charmed baryons
  - ...

(uds-Quarks)

- Experiments in the light meson sector
  - Hall-D (Jlab), CB (Elsa), ...
  - Compass (CERN)
  - $\pi$- and K-Beams (JHF?, MPS?)
  - p-Beams (Cosy)

- Many ambiguities for the interpretation
  - density of states (large)
  - width of states (large)
  - mixing of states (may be large)
Central Production

- CERN-experiments: WA76, WA91, WA102
- Important results in the scalar ($\pi\pi, KK, K_sK_s, 4\pi$) tensor ($\pi\pi, KK, K_sK_s, 4\pi$) pseudoscalar ($KK\pi, \pi\pi\eta$) sectors
- But:
  $\sigma \sim 1/M^2$
  no charm-sector
  partial wave (moment)-analysis complicated
  little $\phi, \omega$ statistics
- Future:
  Compass, much higher statistics
Exotic-Production via FSI

Example: Glueballs

Mixing of States

\[ q \quad \bar{q} \quad g \quad g \]

FSI \ \sim \ \frac{M_1}{M_2} \ \text{tot} \ \sim \ \frac{g}{g}

2-Photon

HallD

Compass

OPE
Current and Proposed Experiments (c-Quarks)

- Earlier Charm-Experiments
  - like FNAL E687, E791 and E835 \((\pi\text{- resp. } \gamma\text{-induced})\)
  - reached their systematic limit ...
  - phasing out

- “new” dedicated Charm-Experiments
  - BES-III, CLEO-C, “Hera-C“ und HESR
Charm-Physics @ CLEO-C

- Leptonic charm-decays
  \( D \rightarrow l\nu \) and \( D_s \rightarrow l\nu \)
  \((f_D, f_{D_s})\)

- Semileptonic charm-decays
  \( D \rightarrow (K, K^*)\nu \), \( D \rightarrow (\pi, \rho, \omega)\nu \),
  \( D_s \rightarrow (\eta, \phi)\nu \), \( D_s \rightarrow (K, K^*)\nu \) and \( \Lambda_c \rightarrow \Lambda\nu \)
  (CKM)

- Hadronic charm-decays
  \( D \rightarrow K\pi \), \( D^\pm \rightarrow K\pi\pi \), \( D_s \rightarrow \phi\pi \)
  (Normalisation)

- Rare decays
- Mixing
- CP-Violation

- Quarkonia:
  light mesons,
  charmonium (vector)

- Radiative J/\(\psi\)-decays
- Multihadron J/\(\psi\)-decays
- Precision measurement
  \( R \) on three spots \((\sigma \sim 2\%)\)
  electroweak \( \rightarrow (g-2) \)
Current and Proposed Experiments (b-Quarks)

- B-factories
  - Babar and Belle
- Hadronic B-factories
  - Hera-B, bTeV and LHCb
- Super-B-factories
  - Super-Babar

- huge charm production rates

- but!
Comparison $\tau$cf and B-Factories

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<tr>
<th>Sensitivity</th>
<th>CLEO-C</th>
<th>BaBar</th>
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<td>$f_D \</td>
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<td>$f_{Ds} \</td>
<td>V_{cs}</td>
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<tr>
<th>Decay Rate</th>
<th>CLEO-C (%)</th>
<th>BaBar (%)</th>
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<tr>
<td>$\Gamma(D \to K\pi\pi)/\Gamma_D$</td>
<td>1.5%</td>
<td>3-5%</td>
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<td>$\Gamma(D_s \to \phi\pi)/\Gamma_{D_s}$</td>
<td>2-3%</td>
<td>5-10%</td>
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<td>$\Gamma(D \to \pi l\nu)/\Gamma_D$</td>
<td>1.4%</td>
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<td>$\Gamma(\Lambda_c \to pK\pi)/\Gamma_{\Lambda_c}$</td>
<td>6%</td>
<td>5-15%</td>
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| ASYMMETRY ($A_{CP}$) | ~1%          | ~1%        |
| x' (mix)             | 0.01         | 0.01       |

Statistics limited

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First Shootout

- CLEO-C dominates all $e^+e^-$-Projects in the charm-sector
  - statistics $> O(10-100)$
    (BES, Babar, Belle)
  - signal-to-background-ratio
    (Super-Babar)

- High energy experiments
  - high charm yields
  - very good vertex resolution (for open charm)
  - bad mass resolution (20-50 MeV)
  - problems with exclusive channels
Mass Resolution of Hadronic B-factories

- Mass resolution is rather poor – for spectroscopy (high momentum tracks)
- Charmonium-Physics excluded
- Open Charm: rare decays

Hera-B: $J/\psi \to \mu^+ \mu^-$
$\sigma_M = 54\text{ MeV}$

$b\text{TeV}: B \to D_s K$
$\sigma_M = 24\text{ MeV}$
Confinement Charmonium-Spectrum

- Structure
  - charmonium spectrum dominated by
    \[ V(r) \sim \frac{a}{r} + br \]
  - FS and non-pertubative effects change individual states
LQCD-Potentials

- Comparison between quenched/unquenched shows compatibility for bbbar-Potentials
- $\sigma_{FD}(\text{stat}) = 1\%$
  unquenched calc: 200 PCs for 3 months
- Vital field with large algorithmic improvements and improved systematic corrections

\[ \frac{[V(r) - V(r_0)]}{r_0} \]

$G. \text{Bali et al., hep-lat/0003012}
\text{SESAM and T L}$

\[ = 0.1575 \]

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Spectroscopy of Light Mesons

- No/small problem with statistics
- Interpretation biased by models (poles, couplings)
- Problem: interpretation of measured states
  - less precise predictions
  - density of states
  - with of states
  - mixing of states

Isoscalar Mixing:
- strong Int.: \( I^G \) und \( J^{PC} \) identical
  - or \( f_2^{-} f_2^{+} \) and/or Glueballs
- \( I=0/I=1 \)-Mixing:
  - elm. Int.: \( I=1 \) z.B.:
  - Kaonmixing:
    - strong Int.: \( C \) undef., \( I^G \) and \( J^P \) identical
      - \( K_{1A} \)-\( K_{1B} \)

I=1 I=1/2
Octett Singlet

\[
\begin{array}{c}
\text{qgq} \\
\text{qgq} \\
\text{qgq} \\
\text{qgq}
\end{array}
\]
Open Problems in Charmonium

- Unclear and missing States (mainly singlet)
  - $\eta_c'$ unconf. (CBall)
  - $h_c$ unconf. (E760)
  - d-States unknown
  - $^1D_2$ can not be populated by radiative transitions
  - nothing known above DDbar-thresholds
  - $\psi$-Levelstructure

- Decays
  - Helicity violation e.g. in $0^{-+} \rightarrow$ Proton-Antiproton
  - strange decay pattern for $\psi(4040)$
  - partial widths mostly unknown

- Others
  - precise measurement $R = N(\mu^+\mu^-)/N(\text{had.})$
  - a.o.m.
Charmonium-Physics @ CLEO-C

- Process $e^+e^- \rightarrow \psi^{(n)} \rightarrow xy$
- Only $J^{PC} = 1^{--}$ directly accessible
  - other states only via decays
- Precision measurement of $R$ and many exclusive channels @ $J/\psi$, $\psi(3770)$ und $\sim\psi(4140)$
  - radiative $J/\psi$-decays
- Expected statistics
  - $10^9 J/\psi$
  - $3 \times 10^7$ D$ar{D}$bar
  - $1.5 \times 10^6$ D$^-_S$-D$^+_S$
Charmonium-Physics @ HESR

- Process $pp \rightarrow \psi^{(n)} \rightarrow xy$ (Formation)
- All $J^{PC}$ accessible
  - Formation from an initial fermion-antifermion-system
  - Understanding the annihilation process is not mandatory, since only the decays are of interest
  - Line of attack: Non-Vector-Sector
- Mandatory: very cold beam with $\delta p/p = 10^{-5}$

![Graph displaying data related to the process $pp \rightarrow \psi^{(n)} \rightarrow xy$]
Gluonic Degrees of Freedom (1)  
Hybrids

- Gluonic excitations of the quark-antiquark-potential may lead to bound states
- LQCD:
  \( m_H \sim 4.2-4.5 \text{ GeV} \)
- Light charmed hybrids could be as narrow as \( \rightarrow O(5-50 \text{ MeV}) \)
  - selection rules
  - # charmed final states (Zweig-Rule)
Density of states (e.g. for Vector Mesons)

- Light mesons have usually larger widths.
- Since $N_Q=3$ (uds) combinatorics yields very many states.
- Ideal: charm-Sector with a much reduced density of states.
Charmed Hybrids

- Fluxtube-Modell predicts DD** decays if $m_H < 4.29 \text{ GeV}$ and $\Gamma_H < 50 \text{ MeV}$
- Some exotics can decay neither to DD nor to DD*
- e.g.: $J^{PC}(H) = 0^{+-}$
  - fluxtube allowed
    - $J/\psi f_2$, $J/\psi (\pi\pi)_{S}, h_{1c} \eta$
  - fluxtube forbidden
    - $\chi c_0 \omega, \chi c_0 \phi$, $\chi c_2 \omega, \chi c_2 \phi$, $\eta c h_1$
- Small number of final states with small phasespace
Exotic Production in Proton-Antiproton

- High production yields for exotic mesons (or with a large fraction of it)
  \( f_0(1500)\pi \rightarrow \sim 25\% \) in 3\( \pi^0 \)
  \( f_0(1500)\pi \rightarrow \sim 25\% \) in 2\( \eta\pi^0 \)
  \( \pi_1(1400)\pi \rightarrow > 10\% \) in \( \pi^\pm\pi^0\eta \)
- Interference with other (conventional) states is mandatory for the phase analysis
# Charmonium Yields in Proton-Antiproton

<table>
<thead>
<tr>
<th></th>
<th>JPC</th>
<th>M [MeV]</th>
<th>$\Gamma_{\text{tot}}$ [MeV]</th>
<th>decay</th>
<th>$\sigma_M$ [pb]*</th>
<th>E./Day** (L=10^{32}cm^{-2}s^{-1})</th>
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<tbody>
<tr>
<td>$\eta_c$</td>
<td>0-+</td>
<td>2980</td>
<td>13,2</td>
<td>$\gamma\gamma$</td>
<td>550</td>
<td>2,2k</td>
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<td></td>
<td></td>
<td>$\phi\phi$</td>
<td>3100</td>
<td>12,4k</td>
</tr>
<tr>
<td>$\eta_c$</td>
<td>0-+</td>
<td>3594</td>
<td>?</td>
<td>$\gamma\gamma$</td>
<td>120</td>
<td>0,5k</td>
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<td></td>
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<td></td>
<td></td>
<td>$\phi\phi$</td>
<td>&gt;&gt;$\gamma\gamma$</td>
<td>&gt;&gt;1k ?</td>
</tr>
<tr>
<td>$\chi_{c1}$</td>
<td>1++</td>
<td>3511</td>
<td>0,88</td>
<td>$\gamma J/\psi$</td>
<td>3600</td>
<td>14,4k</td>
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<tr>
<td>$\chi_{c2}$</td>
<td>2++</td>
<td>3556</td>
<td>2,0</td>
<td>$\gamma J/\psi$</td>
<td>3700</td>
<td>14,8k</td>
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<td>$H_c$</td>
<td>1--</td>
<td>4400</td>
<td>?</td>
<td>$J/\psi\eta$</td>
<td>~100</td>
<td>&gt;~1k</td>
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<tr>
<td>$H_c$</td>
<td>1--</td>
<td>4300</td>
<td>?</td>
<td>$J/\psi\omega,\phi,\gamma$</td>
<td>~10</td>
<td>&gt;~0,1k</td>
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<td>-</td>
<td>-</td>
<td>E760</td>
<td>-</td>
<td>$J/\psi\pi$</td>
<td>120</td>
<td>~1k</td>
</tr>
</tbody>
</table>

* in this decay branch (peak yield)  ** = 8 pb^{-1}/day
Hybrid Formation in Proton-Antiproton

- Gluon rich process creates gluonic excitation in a direct way
  - since ccbar requires the quarks to annihilate (no rearrangement)
  - yield comparable to production of charmonium

- 2 complementary techniques
  - Formation (Broad- and Fine-Scans)
  - Production (Fixed-Momentum)

- Momentum for an complete survey \( p \rightarrow \sim 15 \text{ GeV} \)
Mass regions and $\bar{p}$ momentum

- Neccessary momentum span is driven by the charm-exotics
- Hybrids ($H_C$)
  - $H_C$ non-exotic $J^{PC}$
  - Formation $\rightarrow$10 GeV/c
  - $H_C$ exotic $J^{PC}$
  - Production $\rightarrow$15 GeV/c (+Recoil-Particle+Phsp.)
- $D_{(s)}$-Hybrids
  - $D_sD_s+1$ GeV/c $\sim$12 GeV/c
- Charmed Multiquarks ($M_C$)
  - $M_{C}l^{+}l^{-} \rightarrow$15 GeV/c

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Continuation of Experiments

- First experiments: R704 @ CERN
- Same technique: E760/E835 @ FNAL
  @ TeV-Booster `til Y2k
- Many contributions to the field of charmonium physics
  but:
  - momentum limited to 9 GeV
  - no measurements above open charm threshold
  - no $^1D_2$, $^3D_2$ (both narrow since DDbar forbidden)
- Detector limitations
  - small solid angle
  - no charged tracking, no $\phi\phi$, small luminosity
- FNAL focused on HEP and Post-SM physics
Hybrid Formation with $\pi$-, $K$- and $\gamma$-Beams

- Meson formation via meson exchange process
  - coupling through decay channels
  - only light hybrids possible

- decay channels usually unknown, their partial width could be awfully small
Gluonic Degrees of Freedom (2)

- Light $gg/ggg$-systems are complicated to identify
- Exotic heavy glueballs
  - $m(0^{+-}) = 4140(50)(200)$ MeV
  - $m(2^{+-}) = 4740(70)(230)$ MeV
- Width unknown, but! nature invests more likely in mass than in momentum
- Flavour-blindness predicts decays into charmed final states
- Same run period as hybrids
- In addition: scan $m>2$ GeV/$c^2$

Morningstar und Peardon, PRD60 (1999) 034509
Morningstar und Peardon, PRD56 (1997) 4043
Glueballs: 
Further Production Experimente

- Light Glueballs  
  \( J^{PC}=0^{++}, 0^{-+} \) und \( 2^{++} \)  
  - ideal: in radiative \( J/\psi \)-Decays: 
    \( J/\psi \to \gamma X \)  
  - where \( X \) can be analysed in many exclusive channels

- CLEO-C  
  - \( N(J/\psi) = 20 \times \text{BES} = 200 \times \text{MIII} \)  
  - alternatively \( D(S) \to 3 \text{ PS} \) (only scalar waves)  
  - \( N(D_S) = O(10) \times \text{B-Fab} \)
4-Quark Formation with DiLepton-Tag

- Proton-Antiproton contains already a 4-Quark-System
- Idee: Dilepton-Tag from Drell-Yan-Production
- Advantages
  - trigger
  - less $J^{PC}$-Ambiguitäten
  - 1200 E./day @ 12 GeV
  - 300 E./day @ 5-8 GeV
  - antiproton-Beam
    (für $L=10^{32}$cm$^{-2}$s$^{-1}$)

Bannikov, Gornuschkin, Kopeliovich, Krumshtein and Sapozhnikov, JINR E1-92-344 (1992)
Origin of Mass
Influence of the Nuclear Medium

- Pionic atoms, KAOS/FOPI@GSI exhibit mass shifts in the nuclear medium
- Continue with charm
- Experimental aspects
  - enhanced D-Production at threshold
  - Broadening of the $\psi(3770) (20 \rightarrow 40 \text{ MeV})$ or $\chi_{c2} (0,32 \rightarrow 2,7 \text{ MeV})$ (DiLepton-Channel)
  - Advantages in antiprotonic production $T \sim 0$
    (not like Heavy-Ion)

Hayashi, PLB 487 (2000) 96
Measureable Effects
J/ψ-Absorption in the nucleus

- Indications for Quark-Gluon-Plasma → J/ψ attenuation in heavy-ion collisions
- Experiments at GSI: DiLepton-spectrometer Hades
- Problem: ccbar-interaction in the nucleus unclear
- Existing material from photoproduction ambiguous
- For further investigations a direct measurement of the basic reaction is mandatory
- Proposed reaction \( p\bar{p} (\sim 4 \text{ GeV/c}) + A \rightarrow J/ψ + (A-1) \)
J/ψN in Proton-Antiproton-Reactions

- No competition - unique source
- Fermi-smeared ccbars-Produktion
- J/ψ, ψ' or interference region selected by pbar-Momentum
- Longitudinal und transverse Fermi-distribution is measurable
Further Possibilities

- Charm experiments have additional capabilities apart from the addressed problems in QCD
- Mixing and CP-violation in the D-system
- exclusive decayrates, leptonic and semileptonic decays \( f_{D(s)} \)
- rare decays (SM and beyond)

- Hadronic factories may contribute to specific rare decays (may need special triggers) like Hera-B/C: \( D^0 \to \mu^+\mu^- \)
- Questionable: how does this fit into their schedule?
- Future: bTeV und LHCb

- For CP-violation and mixing: Coherent pair-Production more appropriate
Mixing and CP in the D-Meson-Sector

- small mixing in the charm Sector compared to \( K^0 \) and \( B_{(S)}^0 \)
- Interference of amplitudes may lead to CP-Violation
- Measure \( D^+/D^- \)-asymmetries
Experimental Approach

- Direct CP-Violation
  \[ \alpha_{CP} \sim 10^{-3} \]
- \(10^8\) reconstructed DD-pairs needed (3\(\sigma\))
- Realistic: (D\(_{rec.}\))
  - CLEO-C: \(3 \times 10^7\) DD/y
  - HESR: \(2.5 \times 10^7\) DD/y
  - FOCUS: \(10^6\) D/y
  - B-Fabs: <\(10^7\) DD/y
  - only ccbar-Fragmentation usable, still large background
- CLEO-C and HESR same capabilities
- CLEO-C is advantageous in terms of background, but CESR-C is symmetric and luminosity \@ limit
- HESR need specific triggers, but luminosity upgrades may improve the overall situation \(\rightarrow\) CHALLENGE
Example: CLEO-C
- Large cross section with small particle multiplicity
- Clean initial state coherent D-pairs
- Tagging possibilities
- Very good neutrino-reconstruction (Missing-Mass-Technique)
Summary (1)
Completeness

- All problems can be addressed with the proposed experiments:
  - Confinement (-potential)
    - CLEO-C (only 1--), HESR (all ccbar)
  - Gluonic Components
    - CLEO-C (light gg), HallD (uds-Hybrids),
      HESR (heavy gg, c-Hybrids [uds-Hybrids])
  - Nuclear Interaction
    - HESR (D-Mass shift, J/ψ-Absorption)
Annihilation in Flight – no longer a challenge!

Crystal Barrel has proven that annihilation in flight can be analyzed unambiguously.

Formation:
twobody decays, where at least one particle carries spin!

Production:
integration of the production process or small recoil momena may reduce the available phsp. and the contributing waves dramatically.

Peters, NPA 692 (2001)295
# Timescale (Guestimate)

<table>
<thead>
<tr>
<th>Year</th>
<th>Babar/Belle</th>
<th>HERA-B/C</th>
<th>bTeV /LHCb</th>
<th>SuperBabar</th>
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- **BES**
  - BES II
  - BES III

- **CLEO-III/-C**
  - CLEO III
  - CLEO C
  - ?

- **HaldD**
  - HERA B
  - ?

- **HESR**

- **Hera-B/C**

- **bTeV /LHCb**

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Summary (2)

Interpretation—What do we learn

- LatticeQCD and $\chi$PT are the framework for a complete interpretation of the proposed results.

- In the last 5 years LQCD has made an enormous step forward because of improved knowledge and algorithms, rather than in hardware - still improving.

- New projects allow high precision tests/calibration.

- High-precision and broad range is essential to differentiate LGT from models.
Summary (3)
Complementarity-Uniqueness

- High statistic projects CLEO-C and HESR overlap in charm CP/mixing-physics
- CLEO-C focuses on open charm production and decays and J/ψ-physics
- HESR focused on uncompromised charmonium production and other heavy exotic States
- HESR has also the unique opportunity to measure effects of charm in the nuclear medium
Post Scriptum

- Charm-Physics is an outstanding window to the world of QCD