The BGO-OD experiment at ELSA

Hartmut Schmieden
Physikalisches Institut
Universität Bonn

The house began to feel familiar. Everywhere, that is, except the basement. It just always put me off, and I avoided going down there as best as I could.

Cliff Barlow
The BGO-OD experiment at ELSA

In the Lion's Den
– nucleon structure in the realm of strong QCD

(N. Isgur @ JLab NSTAR conference)

Hartmut Schmieden
Physikalisches Institut
Universität Bonn

The house began to feel familiar. Everywhere, that is, except the basement. It just always put me off, and I avoided going down there as best as I could.

Cliff Barlow
The BGO-OD experiment at ELSA

Overview

• General motivation
• Excited baryons
• Meson sector
• Experimental requirements meson photoproduction
• BGO-OD experiment – setup
• Preliminary (commissioning) results
• Summary
Nucleon Structure – still interesting?
Nucleon Structure – still interesting?
Nucleon Structure – still interesting?
Nucleon Structure – still interesting?
Phenomenologic QCD potential

- fit of the quarkonia spectra obtained with strong coupling
  
  \[ V_{QCD} = -\frac{4}{3} \frac{\alpha_s}{r} + kr \]

  linear confinement

- best fit values (charmonium & bottomonium)

  \[ \alpha_s \approx 0.2 \]
  \[ k \approx 1 \text{ GeV fm}^{-1} \]

  \[ F = -\nabla V \]

  \[ 1 \text{ eV} = 1.6 \times 10^{-19} \text{ Nm} \]
  \[ \approx 1.6 \times 10^{5} \text{ N} \approx 16 \text{ t} \]
Running Coupling

\[ \alpha_s \]

perturbative QCD

strong QCD

radius of nucleon

asymptotic freedom

confinement

Lion's Den

QFT w/o perturbative expansion
Confinement & nucleon mass

\[ G_a^{\mu \nu} G_a^{\mu \nu} \neq 0 \]

\[ m = E/c^2 \]

\[ \Delta p \Delta x > \hbar \]

Distance

Energy

300 MeV

0.6 fm

Delocalization ↔ kinetic energy

Potential energy

nucleon mass

trace anomaly

scale non-invariance

E_{pot} \sim r

“mass without mass”

J. Wheeler
F. Wilczek
QCD potential & Lattice QCD

\[ \mathcal{L}_{\text{QCD}} = q_i \left( i \partial_\mu \gamma^\mu \delta_{ij} + g \frac{\lambda^a_{ij}}{2} A^a_\mu \gamma^\mu - m \delta_{ij} \right) - \frac{1}{4} F^a_{\mu\nu} F^{a \mu\nu} \]

(1) short distance (ultraviolet) regularization
\[ \leftrightarrow \text{mesh of discrete lattice points} \]

(2) infrared cutoff
\[ \leftrightarrow \text{finite lattice volume} \]

(3) functional integrals oscillate rapidly
\[ \rightarrow t \equiv x^0 = -ix_4 \leftrightarrow \text{4-dim Euklidian space} \]
\[ \leftrightarrow \text{damping of oscillation} \]

\[ F^a_{\mu\nu} = \partial_\mu A^\nu - \partial_\nu A^\mu + gf_{abc} A^b_\mu A^c_\nu \]

- Quark
- Gluon field
- Gluon self-coupling
- Time-ordered product
- Gauge field (transporter)
- SU(3) color generators
Energy density distribution inside nucleon in LQCD simulation (F. Wilczek, Physics today 11/99 & 1/00)


slope = k ≈ 1 GeV/fm
Lattice QCD

S. Dürr et al. (BMW-collaboration), Science 322 (2008) 1224

- "unquenched" calculation
- realistic quark masses
Excited states

\( \Delta(1232) \)

\( S_{11}(1535) \)

\( \sigma_{tot}/\mu b \)

Cross section (mb)
Excited states: Quark Model

- "mutually-generated" potential for quarks
- approximate confinement
- linear rise @ large $r$
- plus corrections, e.g. Metsch et al.: t'Hooft Instanton interaction
- no spin-orbit forces
- BUT: no coupling to continuum

$\Rightarrow$ field energy materializes
Excited states: Quark Model

N* resonances

- parity pattern $+ \rightarrow + \rightarrow -$ !?!
- effective degrees of freedom ??
Excited states: LQCD

- $m_{\pi} = 396$ MeV
- reproduces q-models
- wrong parity pattern
- but: no decays!

Λ hyperons: Quark Model

Metsch, Löring, Petry, EPJ A10 (2001)
Λ hyperons: Quark Model

- parity OK
- mass < 1535 ?
- angular mom.

Metsch, Löring, Petry, EPJ A10 (2001)
Threshold Dynamics?

\[
\begin{align*}
\Lambda(1405) & \quad p - \eta \\
K - N & \quad p - \omega \\
K - \Sigma & \quad \rho - \phi \\
\end{align*}
\]

\[
\begin{align*}
K - N & \quad K - \Sigma \\
p - \eta & \quad p - \phi \\
\end{align*}
\]

\[
\begin{align*}
S_{11}(1535) & \quad \text{narrow peak \ & cusp in } \eta \, n/p \\
k^{+} - \Lambda(1520) & \quad \text{narrow peak \ in } \phi \, p \\
k^{+} - \Sigma & \quad \text{cusp in } K \Sigma
\end{align*}
\]

\[
\begin{align*}
1.43 & \quad 1.49 \\
1.68 & \quad 1.7 \\
1.90 & \quad 1.96 \\
2.007 & \quad 2.013 \\
2.08 & \quad \text{cm energy / GeV}
\end{align*}
\]
J.M.M. Hall et al. [Adelaide group], arXiv::1411.3402v2 (2015)
Λ(1405): LQCD

"molecule" as dominating Fock component

genuine 3q
Meson sector: X(3872)

Observed by Belle in $B^\pm \rightarrow K^\pm \pi^+\pi^- J/\psi$

PRL91, 262001(2003)

Meson sector: X(3872)

BaBar / SLAC

CDF / Tevatron

PRL 110 (2013) 222001

J^{PC} = 1^{++}

J^{PC} = 2^{-+}
Meson sector: X(3872)

<table>
<thead>
<tr>
<th></th>
<th>$M(X(3872))$, MeV/c$^2$</th>
<th>$\Gamma(X(3872))$, MeV/c$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \rightarrow X\pi$</td>
<td>3871.46±0.37±0.07</td>
<td>&lt;2.3 @ 90% C.L. (2003)</td>
</tr>
<tr>
<td>$B \rightarrow X\pi$</td>
<td>3871.4±0.6±0.1</td>
<td>&lt;3.3 @ 90% C.L. (2008)</td>
</tr>
<tr>
<td>$X \rightarrow J/\psi\pi^+\pi^-$</td>
<td>3871.61±0.16±0.19</td>
<td>1.34 (fixed from first two)</td>
</tr>
<tr>
<td>average</td>
<td>3871.50±0.19</td>
<td></td>
</tr>
<tr>
<td>$M(D^0)+M(D^{*0})$</td>
<td>3871.81±0.36</td>
<td></td>
</tr>
</tbody>
</table>

"molecule" possible bound state of $D^0 D^{*0}$

$J^P = 0^-$ $1^-$
Meson sector: X(3872) Interpretation

- CP quantum numbers determined $J^{PC} = 1^{++}$
- $X(3872)$ likely not a charmonium state
  - radial excitation of $\chi^{c1}_{c1}$ ($J^{PC} = 1^{++}$) expected at 3950 MeV/c²
  - $\eta^{c2}_{c2}$ ($J^{PC} = 2^{-+}$) should have $X \rightarrow J/\psi \gamma$ suppressed
    $\Rightarrow$ no satisfactory cc assignment
  - explains proximity of $D^0D^{*0}$ threshold
  - favors $DD^*$ decay over $J/\psi \pi\pi$ over $J/\psi \gamma$ (as observed)
  - isospin $I = 0$ favoured
  - expect $X \rightarrow \psi(2S)\gamma$ to be suppressed (contrary to observation)
  - 2 neutral and 2 charged states predicted
  - neutral states produced in $B^0$ and $B^+$ decays: $\Delta m \approx (7 \pm 2)$ MeV
  - measurement $\Delta m = (+0.18\pm0.89\pm0.26)$ MeV in $B \rightarrow J/\psi \pi\pi^+\pi^-$
  - expect charged partners (contrary to observation)
- Dynamic interplay of quark & meson d.o.f @ thresholds?
- Something else?... not yet settled
Baryon sector

- unresolved issues w/ low-lying states
- unexpected narrow structures in threshold vicinity, e.g.
  - $\eta \pi$ @ 1.68 GeV
  - $K^0 \Sigma^+$ @ 2.0 GeV
  - $\phi p$ @ 2.1 GeV
- example $\Lambda(1405)$
  - measurements of line shape etc
  - multiple pole structure
  - meson-baryon dynamics significant
  - genuine 3q structure unlikely
  - $t$-dependence ??
- structure / dynamics of (low lying) states/structures still unresolved
  -> meson-baryon vs. 3q interactions ?
$\gamma + p \rightarrow K_S^0 + \Sigma^+$ ↔ $K^*$ cusp?

most forward bin $<\theta_{K^{*\text{cm}}}> = 0.83$

R. Ewald et al. (CBELSA), PLB 713 (2012)
\[ \gamma + p \rightarrow K_S^0 + \Sigma^+ \rightleftharpoons K^* \text{ cusp?} \]
\[ \gamma + p \rightarrow K_s^0 + \Sigma^+ \quad \leftrightarrow \quad K^* \text{ cusp?} \]
\( \gamma + p \rightarrow K_S^0 + \Sigma^+ \quad \leftrightarrow \quad K^* \) cusp?

R. Ewald et al. (CBELSA), PLB 713 (2012)

M. Nanova et al., EPJ A35 (2008) 333

\( K^* \Sigma^+ \) cross section added

K-MAID (mod.)

SAID

\( K^- \Lambda \quad K^* \Sigma^+ \) thresholds

\( \gamma + p \rightarrow K_S^0 + \Sigma^+ \quad \leftrightarrow \quad K^* \) cusp?
Experimental Requirements

\[ K^* \rightarrow K \mp \pi, \quad K \rightarrow N \Lambda/\Sigma \]

\[ p \Lambda(1405) p \rightarrow K^+ K^- \]
Experimental Requirements

"parallel" kinematics

low t

\[ p_p \quad \Lambda(1405) \quad p \]
Experimental Requirements

- forward (charged) particle
- high momentum

"parallel" kinematics

low t

\[ \begin{align*}
K^+ & \rightarrow K^- \\
K & \rightarrow \Lambda(1405)
\end{align*} \]
Experimental Requirements

- forward (charged) particle
- high momentum

- $4\pi$ decay
- charged & neutral

"parallel" kinematics

\begin{align*}
K^- & \rightarrow K^+ \pi^- \\
\Lambda & \rightarrow K^0 \pi^0
\end{align*}
BGO-OD experiment
BGO-OD experiment at ELSA
BGO-OD incident beam

- ELSA $e^-$ beam $\leq 3.5$ GeV $\rightarrow$ tagged $\gamma$ beam $\leq 3$ GeV
- Current $\leq 2nA$, ideal for tagging
- Linearly polarised $\gamma$ beam using coherent bremsstrahlung off a diamond radiator
- Circularly polarised $\gamma$ beam w/ longitudinally polarised $e^-$ beam maximum polarisation at $E_e \sim 1.7$GeV ($E_{cm} \sim 2$GeV)

Energy region of unresolved resonances and threshold structures covered
Analysis* Overview (Commissioning Data)

Neutral meson reconstruction in the BGO

Charged particle ID in the Forward Spec.

* work of Tom Jude
BGO ball: $K^+$ identification

- time delayed weak decay within BGO ball
- T.C. Jude et al., PLB 735 (2014) 112

Lifetime 12 ns, 2 main decay modes:

\[ K^+ \rightarrow \mu^+ \nu_{\mu} \]
\[ K^+ \rightarrow \pi^+ \pi^0 \]

Simulated data
Experimental data

Fitted $K^+$ lifetime $\approx 11$ ns
Missing hyperon masses from K⁺ in BGO

- (γ_{beam}, K⁺) missing mass
- data subset w/ $\Sigma^0 \rightarrow \Lambda \gamma$ tagged
- $\Sigma^0 \rightarrow \Lambda \gamma$ efficiency $\sim 60\%$
- false assignment $< 10\%$
Particle id in OD spectrometer

To enhance $K^+$ signal

$\pi^0$ mass reconstructed in the BGO
BGO total energy deposition $< 250$ MeV

With Calculated $\beta$

- pions
- kaons
- protons
Missing (Y) mass from $K^+$ in OD spectrometer
Missing (Y) mass from $K^+$ in OD spectromter
SciRi detector

- 2/3 cluster in BGO
- proton in SciRi

MSc thesis G. Scheluchin
Summary

• BGO-OD addresses interesting physics programme
  – meson-baryon dynamics
  – narrow structures
  – $\eta$, $\eta'$, KY, $\omega$, $\phi$ photoproduction
  – $\eta'$ mesic nuclei

• unique detector setup
  – complementary to Crystal Barrel, CLAS, LEPS, ...

• polarised beams & hyperon recoil polarimetry

• successful commissioning

• data taking ahead
Summary

- BGO-OD addresses interesting physics programme
  - meson-baryon dynamics
  - narrow structures
  - $\eta, \eta', KY, \omega, \phi$ photoproduction
  - $\eta'$ mesic nuclei
- unique detector setup
  - complementary to Crystal Barrel, CLAS, LEPS, ...
- polarised beams & hyperon recoil polarimetry
- successful commissioning
- data taking ahead

Thanks to

DFG – SFB/TR-16

- all Students (Bachelor, Master, Diploma, PhD) & postdocs
- postdocs: T. Jude, V. Vegna
- technical coordinators: D. Elsner, J. Hannappel
BGO-OD Collaboration

spokespersons: P. Levi Sandri (INFN Frascati) & H.S.

- Physikalisches Institut Bonn Germany
- HISKP Bonn Germany
- Petersburg Nuclear Physics Institute Gatchina Russia
- Institut für Physik Basel Switzerland
- II. Physikalisches Institut Giessen Germany
- INFN Pavia Pavia Italy
- National Science Center Kharkov Ukraine
- Universita degli Studi Messina Italy
- INFN Catania Catania Italy
- INFN Roma Tor Vergata Rome Italy
- University of Rome Rome Italy
- INFN Torino Rome Italy
- INFN Roma La Sapienza Rome Italy
- Istituto Superiore di Sanita Rome Italy
- INFN Frascati Frascati Italy
- The University of Edinburgh Edinburgh UK
- Russian Academy of Sciences Moscow Russia
- Glasgow University Glasgow UK
- Idaho State University Pocatello USA
BGO-OD

Voyager spacecraft
The Sounds of Earth

Johnny B. Goode
(Chuck Berry)