STUDY OF $K\bar{K}\pi$ AND STRANGEONIA STATES IN THE (1 - 2) GEV MASS RANGE

~2.2

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Outline

• Introduction: light mesons with open and hidden strangeness, and their decay to $K\bar{K}\pi$ final states

• Strangeonia: expected decay channels

• Conventional and exotic strangeonia: experimental status

• Overlapping (possibly exotic) states: the case of the $0^{-+}$ glueball
  – Pseudoscalars vs axial vectors in the 1-2 GeV mass region

• Open possibilities of observations in photoproduction reactions

• CLAS data and CLAS12 benchmark reactions studies

• Summary and Conclusions
Introduction: strange quarkonia

• **Strange quarkonia**: light mesons (u,d,s) with at least one strange quark/antiquark in their valence component
  – **Kaonia/antikaonia**: dominant valence $n\bar{s}/s\bar{n}$ ($n= u, d$)
    • Of 22 expected states below 2.1 GeV, $\sim 13$ are known
  – **Strangeonia**: $s\bar{s}$
    • Of 22 expected states below 2.1 GeV, only less than 10 are steadily established

• Many fundamental information still missing in the 1.2-2.5 GeV mass range

• Necessary to complete the meson spectrum scenario for the study of exotic states
  – Dominantly non q$\bar{q}$ states: glueballs, hybrids, multiquark systems
  – Featuring both exotic and non-exotic quantum numbers
    • Large possibility of strong mixing with conventional quarkonia
    • Overlap in the same mass region
Strangeonia production processes

• Small $s\bar{s}$ production cross section
  – OZI suppressed processes
  – Most effective reactions studied so far:
    • Hadronic reactions:
      – Central production (CERN, Fermilab)
      – Strangeness exchange reactions: $K^-p \rightarrow \Lambda X$ (SLAC)
      – $\pi^-p$ peripheral collisions: low cross sections (BNL, CERN, ...)
    • $e^+e^-$ collisions: pure $J^{PC} = 1^- -$ sector
      – Mixing between possible vector hybrids and quarkonia
    • Diffractive photoproduction: $\gamma p \rightarrow X p$
      – Excitation of $C = -1$ $s\bar{s}$ states: the photon beam can be seen as a superimposition of vector mesons, with meaningful $s\bar{s}$ coupling
      – Lack of intense enough beams (so far)

• Large production of open-strangeness pairs in OZI allowed processes
  – Decay modes are shared between open-flavor mesons and strangeonia: additional complication
Strangeonia decay patterns

- **Smoking gun** decay modes for $S\bar{S}$ states: $\eta\phi$, $\eta'\phi$, $\phi\phi$
  - $\eta\phi$: identification of $C = -1$ $S\bar{S}$ candidates
  - Small branching fraction to non-strange final states

\[
|\eta\rangle = \frac{1}{\sqrt{2}} \left( |n\bar{n}\rangle_{I=0} - |S\bar{S}\rangle \right)
\]

\[
|\eta'\rangle = \frac{1}{\sqrt{2}} \left( |n\bar{n}\rangle_{I=0} + |S\bar{S}\rangle \right)
\]

\[
|n\bar{n}\rangle_{I=0} = \frac{1}{\sqrt{2}} \left( |u\bar{u}\rangle + |d\bar{d}\rangle \right)
\]

- Other relevant channel for $S\bar{S}$ and exotics ($q\bar{q}g$, $q\bar{q}q\bar{q}$): $\phi\pi^0$
- **Decays to open-strangenessness final states do not uniquely identify strangeonia**: $K\bar{K}$, $K\bar{K}^*$ ($K\bar{K}\pi$), $K^*\bar{K}^*$ (+c.c.)
  - Decay channels shared by:
    - light quark iso-singlet mesons:
    - Exotic states
      - Experimental evidences of significant $n\bar{n} \leftrightarrow G \leftrightarrow S\bar{S}$ mixing, especially in the scalar $0^{++}$, **pseudoscalar $0^+$** and $2^+$ sectors
STRANGEONIA STATES: EXPERIMENTAL STATUS
Vector strangeonia $1^{++}$: present experimental status

- The strangeonium spectrum does not simply replicate the spectrum ~250 MeV higher in mass: several channel dependent couplings

- Only three really well established $s\bar{s}$ resonances:
  - $\phi(1020)$ ($1^{--}$)
  - $\phi_3(1854)$ ($1^{--}$)
  - $+ f_2(1525)$ (tensor)

- Several controversial observations of other strange quarkonia states:
  - $h_1(1380)$ ($^{1}P_1$, $1^{+-}$)
  - $\phi(1680)$ ($2^{3}S_1$, $1^{-\pm}$)
  - $+ several$ axial-vectors:
    - $f_1(1420)$, $f_1(1510)$, ...

<table>
<thead>
<tr>
<th>State</th>
<th>Predicted Decay Width</th>
<th>Observed Decay Width</th>
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<tbody>
<tr>
<td></td>
<td>Theory MeV/c²</td>
<td>Expt. MeV/c²</td>
</tr>
<tr>
<td>$\phi(1680)$ 2S</td>
<td>$\Gamma_{\text{theory}} = 378$</td>
<td>$\Gamma_{\text{exp}} = 150 \pm 50$</td>
</tr>
<tr>
<td>$\phi(2050)$ 3S</td>
<td>$\Gamma_{\text{theory}} = 378$</td>
<td>$\Gamma_{\text{exp}} = \text{unknown}$</td>
</tr>
<tr>
<td>$\phi_3(1854)$ 1D</td>
<td>$\Gamma_{\text{theory}} = 104$</td>
<td>$\Gamma_{\text{exp}} = 87^{+28}_{-23}$</td>
</tr>
<tr>
<td>$\phi_2(1850)$ 1D</td>
<td>$\Gamma_{\text{theory}} = 214$</td>
<td>$\Gamma_{\text{exp}} = \text{unknown}$</td>
</tr>
<tr>
<td>$\phi(1850)$ 1D</td>
<td>$\Gamma_{\text{theory}} = 652$</td>
<td>$\Gamma_{\text{exp}} = \text{unknown}$</td>
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</tbody>
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T. Barnes et al., PR D68 054014 (2003)
Strangeonium hadroproduction

- **LASS @ SLAC, 11 GeV/c K^- beam (1988)**

  \[ K^- p \rightarrow K^+ K^- \Lambda, \ K^- p \rightarrow K^0_s K^\pm \Lambda, \ K^- p \rightarrow K^0_s K^0_s \Lambda \]

  - **Favored** production of \( S\bar{S} \) vs glueball

- Observed states: linear orbital ladder up to \( 4^+ f' \)
- **Good evidence for two \( S\bar{S} \) axial vector mesons**
  - \( 1^{++} : m \sim 1530 \text{ MeV} \)
  - \( 1^{+-} : m \sim 1380 \text{ MeV} \Rightarrow h_1(1380) \)
    - Confirmed @ BNL-771 & Crystal Barrel

- No significant production of \( f_1(1420) \) (\( \Rightarrow K^* K \) molecule)
- No evidence of \( f_J(1710) \)

- **Indications of \( f_J(2200) \) \( J^{PC} = 4^{++} \)**
  - Superimposition of two narrow states? one could be strangeonium
The $\phi(1680)$ resonance

- Natural candidate for $\phi(1020)$ 2S excitation
- Observations in KK and KK*
  - Cited as evidence of ss nature, but not enough!
- contrasting observations in different production channels
  - $e^+e^-$: low mass, KK* dominance
    - DM1: $e^+e^- \rightarrow K^0_S K^0_L$
    - VEPP-2M & DM2: $e^+e^- \rightarrow K^+K^-$
    - DM2: $e^+e^- \rightarrow K\bar{K}\pi, \omega\pi^+\pi^-$
    - BaBar: $e^+e^- \rightarrow$ hadrons
    - BELLE: $e^+e^- \rightarrow K^+K^-\pi^+\pi^- ( +\gamma_{\text{ISR}})$
      - $M = 1680 \pm 20$ MeV, $\Gamma = 150 \pm 50$ MeV
  - photoproduction: high mass, KK dominance
    - Omega (CERN), WA57, E401
      - Larger mass, $\sim 1750$ MeV
    - FOCUS: diffractive photoproduction of $K^+K^-$
      - Clear enhancement at large mass
      - $M = 1753 \pm 3$ MeV, $\Gamma = 122.2 \pm 63$ MeV
      - No evidence of KK* decay

FOCUS, $\gamma$ BeO $\rightarrow K^+K^- X$
PL B545, 50 (2002)

BELLE, PR D80, 031101 (2009)
HYBRIDS WITH STRANGENESS: THE C(1460) CASE
First (and only) strange hybrid observation

Lepton-F @Serpukhov, 32.5 GeV/c $\pi^-$ beam (1987)

$\pi^- p \rightarrow \phi \pi^0 n$

- Resonance observed in the $\phi \pi^0$ channel: $C(1480)$
  - $m = 1480 \pm 40$ MeV
  - $\Gamma = 130 \pm 60$ MeV

- Spin-parity assignment: $J^{PC} = 1^{--}$
- Isovector state
- Suggested to be an exotic candidate
- Quite large cross-section at 32.5 GeV/c: $40 \pm 15$ nb
- Needs confirmation!
THE $2^1S_0$ $s\bar{s}$ STATE AND THE CASE OF THE $0^{-+}$ GLUEBALL - $\eta(1440)$
2S pseudoscalar strangeonium

- **$^3P_0$ model**: strong decays occur through the production of a $q\bar{q} 0^{++}$ pair in the intermediate state, which decays in two mesons
  - Experimental evidence: spin 1 $q\bar{q}$

- **2S pseudoscalar $s\bar{s}$ states**
  - Assumption: $\eta$-$\eta'$ flavor mixing does not occur for the radially excited $s\bar{s}$ states
    - the only open strangeness allowed decay mode for is $KK^*$ (P-wave decay)
  - Problem: mass close to $KK^*$ threshold
    - Mass dependent width and distortions due to thresholds opening ($KK^*$, $\eta\pi\pi$)
    - Overlap with other signals sharing the same decay mode in a rather problematic region: $\eta(1440)$
      - is this the lightest glueball?
States decaying into $K\bar{K}\pi$ in the 1.3-1.5 GeV mass region

- Long-standing problem: superimposition of several pseudoscalar+axial states: “$E/\iota$” region

- **Pseudoscalar states $0^{-+}$:** all of them decay in $K\bar{K}\pi$ (direct), $K^*\bar{K}$, $a_0(980)\pi$
  - $\eta(1275)$
    - Can be the first radial excitation of the $\eta$
  - $\eta(1440)$, likely to be splitted in two states
    - $\eta(1405)$
      - Gluonium? not observed in $\gamma\gamma$ collisions
    - $\eta(1475)$

- **Axial states $1^{++}$:**
  - $f_1(1285)$ – does not decay in $KK^*$
  - $f_1(1420)$
    - Arguments favoring its interpretation as hybrid $q\bar{q}g$, or four-quark state, or $K^*\bar{K}$ molecule
  - $f_1(1510)$
    - Not well established
  - Isovector $a_1(1420)$

*OBELIX, PL B462, 453 (1998)*

\[ p\bar{p} \rightarrow K^0K^{\pm}\pi^\mp\pi^+\pi^- \]
\[ \eta(1440): \eta(1405) \oplus \eta(1475) \]

- >20 years of observations (very few recent results!) in different reactions
- Low statistics experiments identify usually only one \( \eta \) (and DM2 reports opposite decay modes)
- Central hadroproduction: no observation

**\( \eta(1405) \): gluonium candidate**
- Dominant decay: \( a_0(980)\pi \), direct \( \eta \pi\pi \), \( K\bar{K}\pi \)
- Not observed in \( \gamma\gamma \) collisions
- Large production in gluon-rich environments
  - \( J/\psi \) radiative decays
  - Peripheral hadroproduction (BNL E769, E852)
  - \( p\bar{p} \) annihilation at rest in LH\(_2\) target (S-wave enhancement)
- Estimated glue content: \( \sim 78\% \) (Li, EPJ C28, 335 (2003))
- Contrary to LQCD expectations: lightest pseudoscalar glueball expected above 2 GeV

**\( \eta(1475) \): s\bar{s} 2S excitation? (first \( \eta' \) radial excitation)**
- Dominant decay: \( \bar{K}K^* + \text{c.c.} \)
- Observed in \( \gamma\gamma \) collisions by L3
- Not observed in \( \eta\pi\pi \)
- If \( \eta(1475) \) is the 2S s\bar{s}: no available slot for \( \eta(1405) \) in the CQM
- The width matches with the value expected in \( ^3P_0 \) model for the radially excited s\bar{s} state
- Flaw: lack of observations in \( K\cdot p \)
OPEN/HIDDEN STRANGENESS IN PHOTOPRODUCTION REACTIONS
Meson spectroscopy with e.m. probes

- The electromagnetic interaction is weaker than the strong one and can be calculated perturbatively with high precision (based on well-known QED)
  - Scattering: one-photon exchange approximation

- Meson photoproduction: high probability of spin-1 meson production from photons

\[ \pi (K)N: \text{Need spin-flip for exotic quantum number} \]

\[ \gamma N: \text{No spin-flip for exotic quantum number} \]

- Expected production rate for exotics and conventional mesons: comparable
- \( \bar{s}s \) coupling to the photon relatively large (beam spin vector)
Photoproduction experiments today: JLAB

- High intensity real and virtual photon beams
- Able to measure exclusively the production reactions and the decays of the emitted particles
- Requirements:
  - Good acceptance, momentum resolution, particle id capabilities

**Hall-D - GlueX Detector**

- Good hermeticity
- Uniform acceptance
- Limited resolution
- Limited pID

**Hall-B - CLAS12 Detector**

- Good resolution
- Good pID
- Reasonable hermeticity
- NON-Uniform acceptance
STRANGEONIA PHOTOPRODUCTION WITH CLAS: EXPLORATORY SEARCHES
CLAS @ 6 GeV
The $\eta \phi$ decay channel: preliminary observations with CLAS6 data

- g12 dataset analysis (M. Saini, FSU, 2012):
  - $\gamma p \rightarrow pK^+K^-\eta_{\text{miss}}$ (photons up to 5.45 GeV/c)
  - Largest sample collected for final state (909 events)
  - A few hints of possible signals emerge in i.m. spectrum
The $(K\bar{K}\pi)$ invariant mass system

Blue: **No K* in the data**

Events within ±1.5σ from the peak central value are excluded

Signals of $f_1(1285)$: its decay in $K^*K$ has never been seen (anti-cut)

No signal for an isovector structure

\[ \gamma p \rightarrow (K^+K^0_{S\pi^-}\text{miss})p \]

\[ \gamma p \rightarrow (K^+K^-\pi^0\text{miss})p \]

\[ \gamma p \rightarrow (K^-K^+\pi^-)n \]
The (φπ) invariant mass system

• Cyan histogram: no K* in the sample

• Hole at about 1450 MeV (where the C(1480) had been observed)

• Clean signal of f_1(1285)/b_1(1235)
  • Γ f_1: 25 MeV narrow
  • Γ b_1: ~140 MeV

• Signal of φ(1680)?
OUTLOOK: CLAS12 PERFORMANCE AND POTENTIALITIES
The CLAS12 Experiment

- **Forward detector**
  - Torus Magnet
  - Forward SVT tracker
  - HT Cherenkov counter
  - Drift chamber system
  - LT Cherenkov counter
  - Forward TOF system
  - Preshower calorimeter
  - EM calorimeter (EC)

- **Central detector**
  - Solenoid magnet
  - Barrel silicon tracker
  - Central TOF

- **Proposed add-ons**
  - Micromegas (CD)
  - Neutron Detector (CD)
  - RICH Detector (FD)
  - Forward tagger (FD)
Low $Q^2$ quasi-real photoproduction

- Electron scattering at “0” deg (2.5°-4.5°)
  - Low $Q^2$ virtual photon $\Rightarrow$ quasi real
- Photon tagging: detection of electron at small angles
  - High energy photons: 6.5 - 10.5 GeV
  - To be accomplished by a “Forward Tagger”

- Quasi real photons: linearly polarized
  - Polarization: 70%-10%, measured event by event
- **High luminosity**: $N_\gamma \sim 5 \times 10^8$, $L \sim 10^{35}$ cm$^{-2}$s$^{-1}$ on 5 cm LH$_2$ target
  - Thin targets can be used
Search for strange hybrids with CLAS12: $\gamma p \rightarrow p \phi \pi^0$

- Production cross section: 10 nb
- CLAS12 acceptance: $\sim$10%
- Good $\pi/K$ separation power required for momenta up to 2.6 GeV/c
- Simulation: good background rejection capabilities using kin. fit and pid of CLAS12
- Expected events in 80 data taking days @ full luminosity: $\sim$ 3000 evts/mass bin
- Expected trigger rate: $<$ 10 kHz
Search for strange hybrids with CLAS12: $\gamma p \rightarrow p \phi \eta$ events with CLAS12 (lab emission angle distribution)

- Acceptance evaluation of $\gamma p \rightarrow p \phi(1850) \rightarrow p\eta\phi \rightarrow pK^+(K^-)_{\text{miss}}\gamma\gamma$ events with CLAS12 (lab emission angle distribution)
  - Good acceptance for neutrals, sizeably increased by FT calorimeter: overall acceptance > 10%

- Expected cross section for strangeonia production: O(10 nb)
  - About half of BR($K^+K^-$)
Summary and Conclusions

• Light meson spectrum with open and hidden strangeness still to be fully understood
  – Many observations in different reactions
  – Many confirmations and many disagreements
  – Too many states observed to be arranged in available CQM slots
    • Exotica? Glueballs? Hybrids?
  – Too few ordinary states (radial excitations) observed where expected

• Photoproduction reactions can be studied now with intense beams at new generation experiments. Expected to be an efficient source of:
  – $s\bar{s}$ pairs, due to the spin vector nature of the photon beam
    • Open and hidden strangeness (strangeonia) mesons
  – spin-1 hybrid states

• Photoproduction: ideal place to study benchmark decay channels
  – Promising outlook for smoking gun decay channels: $\eta\phi$, $\eta'\phi$, $\phi\phi$, $\phi\pi$:
    • $\text{BR}(\eta\phi)/\text{BR}(K^+K^-) = 0.5$
  – Limited outcome from other spectroscopy experiments in the last decade