STRANGE MESON SPECTROSCOPY AT CLAS AND CLAS12

Alessandra Filippi
INFN Torino, Italy

Pion-Kaon Interactions Workshop, JLAB, February 14-15, 2018
Outline

• Introduction
  – Light mesons decaying to $K\bar{K}$ and $K\bar{K}\pi$: open vs hidden strangeness
  – Exotic strangeonia and expected channels

• Studies of photoproduction reactions by real photons: CLAS6
  – The $K\bar{K}$ system: $K^+K^-$ and $K_SK_S$
  – The $K\bar{K}\pi$ and $K\pi\pi$ systems
  – The $\phi\eta$ system

• Studies of photoproduction reactions by virtual photons: CLAS12

• Summary and Conclusions
Introduction: 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, ~13 have been observed
  - Strangeonia: $s\bar{s}$
    - Of 22 expected states below 2.1 GeV, <10 are steadily established

- Strangeonium experimental signatures much less known (and clear) than charmonium

- Large probability of:
  - strong mixing with light mesons & other expected (but still unobserved) structures
  - Overlap of broad states
  - Decay channels shared

Godfrey, Napolitano, Rev. Mod. Phys. 71 (1999), 1411
The meson spectrum + gluons: exotics

- The meson spectrum bears also the information about gluons, which bind quarks

- Which is the expected signature of gluonic degrees of freedom?
  - Observation of extra states possibly with quantum numbers not allowed by CQM

- New states with gluonic content:
  - Glueballs (ggg)
  - Hybrids (q\bar{q}g)
  - Multiquark/molecular states

**EXOTICS**
Remarkable agreement of most recent LQCD calculation with the expected meson spectrum
BUT: the lightest exotic of the spectrum now expected at 1600 MeV (1⁻⁺) and 2 GeV (0⁺⁻)
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

- 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-strangeness 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 $n\bar{n} \leftrightarrow$ gluons $\leftrightarrow s\bar{s}$ mixing, especially in the scalar $0^+$, **pseudoscalar** $0^+$ and $2^+$ sectors
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

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

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

- Expected production rate for exotics and conventional mesons: comparable

- \( \bar{q}s \) coupling to the photon relatively large (beam spin vector)
The $K^+K^-$ system: $\gamma p \rightarrow pK^+K^-$

Physics case: investigation of light meson resonance spectrum
- $\phi(1020)$ main decay mode
- possible sub-threshold decay of $f_0(980)$ and $a_0(980)$ scalars
- issues: $\sigma$ production? Other scalars? $f_0(980)$ coupling to $\pi\pi/K\bar{K}$?

- CLAS6 g11 data set:
  - $E_\gamma = (3-3.8)$ GeV
  - $-t: (0.6-1.3)$ GeV$^2$
  - $p$ and $K^+$ detected in CLAS, $K^-$ reconstructed by missing mass
    - $\pi/K$ misidentification: 10-15%

- Low mass region selected
  - $m_{pK^-} > 1.6$ GeV
  - Baryonic resonance contributions ($\Lambda(1520)$) removed, no overlap
The $K^+K^-$ system: $\gamma p \rightarrow pK^+K^-$

- Study of S-P wave interplay in the $K\bar{K}$ system
  - Cross-sections extraction in each partial wave through likelihood fits

- Method: moments analysis

$$\langle Y_{LM} \rangle = 4\pi \int d\Omega_K \frac{d\sigma}{dtdM_{KK}d\Omega_K} Y_{LM}(\Omega_K)$$

- Moments can be expressed as bilinear combination of partial waves, depending on $L$, $M$ and photon and proton helicities
- Amplitude parameterizations:
  - S wave: $\rho, \omega$ exchange in t-channel
  - P-wave: Pomeron exchange
Physics case: search for a scalar glueball in its kaonic decay

- $K_SK_S$ system: $J^{PC} = (even)^{++}$
- light scalar sector: several candidates, too many states for the nonet
  - $f_0(600)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1700)$, ...
- no study yet in photoproduction reactions

CLAS6 g12 data set:
- $E_\gamma = (2.7 - 3) \&\& (3.1 - 5.1)$ GeV
- $4\pi$ detected in CLAS, $p$ reconstructed by missing mass
- High correlation between $K_S$ pairs

Selection in $t$ ranges
- Low $t$: resonance production in $t$-channel
- Wider $t$ range for $s$-channel production
The $K_S K_S$ system: $\gamma p \rightarrow p K_S K_S$

- Clean signal of $f_0(1500)$ for $|t| < 1$ GeV$^2$, no indication for $|t| > 1$ GeV$^2$
  - t-channel process
  - Good glueball candidate??
- Low acceptance at fw/bw angle: no PW analysis possible
- Angular analysis of Gottfried-Jackson distributions, comparison with simulations
  - S-wave dominance, small D-wave contribution above 1550 MeV

S. Chandavar, UOhio, 2017
arXiv: 1712.02184
The $\bar{K}K\pi$ system: $\gamma p \rightarrow pK^0K^\mp\pi^\mp$

Physics case: superimposition of several axial/scalar states in the 1.3-1.5 GeV mass range with decay in $\bar{K}K\pi$

- $J^P =$ (odd)$^+$ or $J^P =$ (even)$^-$
- $\eta$-like pseudoscalars $0^{-+}$: all of them decay to $\bar{K}K\pi$, $K^*K$, $a_0(980)\pi$
- Axial states $1^{++}$:
  - $f_1(1285)$: not seen in $K^*K$
  - $f_1(1420)$: favored candidate as hybrid $q\bar{q}g$, or 4q state, or $K^*K$ molecule
  - Other: $f_1(1510)$, isovector $a_1(1420)$…

- CLAS6 g11a data set:
  - $E_\gamma =$ (3-3.8) GeV
  - $p$, $K^\pm$, $\pi^\mp$ detected in CLAS, $K^0$ from missing mass
  - Kaon identification by TOF
  - Study of the $p\pi^+\pi^-\eta$ and $p\pi^+\pi^-\gamma$ channels on the same sample
The $K\bar{K}\pi$ system: $\gamma p \rightarrow pK^0K^{\pm}\pi^\mp$

- No evidence found for higher mass $\eta(1405)$, $\eta(1470)$, $f_1(1420)$, $f_1(1510)$
- First observation in photoproduction at $\sim 1280$ MeV, studied in $\pi^+\pi^-\eta$
  - $M = (1281.0 \pm 0.8)$ MeV
  - $\Gamma = (18.4 \pm 1.4)$ MeV
    - More compatible with $f_1(1285)$ than $\eta(1295)$
  - Differential cross sections: flatter trend as compared to $\eta^\prime(958)$
The $K\bar{K}\pi$ system: $\gamma p \rightarrow pK^0K^{\pm}\pi^{\mp}$

- Poor match of the differential cross sections with expectations from t-channel models
  - s-channel substantial contribution?
  - Dynamically produced state via s-channel involving N* excitations or KK* molecular interactions?
  - Larger support for $f_1(1285)$ identification
- First determination of the relative branching ratio: $\Gamma(K\bar{K}\pi)/\Gamma(\eta\pi\pi) = 0.216\pm0.032$
  - Consistent with PDG value: $0.171 \pm 0.013$
  - Not known for $\eta(1295)$
The $K\pi\pi$ system: $\gamma p \rightarrow \Lambda K^+\pi^+\pi^-$

Physics case: search for excited strange mesons

- Low mass region (1-1.5 GeV) extensively studied in past diffractive experiments: $K_1(1270)$, $K_1(1400)$, $K^*(1410)$
- Little is known in the (1.5-2) GeV mass range: $K(1630)$, $K_1(1650)$
- None of these states ever observed in photoproduction (peripheral production: low momentum transfer events)

- CLAS6 g12 data set:
  - $E_{\gamma} = (4.40-5.45)$ GeV
  - Selection of $pK^+\pi^+\pi^-\pi^-$ exclusive final state
  - $\Lambda \rightarrow \pi^-p$ selection by invariant mass
  - Background from $\Sigma^- (1385) \rightarrow \Lambda \pi^-$ decay removed
  - Background from $\pi/K$ misidentification removed

M. Al Ghoul, FSU, 2016
The $K\pi\pi$ system: $\gamma p \rightarrow \Lambda K^+\pi^+\pi^-$

Partial wave analysis 16K evts

- $1^+S$:
  - $\rightarrow K\rho$: observation of $K_1(1270)$ and $K_1(1650)$
  - $\rightarrow K^*\pi$: observation of $K_1(1400)$

- $1^-P$:
  - $\rightarrow K\rho$: observation of $K^*(1650)$?
  - $\rightarrow K^*\pi$: observation of $K^*(1410)$
The $\eta\phi$ decay channel: $\gamma p \rightarrow pK^+K^-\eta$

Physics case: search for a $1^{++}$ strangeonium hybrid

- $g12$ dataset analysis:
  - $\gamma p \rightarrow pK^+K^-\eta_{\text{miss}}$
  - real photons up to 5.45 GeV/c
- Largest sample collected for final state (909 events)
STRANGE MESON SPECTROSCOPY WITH VIRTUAL PHOTONS IN CLAS12
Photoproduction experiments at JLAB today

- 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
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: ~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: ~ 3000 evts/mass bin
- Expected trigger rate: < 10 kHz
Search for strange hybrids with CLAS12: $\gamma p \rightarrow p \phi \eta$

- Acceptance evaluation of $\gamma p \rightarrow p \phi(1850) \rightarrow p \eta \phi \rightarrow p K^+(K^-)_{\text{miss}} \gamma \gamma$ 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: $O(10 \text{ nb})$
  - About half of $\text{BR}(K^+K^-)$
Summary and Conclusions

• Light meson spectrum with open and hidden strangeness still to be fully understood
  – Many observations in different reactions
  – Many confirmations, many disagreements
  – Too many states observed to be arranged in available CQM slots
  – 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:
  – $sar{s}$ 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