Kaon Spectroscopy with Kaon Beam

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COMPASS
The Quest for exotic Forms of Matter

In principle, QCD permits color-neutral meson-like states in addition to $|q\bar{q}\rangle$.

- **Quarkonia**
  
  $|q\bar{q}\rangle$

- **Hybrids**
  
  $|q\bar{q}g\rangle$

- **Glueballs**
  
  $|g\bar{g}\rangle$

- **Multi-quarks**
  
  $|q^2\bar{q}^2\rangle$

**Physical mesons**

- Linear superpositions of all allowed basis states

**Exotic mesons**

- States with small or vanishing $|q\bar{q}\rangle$ component
- Appear either as supernumerous states or mix with conventional states with same quantum numbers
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Why Kaon Spectroscopy?

PDG 2016: 25 kaon states below 3.1 GeV/c²

- Only **12** kaon states in summary table, **13** need confirmation
- Many predicted quark-model states still missing
- Some hints for supernumerous states

![Mass Spectrum of Kaons](image-url)

[Courtesy of S. Wallner, TUM]
Why Kaon Spectroscopy?

Many kaon states need confirmation

- Little progress in the past
  - Most PDG entries more than 30 years old
  - Since 1990 only 4 kaon states added to PDG (only 1 to summary table)

Kaon spectrum crucial to understand light-meson spectrum

- Identify supernumerous states by completing SU(3)$_{\text{flavor}}$ multiplets
  - E.g. $J^P = 0^+$ multiplet with $a_0(980)$, $K_0^*(800)$ [or $\kappa$], $f_0(500)$ [or $\sigma$], and $f_0(980)$ is hypothesized to be tetra-quark multiplet
  - But $K_0^*(800)$ still disputed

Kaon spectrum required to analyze heavy-meson decays

- E.g. search for $CP$ violation in multi-body decays
e.g. $B^\pm \rightarrow D^0 K^\pm$ with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$
  - Dalitz-plot amplitude analysis requires accurate knowledge of resonances in $K_S^0 \pi^\pm$ subsystems
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Production of excited Kaons

- High-energy kaon beam on stationary target (proton or nucleus)
- Excitation of beam kaon into $X$ via Pomeron/Reggeon exchange
- Dissociation of $X$ into various $n$-body mesonic final states
  - $\pi, K, \eta, \eta', \ldots$
- Not very selective: all kaon states can appear as $X$
- Large cross section
How to get more Data?

Main limitation

- **Kaon content** of 190 GeV/c $h^-$ beam from current M2 beam line
- Composition: 97% $\pi^-$, 2% $K^-$, 1% $\bar{p}$
- Intensity of $K^-$ component at COMPASS target: $10^5$ s$^{-1}$

Goal

- Increase intensity of kaons by factor $> 10$
- Would correspond e.g. to $>10^7 K^- \pi^+ \pi^-$ events (assuming same acceptance as current experimental setup)
  $\Rightarrow$ approximately $10 \times$ world data

Possible solution

RF-separated beam at M2 beam line (see talk by J. Bernhard)
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Kaon beam experiments

- **J-PARC K10 beam line**
  - Separated $\bar{p}$ and $K^-$ beams with 2 to 10 GeV/$c$ and $10^7 K^-$ per spill
  - Main focus on hyperon spectroscopy, di-baryons, and study of mesons in nuclear medium
  - Low beam energy
    - Separation between beam and target excitations difficult
    - More complicated production process (various Reggeons)

- **Neutral kaon beam at GlueX (Jlab)**
  - $K_L^0$ beam with 0.3 to 10 GeV/$c$ and $10^4$ s$^{-1}$ intensity
  - Main focus on hyperon spectroscopy
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Competition

Decays of $\tau$ leptons or heavy mesons

- Limited mass reach for charmed mesons and $\tau$ leptons
- Mainly BESIII, Belle II, LHCb
- Current data samples typically factor 10 smaller than existing COMPASS data set

**COMPASS:** $K^- \pi^+ \pi^-$

![Graph showing decay of $K^- \pi^+ \pi^-$ with peaks at $K_1(1270)$, $K_1(1400)$, and $K_2(1770)$]

**Belle:** $B^+ \rightarrow J/\psi K^+ \pi^+ \pi^-$

![Graph showing Belle data with $M(K\pi\pi)$ distribution]

Belle, PRD 83 (2011) 032005
Photoproduction: $\gamma p \rightarrow X p$

- **GlueX Phase IV** proposal (Jlab)
  - $100 \times 10^6 \ X \rightarrow KK\pi\pi$ events
  - $30 \times 10^6 \ X \rightarrow KK\pi$ events

- **Excited kaons appear in subsystems**
  - Could be extracted using **freed-isobar method**
  - More complicated compared to direct production
  - Possible distortions due to rescattering effects
  - More difficult to find new states
Requirements for experimental Setup

**Beam PID**

- Upgrade of CEDAR detectors
  ⇒ improve rate capability and thermal stability
- CEDAR PID requires precise measurement of beam inclination with resolution $< 40 \mu\text{rad}$ ⇒ silicon beam telescope

**Spectrometer**

- As uniform acceptance as possible
- High-precision tracking over broad kinematic range
- New vertex detector: precise measurement of vertex position
- Improved RPD: detection of target recoil particle
  - Higher resolution of exclusivity variables
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Final-state PID

- Existing RICH 1 kaon ID covers only $10 < p < 50 \text{ GeV}/c$

- More than 50% of kaons in $K^- \pi^+ \pi^-$ outside of acceptance

- Lower beam momentum $\Rightarrow$ more events in RICH 1 acceptance

- Goal: extend kaon ID to increase acceptance $\Rightarrow$ RICH 0?
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Electromagnetic calorimeters

- Efficient detection of photons over broad kinematic range is essential
- Gives access to interesting final states: $K^- \eta^{(')}, K^- \pi^0 \pi^0, K^- \omega, \ldots$

Work in progress

Detailed studies of experimental setup once beam energy is fixed
Electromagnetic calorimeters

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Work in progress

Detailed studies of experimental setup once beam energy is fixed
Conclusions

**Kaon spectroscopy**

- Many kaon states
  - Require further confirmation or more precise measurement of their parameters
  - Have not yet been found

**Future program**

- **Goal**: collect data set that exceeds existing ones by at least a factor of 10 using high-intensity RF-separated kaon beam
- **High physics potential**: rewrite PDG for kaon states above 1.5 GeV$/c^2$ (like LASS and WA03 did 30 year ago)
- No direct competitors
- Requires experimental setup with uniform acceptance over wide kinematic range (including PID and calorimeters)
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Backup slides

- Introduction
- The COMPASS Experiment at the CERN SPS
- *Example*: Analysis of $K^- \pi^+ \pi^-$ Final State
- Why do we need even larger data sets?
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“Light-meson frontier”

- Many states need confirmation in mass region $m \gtrsim 2$ GeV/$c^2$
- Many wide states ⇒ overlap and mixing
- Identification of higher excitations becomes exceedingly difficult

Main focus of current COMPASS program
Light-Meson Spectrum

“Light-meson frontier”

- Many states need confirmation in mass region \( m \gtrsim 2 \text{ GeV/c}^2 \)
- Many wide states \( \Rightarrow \) overlap and mixing
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Main focus of current COMPASS program

[Courtesy K. Götzen, GSI]
Many states need confirmation in mass region $m \gtrsim 2 \text{ GeV}/c^2$.

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[Courtesy K. Götzen, GSI]
Essentially recovers quark-model pattern
High towers of excited states
Additional hybrid-meson super-multiplet
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The COMPASS Experiment at the CERN SPS

Experimental Setup

C. Adolph, NIMA 779 (2015) 69

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Kaon Spectroscopy with Kaon Beam

Fixed-target experiment

- Two-stage spectrometer
- Large acceptance over wide kinematic range
- Electromagnetic and hadronic calorimeters
- Beam and final-state particle ID (CEDARs, RICH)
Fixed-target experiment

- Two-stage spectrometer
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- Electromagnetic and hadronic calorimeters
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Hadron spectroscopy 2008, 2009

- 190 GeV/c secondary hadron beam
  - $h^-$ beam: 97% $\pi^-$, 2% $K^-$, 1% $\bar{p}$
  - $\ell H_2$ target
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**Example: Analysis of $K^- \pi^+ \pi^-$ Final State**

- **Diffractive production** of excited kaon states $X^-$ that decay into $K^- \pi^+ \pi^-$
  - Beam-particle ID via Cherenkov detectors (CEDARs)
    - Ca. $50 \times$ more $\pi^-$ than $K^-$ in beam
  - Final-state PID via RICH detector
    - Distinguish $K^-$ from $\pi^-$ over wide momentum range
**Example: Analysis of $K^− π^+ π^−$ Final State**

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From 2008 data taking campaign
- 270,000 events
- $0.07 < t' < 0.7 \text{ (GeV/c)}^2$
- Exclusivity ensured by measuring recoil proton
  - Also suppresses target excitations
Example: Analysis of $K^- \pi^+ \pi^-$ Final State

Invariant Mass of $\pi^- \pi^+$ Subsystem

COMPASS: $K^- \pi^+ \pi^-$

![Graph showing $K^- \pi^+ \pi^-$ analysis](image1)

COMPASS 2008 negative hadron beam

$K^- p \rightarrow K^- \pi^+ \pi^- p_{\text{recoil}}$

not acceptance corrected

$\rho(770)$, $f_0(980)$, $f_2(1270)$

COMPASS: $\pi^- \pi^- \pi^+$

![Graph showing $\pi^- \pi^- \pi^+$ analysis](image2)

$\rho(770)$, $f_0(980)$, $f_2(1270)$, $\rho_3(1690)$

COMPASS, PRD 95 (2017) 032004

$m_{\pi^- \pi^+}$ spectrum contains states already known from analysis of diffractively produced $\pi^- \pi^- \pi^+$
Example: Analysis of $K^- \pi^+ \pi^-$ Final State

Invariant Mass of $K^- \pi^+$ Subsystem

- Clear $K^*(892)$ and $K_2^*(1430)$ signals
- Data set slightly larger than that of most precise previous experiment (WA03)
Example: Analysis of $K^− π^+ π^−$ Final State

Invariant Mass of $K^− π^+ π^−$ System

**COMPASS**

$0.07 < t' < 0.7 \text{(GeV/c)}^2$

**WA03 (CERN)**

$0 < t' < 0.7 \text{(GeV/c)}^2$

**Events / 10 [MeV/c^2]**

- Various potential resonance signals
- Need partial-wave analysis (PWA) to disentangle contributions from various $J^P$ quantum numbers

**ACCMOR, NPB 187 (1981) 1**
**Example: Analysis of $K^- \pi^+ \pi^-$ Final State**

**Invariant Mass of $K^- \pi^+ \pi^-$ System**

**COMPASS**

$0.07 < t' < 0.7 \text{ (GeV/c)}^2$

### Various potential resonance signals

- $K_1(1270)$
- $K_1(1400)$
- $K_2(1770)$

### Belle

$B^+ \rightarrow J/\psi K^+ \pi^+ \pi^-$

**Preliminary COMPASS 2008 negative hadron beam**

$K^- p \rightarrow K^- \pi^+ \pi^- p_{\text{recoil}}$

Not acceptance corrected

Belle, *PRD 83* (2011) 032005

- Need partial-wave analysis (PWA) to disentangle contributions from various $J^P$ quantum numbers
Partial-Wave Analysis Method

\[ I(\tau; m_X) = \left| \sum_{i} \mathcal{T}_i(m_X) \Psi_i(\tau; m_X) \right|^2 \]

- **Ansatz**: Factorization of production and decay

- **Fit model**: coherent sum of partial-wave amplitudes
- **Decay amplitudes** \( \Psi_i(\tau; m_X) \)
  - Describe kinematic distribution of partial waves
  - Calculated using isobar model and helicity formalism (Wigner \( D \)-functions)
- **Transition amplitudes** \( \mathcal{T}_i(m_X) \Rightarrow \) interesting physics
  - \( m_X \) dependence unknown
  - Extracted from data by performing PWA fit in narrow \( m_X \) bins
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Partial-Wave Analysis of $K^- \pi^+ \pi^-$ Final State

PWA model similar to WA03

$$\mathcal{I}(\tau; m_X) = \left| \sum_i \mathcal{T}_i(m_X) \Psi_i(\tau; m_X) \right|^2$$

- 6 isobars
  - $\pi^- \pi^+$ subsystem: $f_0(500)$, $\rho(770)$, and $f_2(1270)$
  - $K^- \pi^+$ subsystem: $K^*_0(800)$, $K^*(892)$, and $K^*_2(1430)$
    - $K^*_0(800)$ described by Breit-Wigner amplitude
- 19 waves = combinations of $X^-$ quantum numbers and decay modes
Example: Analysis of $K^- \pi^+ \pi^-$ Final State

Results of Partial-Wave Analysis

$1^+ \rightarrow K^*(892) + \pi^-$ in \textit{S}-wave

- Clear signals from $K_1(1270)$ and $K_1(1400)$

$2^+ \rightarrow K^*(892) + \pi^-$ in \textit{D}-wave

- Clear signal from $K_2^*(1430)$
- $K_2^*(1980)$?
**Example: Analysis of $K^- \pi^+ \pi^-$ Final State**

Results of Partial-Wave Analysis

Clear signals from $K_1(1270)$ and $K_1(1400)$

Clear signal from $K_2^*(1430)$

$K_2^*(1980)$?
**Example: Analysis of \(K^- \pi^+ \pi^-\) Final State**

Results of Partial-Wave Analysis

![Graph showing the analysis of the \(K^- \pi^+ \pi^-\) final state.](image)

2\(^-\) → \(K^*_{2}(1430)\) + \(\pi^-\) in S-wave

- Possible signals from \(K_2(1770)\) and \(K_2(1820)\)
- \(K_2(1580)\) and \(K_2(2250)\)?

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**Work in progress: improving analysis**

- Improved beam PID + data sample from 2009 run
  - ⇒ ca. 800 000 \(K^- \pi^+ \pi^-\) events
  - ⇒ world’s largest data set (4× WA03)
- Improved PWA model ⇒ clearer resonance signals
- Resonance-model fit ⇒ extraction of \(K^- \pi^+ \pi^-\) resonances and their parameters
Example: Analysis of $K^- \pi^+ \pi^-$ Final State

Results of Partial-Wave Analysis

**COMPASS 2008**

$K^- p \rightarrow K^+ \pi^- p$

$0.07 \text{ GeV}^2/c^2 < t' < 0.7 \text{ GeV}^2/c^2$

$2^- 0^+ K_2^*(1430)[02] \pi^-$

---

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**Example: Analysis of** $K^- \pi^+ \pi^-$ **Final State**

**Results of Partial-Wave Analysis**

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**Example: Analysis of $K^- \pi^+ \pi^-$ Final State**

Results of Partial-Wave Analysis

**COMPASS 2008**

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$^2O^+ K_2^*(1430)[02] \pi^-$

**Further final states accessible by COMPASS**

- Isospin partner channel $K^- \pi^0 \pi^0$
- $K^- K^+ K^-$
- $K^- \pi^0, K_S^0 \pi^-, K^- \eta^{(')}, K^- \omega$
- ...

**Possible signals from $K_2(1770)$ and $K_2(1820)$**

- $K_2(1580)$ and $K_2(2250)$?
Backup slides

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- The COMPASS Experiment at the CERN SPS
- *Example:* Analysis of $K^- \pi^+ \pi^-$ Final State
- **Why do we need even larger data sets?**
Why do we need even larger data sets?

Example: $\pi^- + p \rightarrow \pi^- \pi^- \pi^+ + p_{\text{recoil}}$

$\pi^-_{\text{beam}} \rightarrow \pi^- \pi^- \pi^+ + p_{\text{recoil}}$

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Why do we need even larger data sets?

Example: $\pi^- + p \rightarrow \pi^- \pi^- \pi^+ + p_{\text{recoil}}$

- $50 \times 10^6 \pi^- \pi^- \pi^+ \text{ events} \Rightarrow \text{approx. } 10 \times \text{world data}$
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Example: \( \pi^- + p \rightarrow \pi^- \pi^- \pi^+ + p_{\text{recoil}} \)

\[ \begin{align*}
\pi^-_{\text{beam}} & \rightarrow X^- \\
\pi^- & \rightarrow \pi^- \pi^- \pi^+ \\
\rho_{\text{target}} & \rightarrow X^- \\
p_{\text{recoil}} & \rightarrow \pi^- \pi^- \pi^+
\end{align*} \]

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**Improved sensitivity for small signals**
- E.g. surprising find: resonance-like $a_1(1420)$ signal in peculiar decay mode
- Only 0.3% of total intensity

---

![Graph showing data points and curves labeled (1), (2), and (3).](image)

1$^{++0^+}$ $f_0(980)$ $\pi P$

$0.1 < t' < 1.0$ (GeV/c)$^2$

(1) Model curve
(2) $a_1(1420)$ resonance
(3) Non-resonant term

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*COMPASS, PRL 115 (2015) 082001*
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PWA in narrow bins of four-momentum transfer squared $t'$

- Resolve $t'$ dependence of partial-wave amplitudes
- Improved separation between resonant and nonresonant components in resonance-model fits
- First extraction of $t'$ spectra of resonances from such an analysis
  $\Rightarrow$ can study production mechanism(s)
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Novel analysis technique
“freed-isobar” PWA

Conventional PWA requires complete knowledge of isobar amplitude

Novel approach: replace fixed parametrization by step-like function

- Isobar amplitude determined from data \( \Rightarrow \) reduced model dependence
- E.g. amplitude of \( \pi^- \pi^+ \) subsystem with \( J^{PC} = 0^{++} \)
  \( \Rightarrow f_0(500) (\text{?}), f_0(980), f_0(1500) \)
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[arXiv:1710.09849]

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Would allow to study $K^- \pi^+$ subsystem with $J^P = 0^+$ in $K^- \pi^+ \pi^-$

Requires huge data samples

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$0^{-+}0^+ [\pi\pi]_0^+, \pi S$

$0.194 < t' < 0.326 \ (\text{GeV}/c)^2$

$1.78 < m_{3\pi} < 1.82 \ (\text{GeV}/c)^2$

$|T^*| \approx 0.925$

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- Lower beam momentum $\lesssim 100 \text{ GeV}/c$
  - Not an issue: diffractive production depends only weakly on energy
- Estimated kaon intensity: $3.7 \times 10^6 \text{ s}^{-1}$
  - More than factor 35 increase w.r.t. conventional beam line
  - Would correspond to $10$ to $20 \times 10^6 K^−\pi^+\pi^−$ events assuming same acceptance as current experimental setup
    $\Rightarrow$ would be $\approx 10 \times$ world data
- More detailed studies needed to determine beam parameters more precisely
- Requires major investment
RF-separated Kaon Beam

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