Prospects for Measuring \( BR(K^0_L \rightarrow \pi^0 \nu \bar{\nu}) \) at the CERN SPS

Phil Rubin, George Mason University

On behalf of
Unitary Triangle
Checking Unitarity with Rare Kaon Decays
$K \rightarrow \pi \nu \bar{\nu}$: Clean

- Loops dominated by top
- Hadronic elements from measured Ke3 rates
- No long-distance contributions from intermediate photons
SM Expected Rates

\[ BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11} \]

\[ BR(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) = (3.4 \pm 0.6) \times 10^{-11} \]

Buras et al., 2015
Sensitive to New Physics

\[ \mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \quad [10^{-11}] \]

\[ \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \quad [10^{-11}] \]

MFV:
\[ \arg \Delta_L = \arg V_{td}V_{ts}^* \]

\[ \Delta_L \text{ or } \Delta_R \text{ only:} \]
\[ |\epsilon_K|^{NP} \propto \text{Im} \frac{\Delta^2_{L(R)}}{M^2_{Z'}(c)} \]

General NP \[ \propto \frac{|\Delta_L + \Delta_R| \times |\epsilon''_K|}{M^2_{Z'}(c)} \]

Current Status

- $BR(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-11}$
  
  BNL E787 and 949 (7 events)
  
  NA62 (Perrin-Terrin)

- $BR(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) < 2.6 \times 10^{-8}$ (90%)
  
  KEK E391a
  
  KOTO
KOTO

- 2015: Took x20 data than 2013 run
- 2016: Running now
- 2018: Add MPPCs on CsI calorimeter
- 2019?: Increase beam power 42 kW → 100 kW
- SM sensitivity
- KOTO-2: ~10 events/yr
Can It Be Done with the SPS?

- High-energy kaons
  - Photon vetoing easier, but larger veto volume required
  - Photon vetoing needs to extend only to 100 mr (polar angle)

Primary background from $K_L^0 \rightarrow \pi^0 \pi^0$
Beam

- Primary beam momentum: $p_0 = 400$ GeV
- Beryllium rod target, thickness $L = 400$ mm ($0.95\lambda_{\text{int}}$)
- Targeting angle: $\theta = 2.4$ mrad
- Secondary beam angular acceptance: $\Delta \theta = 0.3$ mrad, conical

\[ \bar{p}_{KL} = 97 \text{ GeV} \]
Beam

\[
\frac{N(\gamma)}{N(K_L[\text{FV}])} \sim 80 \quad \frac{N(n)}{N(K_L[\text{FV}])} \sim 120
\]

\[
\frac{(N(K_L[\text{FV}])^2}{N(\gamma) \sin \theta} \quad \frac{(N(K_L[\text{FV}])^2}{N(n) \sin \theta}
\]
Beam

- Secondary beam: $2.8 \times 10^{-5} K^0_L$ per proton
- Spill length 4.8 s and duty cycle 16.8 s
- Effective spill length: 3 s
- Primary beam intensity: $2 \times 10^{13}$ ppp
- Nominal data-taking period: 200 days/year with 50% experimental uptime

Current beamline cavern and experimental area require significant upgrades
Detector—Baseline Model
Detector—Baseline Model

- Reuse NA48 LKr calorimeter
  - $1 - \epsilon_\gamma < 9 \times 10^{-6}$, $E_\gamma > 10$ GeV
  - Photon cluster separation resolvable to about 6 cm
  - $\sigma_t = 2.5 \text{ ns}/\sqrt{E} \text{ (GeV)}$ May need to be improved
Detector—Baseline Model

- High-efficiency photon vetoes around an 140-m-long vacuum volume covering out to 100 mrad polar angle

\[ E \text{ vs } \theta \text{ of Otherwise Undetected Photons} \]
Detector—Baseline Model

• Small-angle vetoes
  – Intermediate Ring calorimeter (IRC): photons that pass through LKr bore (downstream decays)
  – Small-Angle Calorimeter (SAC): photons heading down the beam pipe, as well as neutral beam
    • Among the toughest experimental challenges
    • Absorber after target can modulate neutral beam
    • Studies ongoing with crystals
Detector—Baseline Model

- Charged-particle vetoes
  - Thin detector(s) (scintillator?) upstream
  - Hadronic calorimeter downstream
Sensitivity Studies

- Two simulation packages
  - Fast MC
    - hard-coded geometry
    - straight-line particle propagation
    - parameterized detector efficiencies
  - Geant4-based MC
Sensitivity Studies

$K^0_L \rightarrow \pi^0 \nu \bar{\nu}$ Simulation
Sensitivity Studies

$K_L^0 \rightarrow \pi^0\pi^0$ Simulation

same $\pi^0$ (even) \quad different $\pi^0$s (odd) \quad 2 merged + 1 (fused)
## Sensitivity Studies

<table>
<thead>
<tr>
<th>Analysis stage</th>
<th>$\pi^0\nu\bar{\nu}$</th>
<th>$\pi^0\pi^0$</th>
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<tbody>
<tr>
<td>Generated</td>
<td>956.3 M (100 kyr)</td>
<td>1,215 G (5 yr)</td>
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### Cuts

- $2\gamma$ on LKr
- $105 \text{ m} < z_{\text{rec}} < 155 \text{ m}$
- $r_{\text{min}} > 35 \text{ cm}$
- $p_{\perp} < 0.12 \text{ GeV}$
- All cuts, 1 yr

Without charged-particle vetoes,

\[(BR \times \epsilon)_{K\mu3} = 3 \times 10^{-5}\]
\[(BR \times \epsilon)_{\pi^0\nu\bar{\nu}} = 8 \times 10^{-14}\]

With, $< 1 / \text{yr}$ expected
Conclusion

• A competitive and useful decay-in-flight measurement of $BR(K^0_L \rightarrow \pi^0 \nu \bar{\nu})$ seems feasible

• Design challenges—primarily in background suppression and small-angle activity—remain to be worked out

• Alternative detector elements being considered

• A reasonable time frame for such an experiment would be LHC after run 4