Light Scalars and the KOTO Anomaly

arXiv:1911.10203 (accepted in PRL)

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In collaboration with D. Egaña-Ugrinovic and Patrick Meade

APS April Meeting, April 21, 2020
KOTO Measures Rare Kaon Decays

KOTO is an experiment at J-PARC searching for the rare decay of a neutral Kaon into a pion + neutrinos

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

Buras et al., arXiv:1503.02693
KOTO Measures Rare Kaon Decays

Measure angle between photons and their energies

Demand no other activity in the detector
The KOTO “Anomaly”  

As of Fall 2019

SM Signal + Background expectation: $0.1 \pm 0.02$ events

Single Event Sensitivity: $6.9 \times 10^{-10}$
The KOTO “Anomaly”

As of Early 2020

SM Signal + Background expectation: $0.39 \pm 0.08$ events

Single Event Sensitivity: $7.1 \times 10^{-10}$

Including preliminary estimate of charged Kaon contamination

Shinohara, KAON 2019
Confronting the Anomaly

The 2 events are consistent with:

$$\text{Br}(K_L \rightarrow \pi^0 + \text{inv.})_{\text{KOTO}} = 1.4^{+1.8(3.7)}_{-0.9(1.2)} \times 10^{-9}$$

Theoretical perspective: are there simple & motivated ways of explaining this result with new physics?

Yes!

The absolute simplest: add a scalar singlet to the SM
Higgs Portal Explanation of KOTO

Egana-Ugrinovic, SH, Meade [1911.10203]

Add to the SM a scalar singlet, mixing with the Higgs:

\[ \zeta (H^+ H \varphi) \rightarrow \zeta (v h \varphi) \rightarrow \sin \theta \sim \zeta v / m_h^2 \]

All couplings dictated by the mixing angle

Scalar is long lived

escapes KOTO undetected, mimicking the neutrinos
Higgs Portal Explanation of KOTO
Egana-Ugrinovic, SH, Meade [1911.10203]

Blue: preferred KOTO region (2 events)
Dashed-gray: scalar lifetime

$\sin \theta$

$10^{-2}$

$10^{-3}$

$10^{-4}$

$1 \text{ km}$

$10 \text{ km}$

$100 \text{ km}$

$10^3 \text{ km}$

Belle

Beam Dumps

E949

NA62

KOTO Signal

$m_\phi (\text{MeV})$

50

100

150

200
Higgs Portal Explanation of KOTO
Egana-Ugrinovic, SH, Meade [1911.10203]

Consistent with all other bounds and explains the 2 events!
Bounds: Charged Kaon Decays

The same diagram also leads to charged Kaon decays:

\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \]


Constrained by NA62 and E949

For charged pions, can reconstruct the missing mass

\[ \rightarrow \text{Large background when } m_\varphi \sim m_\pi \]

(“predicted” by Hou et al., 1412.4397, 1611.09673)

“‘Blessed are the Blind, for they shall see the Heavens open’ …

… So, please: Analyze, KOTO, Analyze!”
Bounds: Proton Beam Dumps

CHARM: 400 GeV (SPS) proton beam dump

\[ K \rightarrow \pi \varphi \]

\[ \eta \rightarrow \pi \varphi \]

400 GeV beam

\[ \varphi \rightarrow e^+ e^- \]

35 m

5 m

Bounds cover a large portion of the window left open by NA62


Beam Dumps lead to tension with “intermediate lifetime” explanations of the KOTO events
What if we change the scalar couplings?

Different Flavor textures let us investigate alternative solutions to KOTO

$$\frac{C_{ij}^u}{M} \varphi H Q_i \bar{u}_j \rightarrow \begin{cases} g_u \varphi u \bar{u} \\ g_c \varphi c \bar{c} \\ g_t \varphi t \bar{t} \end{cases}$$

Coupling predominantly to charm leads to intermediate-lifetime scalars

Similar to Minimal Higgs Portal!
What if we change the scalar couplings?

Different Flavor textures let us investigate alternative solutions to KOTO

\[
\frac{C_{ij}}{M} \varphi H Q_i \bar{u}_j \rightarrow \begin{cases} 
  g_u \varphi u \bar{u} \\
  g_c \varphi c \bar{c} \\
  g_t \varphi t \bar{t}
\end{cases}
\]

Coupling predominantly to charm leads to intermediate-lifetime scalars

What if we change the scalar couplings?
Summary

• There’s a large anomaly in rare Kaon decays

• Events can be explained by the *simplest* extension of the SM

• Strongest constraints come from beam-dumps and charged Kaons

• Non-minimal solutions using a shorter lifetime can work, but are in tension with beam dump constraints

What’s Next?

• Look out for KOTO final analysis (expected to finish this Summer)

• More data from 2019 KOTO Run

• New NA62 results? (Volpe, Tues. Flavor Session)

• Future LLP Experiments? (See PBC Summary: 1901.09966)

DM Implications: Pospelov, Ritz, Voloshin 0711.4866, Krnjaic, 1512.04119
Backup
2 Events vs. 3 Events

3 events

2 events
2 Events vs. 3 Events

3 events

2 events
Future Constraints (PBC)
2016-2018 Background Estimation
from Satoshi Shinohara, KAON 2019

S.E.S : $6.9 \times 10^{-10}$

<table>
<thead>
<tr>
<th>#BG</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>KLpi0pi0</td>
<td>&lt;0.18</td>
</tr>
<tr>
<td>KLpi+pi-pi0</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>KL3pi0 (overlapped pulse)</td>
<td>&lt;0.04</td>
</tr>
<tr>
<td>Ke3 (overlapped pulse)</td>
<td>&lt;0.09</td>
</tr>
<tr>
<td>KL2gamma</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>Upstream $\pi^0$</td>
<td>0.00 ± 0.00</td>
</tr>
<tr>
<td>Hadron cluster</td>
<td>0.02 ± 0.00</td>
</tr>
<tr>
<td>CV-pi0</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>CV-eta</td>
<td>0.03 ± 0.01</td>
</tr>
<tr>
<td>Total</td>
<td>0.05 ± 0.02</td>
</tr>
</tbody>
</table>

Preliminary

observed expectation
# Updated Background Estimates

As of January, 2020

from T. Nomura, J-PARC Meeting

<table>
<thead>
<tr>
<th>source</th>
<th>$#BG$ (U.L. at 90% C.L.)</th>
<th>$#BG$ (U.L. at 68% C.L.)</th>
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<tbody>
<tr>
<td>$K_L \to 2\pi^0$</td>
<td>&lt;0.09</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>$K_L \to \pi^0\pi^0\pi^0$</td>
<td>&lt;0.02</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>$K_L \to 3\pi^0$ (overlapped pulse)</td>
<td>&lt;0.04</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>$Ke3$ (overlapped pulse)</td>
<td>&lt;0.09</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>$K_L \to 2\gamma$</td>
<td>0.001±0.001</td>
<td>0.001±0.001</td>
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<tr>
<td>$Ke3$ ($\pi^0$ produced)</td>
<td>&lt;0.04</td>
<td>&lt;0.02</td>
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<tr>
<td>radiative $Ke3$</td>
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<td>&lt;0.023</td>
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<tr>
<td>$Ke4$</td>
<td>&lt;0.04</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>$K_L \to ee\gamma$</td>
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<td>&lt;0.05</td>
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<tr>
<td>$K_L \to \pi\pi\pi$</td>
<td>&lt;0.03</td>
<td>&lt;0.02</td>
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<tr>
<td>$K_L \to 2\gamma$ (core-like)</td>
<td>&lt;0.11</td>
<td>&lt;0.06</td>
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<tr>
<td>$K_L \to 2\gamma$ (halo)</td>
<td>&lt;0.19</td>
<td>&lt;0.10</td>
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<tr>
<td>$Ke3$ ($\pi^0\to\pi^0e^+\nu$)</td>
<td>&lt;0.01</td>
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**New**

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</thead>
<tbody>
<tr>
<td>$K^\pm \to \pi^0\nu\bar{\nu}$</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
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<tr>
<td>$K^\pm \to \pi^0e^+\nu$</td>
<td>0.29±0.08</td>
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<tr>
<td>$K^\pm \to \pi^0\mu^+\nu$</td>
<td>&lt;0.02</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Neutron</td>
<td>Upstream $\pi^0$</td>
<td>0.001±0.001</td>
</tr>
<tr>
<td>Hadron cluster</td>
<td>0.02 ±0.00</td>
<td>0.02 ±0.00</td>
</tr>
<tr>
<td>CV-$\pi^0$</td>
<td>&lt;0.10</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>CV-$\eta$</td>
<td>0.03±0.01</td>
<td>0.03±0.01</td>
</tr>
<tr>
<td>Total</td>
<td>central value</td>
<td>0.34(±0.08)</td>
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</table>

**Updated**

### Branching ratio

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching ratio</th>
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<tbody>
<tr>
<td>$K^\pm \to \pi^0\nu\bar{\nu}$</td>
<td>20.7%</td>
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<tr>
<td>$K^\pm \to \pi^0e^+\nu$</td>
<td>5.1%</td>
</tr>
<tr>
<td>$K^\pm \to \pi^0\mu^+\nu$</td>
<td>3.4%</td>
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</tbody>
</table>
Updated Background Estimates
As of January, 2020

from T. Nomura, J-PARC Meeting (Jan. 17, 2020)

At KAON 2019
S.E.S : 6.9 \times 10^{-10}

As of today
S.E.S : 7.1 \times 10^{-10}

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observed expectation

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KOTO 2015 Result

BR < $3.0 \times 10^{-9}$
(90% C.L.)
KOTO Runs

From Taku Yamanaka, KAON2019

Diagram showing the KOTO runs from 2012 to 2018, with data points and notes on published results, finalizing analysis, and new data.