Rare K-meson and lepton decays
A.M. Baldini – INFN Pisa
1) The contribution to these processes due to the Standard Theory is strongly suppressed ($<10^{-10}$) and calculable with excellent precision ($\sim\%$).

2) They are very sensitive to possible contributions from New Physics.

$$R_K = \frac{\Gamma(K^+ \rightarrow e^+\nu)}{\Gamma(K^+ \rightarrow \mu^+\nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{\text{rad.corr.}})$$

\[
(2.477 \pm 0.001) \times 10^{-5} \quad \text{(V. Cirigliano, I. Rosell, JHEP 0710:005 (2007))}
\]

New Physics could contribute to up to 1% (Masiero, Paradisi, Petronzio, PRD 74, 2006)

3) In the lepton case SM prediction unobservable! $\tau \rightarrow l\nu$, $\mu \rightarrow e\gamma$

Observation = New Physics (Isidori’s talk)
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ History

E787/E949 Final: 7 events observed
$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$

Standard Model:
$B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$

Ratio P996/E949
$11.3^{+3.3}_{-2.3}$ Detector acceptance
$6.3 \pm 2.1$ Stopped kaons per hour
$5.3$ Hours per year

Tevatron used as a stretcher
200 events/year

J. Lewis Poster at this Conference
At CERN SPS

Unseparated $K^+$ (75 GeV/c) decay in flight

$$m_{\text{miss}}^2 \approx m_K^2 \left( 1 - \left| \frac{P_{\pi}}{P_K} \right| \right) + m_\pi^2 \left( 1 - \left| \frac{P_K}{P_\pi} \right| \right) - |P_K||P_\pi| \theta_{\pi K}^2$$

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \mu^+\nu (K_{\mu2})$</td>
<td>0.64</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0 (K_{\pi2})$</td>
<td>0.21</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^+$</td>
<td></td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0\pi^0$</td>
<td>0.07</td>
</tr>
</tbody>
</table>

• R&D/Construction phase
• Technical run: end of 2012
### NA62 Sensitivity

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>**Signal: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ SM ($\text{flux} = 4.8 \times 10^{12}$ decay/year)</td>
<td>55 evt/year</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0$ ($\eta_{\pi^0} = 2 \times 10^{-8} (3.5 \times 10^{-8})$)</td>
<td>4.3% (7.5%)</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu$</td>
<td>2.2%</td>
</tr>
<tr>
<td>$K^+ \rightarrow e^+\pi^+\pi^-$</td>
<td>$\leq 3%$</td>
</tr>
<tr>
<td>Other 3-track decays</td>
<td>$\leq 1.5%$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0 \gamma$</td>
<td>$\sim 2%$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu \gamma$</td>
<td>$\sim 0.7%$</td>
</tr>
<tr>
<td>$K^+ \rightarrow e^+(\mu^+) \pi^0 \nu$, others</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>Expected background</strong></td>
<td>$\leq 13.5%$ ($\leq 17%$)</td>
</tr>
</tbody>
</table>

**Definition of “year” and running efficiencies based on NA48 experience:**

~100 days/year; 60% overall efficiency

---

**Meanwhile…from 48 to 62**

$K \rightarrow e\nu/K \rightarrow \mu\nu$

**Data taking:**

- **Four months in 2007 (23/06 - 22/10):**
  - ~400k SPS spills, 300 TB of raw data (90 TB recorded), data preparation finished

- **Two weeks in 2008 (11/09 - 24/09):**
  - Special data sets allowing reduction of systematic uncertainties

**Magnetic spectrometer**

**Scintillator hodoscope**

**Liquid Kr EM calorimeter**

**NA48**
**Ke\(_2\)** and **K\(_\mu\)_2 selection**

**Large common part** (topological similarity)
- One reconstructed track
- Geometrical acceptance cuts
- Decay vertex defined as closest approach of track + nominal kaon axis
- Veto extra LKr energy deposition clusters
- Track momentum 13-65 GeV/c

**Kinematic separation**

\[ M_{\text{miss}}^2 = (P_K - P_t)^2 \]

- \( P_K \) average measured with \( K^{\pm} \rightarrow 3\pi \) decays

\[ \Rightarrow \text{No K}_\mu_2 \text{ background in K}_e_2 \text{ only for momenta < 25 GeV/c (\sim 15 \% of data)} \]

**Particle identification**

\[ \frac{E}{p} \] LKr energy deposit / track momentum

- <0.85 for muons, electrons: (0.90-0.95)<E/p<1.10

\[ \rightarrow \text{powerful } \mu^{\pm} \text{ suppression in } e^{\pm} \text{ sample (\sim 10^6)} \]

\[ P_{\mu e} / R_K \sim 10\% \Rightarrow \text{K}_\mu_2 \text{ decays represent the major background} \]

**Solution:** direct measurement of \( P_{\mu e} \)

\[ \Rightarrow \text{Lead wall (9.2 } X_0 \text{) in front of LKr (between the hodoscope planes)} \]
40% of data set

59963 $K^+ \to e^+\nu$ candidates
(99.27 $\pm$ 0.05)% electron ID efficiency
$B/(S+B) = (8.8 \pm 0.3)%$

cf. KLOE: 13.8k candidates (both $K^+$ and $K^-$),
$\sim 90%$ electron ID efficiency, 16% bkg.

18.03M $K^+ \to \mu^+\nu$ candidates
with very low background
$B/(S+B) = (0.38 \pm 0.01)%$

A. Winhart this Conference
Final result based on (~ 40%) of the NA62 $K_{e2}$ sample:
$R_K = (2.486 \pm 0.013) \times 10^{-5}$ with a record accuracy of ~ 0.5%, being compatible with the SM prediction.

With full data sample, overall uncertainty of 0.4%, as declared in the proposal, is within reach.

Future experiments for further improvement:
NA62 phase II (2013-2015) and KLOE-2 (> 2010) aim at ~0.2% and ~0.4% precision.
1. Hermetic veto with high detection efficiency: To count number of photons. 
   - $K_L \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma$ is most serious background by missing 2 $\gamma$.

2. Pencil Beam: to obtain kinematical constraints. $\rightarrow K_L$ decay on Z-axis. 
   - reconstruction of decay vertex($Z_{vtx}$) and transverse momentum($P_T$) of $\pi^0$.

H. Watanabe this Conference

E391a (KEK) $\Rightarrow$ KOTO (JPARC)
Previous experiment: Sensitivity in KEK-E391a

<table>
<thead>
<tr>
<th>Run</th>
<th>Run period</th>
<th>POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run-2</td>
<td>Feb.–Apr. 2005</td>
<td>$1.4 \times 10^{18}$</td>
</tr>
</tbody>
</table>

- Number of $K_L$ decay
  \[(8.70 \pm 0.17_{\text{stat.}} \pm 0.59_{\text{syst.}}) \times 10^9\]

- Signal Acceptance
  \[A_{\text{signal}} = (1.06 \pm 0.08)\% \text{ (for Run-2)}\]
  \[A_{\text{signal}} = (1.01 \pm 0.06)\% \text{ (for Run-3)}\]

- Single event sensitivity
  \[(1.11 \pm 0.02_{\text{stat.}} \pm 0.10_{\text{syst.}}) \times 10^{-8}\]

\[\text{Br}(K_L \rightarrow \pi^0\nu\nu) < 2.6 \times 10^{-8}\]

H. Watanabe this Conference
Strategy

✓ Step by Step approach.

✓ KEK-E391a (previous experiment)  
→ Establishment of experimental method.

✓ J-PARC Step-1 (E14 KOTO)  
→ First observation.  
→ Search for enhancement by New Physics.

✓ J-PARC Step-2  
→ > 100 events
Measurement of $K_L$ Yield by detecting $K_L \rightarrow \pi^+\pi^-\pi^0$

- No data for 16° extraction at 30GeV.
- Big differences between M.C. simulations.

### Reconstructed Mass

- Events: $1.83 \times 10^7$ Kₐ’s/2x10¹⁴ p.o.t. (*preliminary number)

<table>
<thead>
<tr>
<th>MC package</th>
<th>#KL/2E+14pot</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEANT3</td>
<td>1.5x10⁷</td>
</tr>
<tr>
<td>GEANT4(QGSP)</td>
<td>0.88x10⁷</td>
</tr>
<tr>
<td>GENAT4(QBBC)</td>
<td>1.0x10⁷</td>
</tr>
<tr>
<td>FLUKA</td>
<td>3.2x10⁷</td>
</tr>
</tbody>
</table>

It corresponds to

- Proposal-yield x 2.3
  (*MR DCCT normalization)

Poster K. Shiomi at this Conference

H. Watanabe this Conference
Leptons: $\tau \rightarrow l_x$

KEKB/Belle

B-factory: $E$ at CM = $Y (4S)$
$e^+(3.5 \text{ GeV}) e^-(8 \text{ GeV})$

total: $\gg 1 \text{ ab}^{-1}$
$Y (4S): 711 \text{ fb}^{-1}$
$Y (5S): 121 \text{ fb}^{-1}$
$Y (3S): 30 \text{ fb}^{-1}$
$Y (2S): 24 \text{ fb}^{-1}$
$Y (1S): 57 \text{ fb}^{-1}$
Off-resonance: $87 \text{ fb}^{-1}$

$\sigma(\tau\tau) \sim 0.9 \text{ nb}$, $\sigma(bb) \sim 1.1 \text{ nb}$
A B-factory is also a $\tau$-factory!
World-largest data sample!

Good track reconstruction and particle identification
Lepton ID $\sim (80-90)\%$
Fake ID $\sim (0.1-3)\%$

$\sim 9 \times 10^8 \tau\tau$ at Belle

K. Hayasaka this Conference
Analysis method

$e^+e^- \rightarrow \tau^+\tau^-$

1 prong + missing (tag side)

$\mu + \eta$ (signal side)

$\gamma + \gamma$

Signal extraction: $M_{\mu\eta} - \Delta E$ plane

$M_{\mu\eta} = \sqrt{(E_{\mu\eta}^2 - p_{\mu\eta}^2)}$

$\Delta E = E_{\mu\eta}^{CM} - E_{beam}^{CM}$

Blind analysis

$\Rightarrow$ Blind signal region

Estimate number of BG in the signal region using sideband data and MC

$M_{\mu\eta}$ (GeV/$c^2$)

K. Hayasaka this Conference
New Upper Limits on LFV $\tau$ Decay

Our sensitivity reaches $O(10^{-8})!$

@ SuperB factories one order of magnitude improvement

K. Hayasaka this Conference
Signal and Background

**Signal**
- 180°
- $\mu^+ \rightarrow e^+ \gamma$

**Prompt Background**
- $\nu$ incoming
- $\mu^+ \rightarrow e^+ \gamma$

**Accidental Background**
- $\gamma$ incoming
- $\mu^+ \rightarrow e^+ \gamma$

\[
B_{acc} \propto \delta E_{e^+} (\delta E_{\gamma})^2 \cdot (\delta t_{\gamma})^2 \cdot \delta t_{\gamma}
\]

<table>
<thead>
<tr>
<th>Angle</th>
<th>Back-to-Back</th>
<th>Any angle</th>
<th>Any angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>52.8 MeV/c</td>
<td>&lt; 52.8 MeV/c</td>
<td>&lt; 52.8 MeV/c</td>
</tr>
<tr>
<td>Time</td>
<td>Same time</td>
<td>Same time</td>
<td>Flat</td>
</tr>
</tbody>
</table>

Dominant background is accidental.

Detector resolution is crucial.
MEG: The Experiment

PSI: most intense DC muon

Beam transport system
stopping rate up to $10^8$/sec
on target

Various calibration and
monitoring systems.

Drift chamber
Made of light materials
Precise measurement of
positron tracks

Timing counter
Good time resolution
Work in B-field

LXe gamma detector
2.7 tons of liquid xenon
Good time, position energy resolution
Fast signal: pileup identification
Calibration and Monitoring

- PMT gain monitored by LED, QE by $\alpha$
- Light yield monitoring (CW, CR, AmBe etc.)
- Cockcroft-Walton proton accelerator
  - 17.6 MeV $\gamma$ by Li($p,\gamma$)Be reaction
  - Light yield monitoring & $\sigma_E$ at 17.6 MeV

2008 physics run and shutdown:
gaseous purification to increase light yield

Light yield became as much as expected
And decay time of $\gamma$ waveform changed

2009 physics run: no purification

Light yield monitoring: < 1% level
Time line and 2009 run

2008 seperated to December: Physics data taking
(lower efficiency and resolutions due to hardware problem)

2008 run result: Sensitivity = $1.3 \times 10^{-11}$
90% U.L. = $2.8 \times 10^{-11}$

2009: Analysis of 2008 data
Hardware upgrades

2009 November to December: Physics data taking

2009 December: Analysis of 2009 data
Hardware upgrades

2010 January: Physics data taking

43 days physics data taking
Data samples

Analysis box (~10σ width)
- $48 \leq E_\gamma \leq 58$ MeV
- $50 \leq E_e \leq 56$ MeV
- $|T_{e\gamma}| \leq 0.7$ ns
- $|\phi_{e\gamma}|, |\theta_{e\gamma}| \leq 50$ mrad

Analysis box was blinded during calibration and optimization of physics analysis.

Time and $E_\gamma$ sideband
- Accidental background PDF was made directly from sideband data. (Important because dominating background is accidentals)
- Positron detector response is studied by using Michel positrons.
- Time resolution is measured by using RMD peak in low gamma energy sideband.

* Angle is between gamma and flipped positron vectors.
Analysis Method

Extended unbinned maximum likelihood analysis on number of events

\[ \mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = \frac{N^{N_{\text{obs}}} \exp^{-N}}{N_{\text{obs}}!} \prod_{i=1}^{N_{\text{obs}}} \left[ \frac{N_{\text{sig}}}{N} S + \frac{N_{\text{RMD}}}{N} R + \frac{N_{\text{BG}}}{N} B \right] \]

“BG” in this talk means accidental background.

Event types: Signal, RMD and Accidental background

Observables: \( E_y, E_e, \) Relative time and Relative angle

- Fit is done for wide widow (about 10\( \sigma \) of each variable), and background events are fitted together.
- Fit is done by three independent likelihood analysis tools to check possible systematic effects.
- Event-by-event PDF
  - Position dependent PDF of gamma rays.
  - Two category PDF of positrons by reconstruction quality (fitting uncertainty etc.)
  - Most of PDFs are made from data (next slide)
  - RMD PDF is formed from theoretical shape and detector response.

Normalization factor is obtained from number of observed Michel positrons taken simultaneously.

\[ \text{B.R.} = \frac{N_{\text{sig}}}{1.0 \pm 0.1 \times 10^{12}} \]
PDFs

Gamma

Signal PDF from 55 MeV calibration gamma ($\pi^0$ decay)

BG measured in sideband

RMD peak mostly in low energy part

Relative time

Signal PDF from measured RMD peak

Positron

Signal PDF from Michel positrons

BG measured in sideband

Relative angle

From measured double turn tracks
Sensitivity
Average 90% C.L. upper limit of toy MC with null signal.

Sensitivity : $6.1 \times 10^{-12}$

Sideband fit result is consistent. $Br < 4 \sim 6 \times 10^{-12}$

Blue lines are 1(39.3 % included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions. For each plot, cut on other variables for roughly 90% window is applied.

(Current B.R. upper limit is $1.2 \times 10^{-11}$ by MEGA)
Event distribution after unblinding

Blue lines are 1(39.3 % included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions.
For each plot, cut on other variables for roughly 90% window is applied.
Fit Result

Preliminary

Accidental BG
RMD
Signal
Total

$N_{\text{RMD}} = 35^{+24}_{-22}$
(Expectation from sideband = $32^{\pm2}$)

Dashed lines: 90% C.L. UL of $N_{\text{sig}}$

$N_{\text{sig}} < 14.5$ @ 90% C.L
$N_{\text{sig}} = 0$ is in 90% confidence region

$N_{\text{sig}}$ best fit = 3.0

Fitting was done by three groups with different parametrization, analysis window and statistical approaches, and confirmed to be consistent ($N_{\text{sig}}$ best fit = 3.0-4.5, UL = $1.2-1.5 \times 10^{-11}$)
Event display
One of the most signal-like events.

Each highly ranked event is checked carefully.

$E_Y = 52.25$ MeV
$E_{e^+} = 52.84$ MeV
$\Delta \theta = 178.8$ degrees
$\Delta T = 2.68 \times 10^{-11}$ s
Check of events

High quality $e^+$ track category events

Selected by number of drift chamber (DC) hits, $E_e$, $\theta_e$, $\Phi_e$ fitting uncertainties, track fitting $\chi^2$, $r$ and $z$ difference between timing counter hit and extrapolation of a track.

Events around signal region do not disappear by selecting high quality track events.

High quality fraction = 59%

Blue lines are $1(39.3\%$ included inside the region w.r.t. analysis window), $1.64(74.2\%)$ and $2(86.5\%)$ sigma regions. For each plot, cut on other variables for roughly 90\% window is applied.
Prospects

- Possible improvements
  - Improvement of synchronization of waveform digitizer (DRS4) improves $\sigma_T$
  - Possible better calibration with monochromatic positron beam and improve positron tracking
  - Noise reduction and electronics modification for DC
  - Refinement in calorimeter analysis

- 3 years physics data (2010-2012)
  - Sensitivity will reach our goal, a few $\times 10^{-13}$
  - Each detector performance could be improved further!

<table>
<thead>
<tr>
<th></th>
<th>2010 (preliminary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma Energy (%)</td>
<td>1.5 (w&gt;2cm)</td>
</tr>
<tr>
<td>Gamma Timing (psec)</td>
<td>67</td>
</tr>
<tr>
<td>Gamma Position (mm)</td>
<td>5(u,v)/6(w)</td>
</tr>
<tr>
<td>$e^+$ Timing (psec)</td>
<td>90</td>
</tr>
<tr>
<td>$e^+$ Momentum (%)</td>
<td>0.7</td>
</tr>
<tr>
<td>$e^+$ angle (mrad)</td>
<td>$8(\phi)/8(\theta)$</td>
</tr>
<tr>
<td>$e^+$ - gamma timing (psec)</td>
<td>120</td>
</tr>
<tr>
<td>Muon Decay Point (mm)</td>
<td>1.4(R)/2.5(Z)</td>
</tr>
<tr>
<td>Stopping Muon Rate (sec$^{-4}$)</td>
<td>$3 \times 10^7$</td>
</tr>
<tr>
<td>DAQ time / Real time (days)</td>
<td>95/117</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>$2.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>BR upper limit</td>
<td>-</td>
</tr>
</tbody>
</table>
Summary

• Rare decay experiments are complementary to LHC in search of new physics
• New experiments in this field are (about) going to start data taking
• MEG will clarify the situation in its analysis box since it is now starting a long term stable data taking period
• Future experiments

  COMET at JPARC ($\mu \rightarrow e$ conversion): Y. Kuno Poster
  Mu2e at Fermilab: Y. Kolomensky Poster
  Experiments at ProjectX

could maybe discriminate among different models
## Performance

<table>
<thead>
<tr>
<th></th>
<th>2008</th>
<th>2009 (preliminary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma Energy (%)</td>
<td>2.0 (w&gt;2cm)</td>
<td>2.1 (w&gt;2cm)</td>
</tr>
<tr>
<td>Gamma Timing (psec)</td>
<td>80</td>
<td>&gt;67</td>
</tr>
<tr>
<td>Gamma Position (mm)</td>
<td>5(u,v)/6(w)</td>
<td>←</td>
</tr>
<tr>
<td>Gamma Efficiency (%)</td>
<td>63</td>
<td>58</td>
</tr>
<tr>
<td>e⁻ Timing (psec)</td>
<td>≤125</td>
<td>←</td>
</tr>
<tr>
<td>e⁻ Momentum (%)</td>
<td>1.6</td>
<td>0.74(core)</td>
</tr>
<tr>
<td>e⁻ efficiency (%)</td>
<td>14</td>
<td>30~40%</td>
</tr>
<tr>
<td>e⁻ angle (mrad)</td>
<td>10(ϕ)/18(θ)</td>
<td>7.1(ϕ core)/11.2(θ)</td>
</tr>
<tr>
<td>e⁻ - gamma timing (psec)</td>
<td>148</td>
<td>142(core)</td>
</tr>
<tr>
<td>Muon Decay Point (mm)</td>
<td>3.2(R)/4.5(Z)</td>
<td>3.3(R)/3.4(Z)</td>
</tr>
<tr>
<td>Trigger efficiency (%)</td>
<td>66</td>
<td>83.5</td>
</tr>
<tr>
<td>Stopping Muon Rate (sec⁻¹)</td>
<td>3x10⁷</td>
<td>2.9x10⁷(300μm)</td>
</tr>
<tr>
<td>DAQ time / Real time (days)</td>
<td>48/78</td>
<td>35/43</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>1.3x10⁻¹¹</td>
<td>6.1x10⁻¹²</td>
</tr>
<tr>
<td>BR upper limit (obtained)</td>
<td>2.8x10⁻¹¹</td>
<td>1.5x10⁻¹¹</td>
</tr>
</tbody>
</table>

- In 2008, sensitivity was $1.3 \times 10^{-11}$, and our result was the BR UL $2.8 \times 10^{-11}$ (90% C.L.).
- In 2009, our sensitivity reached $6.1 \times 10^{-12}$, and the BR UL was $1.5 \times 10^{-11}$ (90% C.L., these numbers are preliminary).
Event distribution after unblinding

Blue lines are 1(39.3 % included inside the region w.r.t. analysis window), 1.64(74.2%) and 2(86.5%) sigma regions.
For each plot, cut on other variables for roughly 90% window is applied.
Numbers in figures are ranking by \( \frac{L_{99}}{(L_{RMD}+L_{BG})} \). Same numbered dots in the right and the left figure are an identical event.
Drift chamber

- 2008
  - Discharge problem reduced $e^+$ detection efficiency and resolution for positron measurement
    - $\varepsilon \sim 14\% (\sim 1/3)$, $\sigma_{E^+}$, $\sigma_{ob}$ were worse
  - The problem was long term exposure to helium, fixed before physics run in 2009

- 2009
  - $e^+$ detection efficiency (30~40%, including TC matching) and resolutions improved

ICHEP July 22-28, 2010, Palais des Congres, Paris

Toshiyuki Iwamoto