Charged Lepton Flavour & Dipole Moments

T. Mori
The University of Tokyo
This talk reviews the experiments which study:

- charged lepton flavour violation (CLFV)
- electric dipole moments (EDM)
CLFV & EDM

definite evidence of new physics

\[ \frac{3\alpha}{32\pi} \left| \sum_i U_{\mu i}^* \left( \frac{m_{\nu i}^2}{M_W^2} \right) U_{ei} \right|^2 \leq 10^{-45} \]

The SM effects are very tiny!!
CLFV & EDM

- Experiments to search for new physics
  - TeV scale new physics (and beyond) = sources of CLFV and EDM
- Competitive & complementary to LHC
• We might be already seeing them...
  • some B asymmetry variables
  • muon’s anomalous magnetic moment
Topics

• EDM
  • electron EDM - new development
  • neutron EDM - coming soon
  • muon EDM - new idea

• CLFV
  • tau decays - B factories finishing up
  • muon decays - new MEG result
EDM
Origin of the EDMs

- **Fundamental CP phases**
  - $d_\mu$, $d_e$
  - $C_{qe}, C_{qq}$
  - $\theta, d_q, \tilde{d}_q, w$
  - $\bar{g}_{\pi NN}$
  - $C_{s,p,t}$

- **Energy**
  - TeV
  - QCD

- **Muon EDM**

- **EDMs of paramagnetic molecules**
  - (YbF, PbO, HfF$^+$)
  - Atoms in traps (Tl, Rb, Cs)

- **EDMs of diamagnetic atoms**
  - (Hg, Xe, Ra, Rn)

- **EDMs of nuclei and ions**
  - (deuteron, etc)

- **Neutron EDM ($d_n$)**

- **eN couplings**

- **gluon self-couplings**

Pospelov Ritz, Ann Phys 318 (05) 119
Technique to measure EDM

- precesses with Larmor freq
  \[ \omega_B = -\frac{2\mu_B B}{\hbar} \]

- additional precession
  \[ \omega_E = \frac{2d_E E}{\hbar} \]

- flip E and measure the difference
  \[ \omega_E|_B - \omega_{E\text{anti-}}|B \equiv \Delta \omega = \frac{4d_E E}{\hbar} \]
Origin of the EDMs

- Neutron EDM
- Energy
  - TeV
  - QCD
- Atomic EDMs of paramagnetic molecules (YbF, PbO, HfF\(^+\))
  - Atoms in traps (Tl, Rb, Cs)
- Muon EDM
- \(d_\mu, d_e\)
- \(C_{q_e, C_{q_q}}\)
- Origin of the EDMs
  - Nuclear EDM and ions (deuteron, etc)
  - Neutron EDM (\(d_n\))
EDM of dipolar molecules YbF

- Easier to polarize molecules than atoms
- Enhances effective $E$ field seen by the unpaired electron by a factor up to $10^5$
- Look for interferometer phase shift of the two spin states (hyperfine levels of the ground state) when $E$ reversed
- “Schiff shielding” strongly violated by relativistic effects
The electron is predicted to be slightly aspheric providing a constraint on any possible new interactions. We obtain electron EDM at the highest level of precision reported so far, molecules may exist at masses of a few hundred GeV/s. In particular, the popular idea that new supersymmetric scale has two great advantages. First, at our modest operating field the dipolar molecule YbF (ref. 8) instead of the spherical Tl atom. This changes sign when the electric field is reversed.

An alternative description of the method is in terms of the mean potential energy difference. An alternative description is in terms of the mean potential energy. The component that reverses synchronously with the electric field reverses perfectly as long as the field plates relative to the surrounding grounded apparatus. Near the direction of the field reverses perfectly as long as the field plates relative to the surrounding grounded apparatus.

We find no evidence of any residual systematic EDM that depends on moment, an electric dipole moment in the non-relativistic limit. A permanent EDM of the electron, which sets a new upper limit of 100 times larger than that of YbF due to this mechanism.

The units are 10^6 cm. The statistical uncertainty on the corrections gives a measure of their random nature. The EDM values obtained from the signal drifts from this channel is the velocity of the molecules with respect to the apparatus. Then they enter a pair of electric field plates, between which they are accelerated by an electric field.

Each molecule is transferred from one field plate to the other every 40 ms and travel through the r.f. regions we have made measurements in which we deliberately change the r.f. frequency switching around their optima. A computer places the machine in a new switch value, a computer places the machine in a new switch value, a computer places the machine in a new switch value, a computer places the machine in a new switch value.

The primary signal is the probe fluorescence normalized to the pump fluorescence. The line detector.

The component that reverses synchronously with the r.f. phase correction gives rise to a change resulting from a detuning of the first r.f. pulse is measured to be 2(μB\textit{B}-d_e\textit{E})t.

This contributes a little to the noise in the EDM, as the EDM is a function of the magnetic moment. The component that reverses synchronously with the r.f. phase correction gives rise to a change resulting from a detuning of the first r.f. pulse is measured to be 2(μB\textit{B}-d_e\textit{E})t.

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The correlation of this signal is 

\[ d_e = (-2.4 \pm 5.7_{\text{stat}} \pm 1.5_{\text{syst}}) \times 10^{-28} \text{cm} \]

\[ |d_e| < 10.5 \times 10^{-28} \text{cm} \quad 90\% \text{ C.L.} \]
• a pioneering work of the new method, though a modest $1.5 \times$ improvement over the previous Tl experiment

  • still statistically limited

• $\times 10$ improvement within a few years; $\times 100$ expected eventually

  • several groups working
Origin of the EDMs

Energy

TeV

QCD

Fundamental CP phases

$C_{qe}, C_{qq}$

$\theta, d_q, \tilde{d}_q, w$

Muon EDM

$C_{S,P,T}$

EDMs of nuclei and ions (deuteron, etc)

EDMs of paramagnetic molecules (YbF, PbO, HfF$^+$)
Atoms in traps (Tl, Rb, Cs)

EDMs of diamagnetic atoms (Hg, Xe, Ra, Rn)

Neutron EDM ($d_n$)
Present limits $< 2.9 \times 10^{-26} \text{ecm}$  
C.A. Baker et al, PRL 97 (2006) 131801

# Summary of active nEDM projects

<table>
<thead>
<tr>
<th>Group</th>
<th># people</th>
<th>Anticipated sensitivity (ecm)</th>
<th>By...</th>
</tr>
</thead>
<tbody>
<tr>
<td>nEDM@PSI n2EDM</td>
<td>~50</td>
<td>~5E-27, ~5E-28</td>
<td>2013, 2016</td>
</tr>
<tr>
<td>CryoEDM@ILL</td>
<td>~25</td>
<td>~3E-27</td>
<td>2016</td>
</tr>
<tr>
<td>nEDM@SNS</td>
<td>~90</td>
<td>~3E-28</td>
<td>~2020</td>
</tr>
<tr>
<td>nEDM@RCNP @TRIUMF</td>
<td>~35</td>
<td>~1E-26, ~1E-27, ~1E-28</td>
<td>2014, 2017, &gt;2020</td>
</tr>
<tr>
<td>PNPI@ILL</td>
<td>~10-20</td>
<td>~1E-26</td>
<td>2012</td>
</tr>
</tbody>
</table>

~$d_n \approx 10^{-23} \text{ e cm } \left(\frac{300 \text{ GeV/c}}{M_{\text{SUSY}}}\right)^2 \sin \phi_{\text{SUSY}}$
High Intensity Proton accelerator & UCN Source

590 MeV Proton Cyclotron
2.2 mA Beam Current
(currently testing 2.4 mA)

First UCN production 16./17./22.12.2010
Full approval for operation: 27.6.2011

2 experimental areas / 3 beamlines

nEDM ready for UCN

Beam dump

UCN-Source

nEDM
• Approval for full operation obtained by Swiss federal authorities end of June 2011
• Presently commissioning, expect more routine UCN production soon
Installing nEDM at PSI in 2009

Coming from ILL
Sussex-RAL-ILL collaboration
PRL 97 (2006) 131801
Apparatus

- 5T magnet to spin polarize UCNs
- Switch to distribute the UCNs to different parts of the apparatus
- Precession chamber where neutrons precess
- Vacuum chamber
- Magnetic field coils $B_0$-correction coils
- High voltage lead
- Electrode (upper)
- Spin analyzer
- Neutron detector

$E \approx 12 \text{ kV/cm}$

$B = 1 \text{ mT}$
UCN stored

First UCN stored in apparatus @ PSI: Wednesday, December 22nd, 2010

- 8s Pulse on target ①
- 40s filling
- Closing of UCN shutter
- Turning switch in emptying position ②
- Opening of shutter ③
- Emptying into detector
Statistical Sensitivity

\[ \sigma(d_n) = \frac{\hbar}{2\alpha ET\sqrt{N}} \]

\[ \alpha = 0.75 \]

\[ E = 12 \text{ kV/cm} \]

\[ T = 150 \text{ s} \]

\[ N = 350'000 \]

\[ \sigma(d_n) = 4 \times 10^{-25} \text{ ecm / cycle} \]

\[ = 3 \times 10^{-26} \text{ ecm / day} \]

\[ = 3 \times 10^{-27} \text{ ecm / year} \]

Performance needs to be demonstrated

After 2 years*, statistics only
\[ d_n = 0: |d_n| < 4 \times 10^{-27} \text{ ecm (95% C.L.)} \]

* 200 nights each

Obtain same figures with
\[ E=10\text{kV/cm}, T=130\text{s}, 200\text{s cycle} \]
1.03 meV (11 K) neutrons downscatter by emission of phonon in liquid helium at 0.5 K

Upscattering suppressed: Boltzmann factor $e^{-E/kT}$ means not many 11 K phonons present
CryoEDM at ILL

successful production/storage - need to reduce losses
E field/polarization/efficiency/B stability to be improved
neutron EDM - Prospects

- Sensitivity is expected to improve
  - by a factor of 5 in a couple of years
  - by two orders of magnitude within the next decade
Origin of the EDMs

Muon EDM

$C_{q_e, C_{qq}}$

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$C_{S,P,T}$

EDMs of paramagnetic molecules (YbF, PbO, HfF$^+$)
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$\bar{g}_{\pi NN}$

Fundamental CP phases

Neutron EDM ($d_n$)

Energy

QCD

TeV

nuclear

atomic
Resonant Laser Ionization of Muonium ($\sim 10^6 \mu^+/s$)

Graphite target (20 mm)

Surface muon beam (28 MeV/c, $4 \times 10^8$/s)

Muonium Production (300 K $\sim 25$ meV)

Muon LINAC (300 MeV/c)

Silicon Tracker

Super Precision Magnetic Field (3T, $\sim 1$ ppm local precision)

3 GeV proton beam (333 uA)

New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam
Spin Rotation and EDM

- Precession frequency vector with g-2 and EDM

\[
\vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]
\]

Choose \( B, E \) and \( \gamma \) to cancel g-2 rotation
ex. \( p_\mu = 125 \text{ MeV}/c \)
\( B = 1 \text{ T}, \ E = 0.64 \text{ MV/m} \)

Spin Frozen mode

\[
\vec{\omega} = -\frac{e}{m} \left[ \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right]
\]

Eliminate \( E \)-field with Ultra-cold muon beam

\[
\vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} \right) \right]
\]
Spin Rotation and EDM

• “Spin Frozen” method and and “E=0” method

\[ \vec{\Omega}_{\text{T-BMT}} = \vec{\Omega}_C \]
\[ \eta = 5 \times 10^{-6} \]

Spin Frozen case
pure EDM effect can be extracted if “frozen condition” is satisfied precisely.

\[ \vec{\omega} = -\frac{e}{m} \left[ \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right) \right] \]

E=0 with spin // B case
“beat” with g-2 frequency with amplitude proportional to EDM \( \Rightarrow \) Use g-2 rotation as systematics control

\[ \vec{\omega} = -\frac{e}{m} \left[ a_\mu \vec{B} + \frac{\eta}{2} \left( \vec{\beta} \times \vec{B} \right) \right] \]
Muon EDM Prospects

- Present limit $\sim 10^{-19}$ ecm
- J-PARC g-2/EDM experiment could push it down to $\sim 10^{-21}$ ecm

$-2.2 < Re(d_\tau) < 4.5 \ (10^{-17} \text{ e cm}),$
$-2.5 < Im(d_\tau) < 0.8 \ (10^{-17} \text{ e cm}).$

Belle Collaboration (K. Inami et al.).
B-factories

B-factories: \( E \) at CM = \( \Upsilon(4S) \)
\( e^+(3.5 \ (3.1) \text{ GeV}) \ e^-(8 \ (9) \text{ GeV}) \) for KEKB \ (PEP II)
\[ \sigma(\tau\tau) \sim 0.9 \text{nb}, \sigma(bb) \sim 1.1 \text{nb} \]

A B-factory is also a \( \tau \)-factory!

Detector:

Good track reconstruction and particle identification

Lepton ID \sim (80-90)\%
Fake ID \sim O(0.1-1)\%

\( \sim 9 \times 10^8 \tau\tau \) at Belle
\( \sim 4.8 \times 10^8 \tau\tau \) at BaBar
Results for $\tau \to \ell hh'$

In the signal region

1 event: in $\mu^+\pi^-\pi^-$ and $\mu^-\pi^+K^-$

no events: in other modes

$\Rightarrow$ no significant excess

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{BG}$</th>
<th>$\sigma_{syst}$ (%)</th>
<th>$N_{obs}$</th>
<th>$s_{90}$</th>
<th>$B$ ($10^{-8}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \to \mu^-\pi^+\pi^-$</td>
<td>5.83</td>
<td>0.63 ± 0.23</td>
<td>5.3</td>
<td>0</td>
<td>1.87</td>
<td>2.1</td>
</tr>
<tr>
<td>$\tau^- \to \mu^+\pi^-\pi^-$</td>
<td>6.55</td>
<td>0.33 ± 0.16</td>
<td>5.3</td>
<td>1</td>
<td>4.02</td>
<td>3.9</td>
</tr>
<tr>
<td>$\tau^- \to e^-\pi^+\pi^-$</td>
<td>5.45</td>
<td>0.55 ± 0.23</td>
<td>5.4</td>
<td>0</td>
<td>1.94</td>
<td>2.3</td>
</tr>
<tr>
<td>$\tau^- \to e^+\pi^-\pi^-$</td>
<td>6.56</td>
<td>0.37 ± 0.18</td>
<td>5.4</td>
<td>0</td>
<td>2.10</td>
<td>2.0</td>
</tr>
<tr>
<td>$\tau^- \to \mu^-K^+K^-$</td>
<td>2.85</td>
<td>0.51 ± 0.18</td>
<td>5.9</td>
<td>0</td>
<td>1.97</td>
<td>4.4</td>
</tr>
<tr>
<td>$\tau^- \to \mu^+K^-K^-$</td>
<td>2.98</td>
<td>0.25 ± 0.13</td>
<td>5.9</td>
<td>0</td>
<td>2.21</td>
<td>4.7</td>
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<tr>
<td>$\tau^- \to e^-K^+K^-$</td>
<td>4.29</td>
<td>0.17 ± 0.10</td>
<td>6.0</td>
<td>0</td>
<td>2.28</td>
<td>3.4</td>
</tr>
<tr>
<td>$\tau^- \to e^+K^-K^-$</td>
<td>4.64</td>
<td>0.06 ± 0.06</td>
<td>6.0</td>
<td>0</td>
<td>2.38</td>
<td>3.3</td>
</tr>
<tr>
<td>$\tau^- \to \mu^-\pi^-K^-$</td>
<td>2.72</td>
<td>0.72 ± 0.27</td>
<td>5.6</td>
<td>1</td>
<td>3.65</td>
<td>8.6</td>
</tr>
<tr>
<td>$\tau^- \to \mu^+\pi^-K^-$</td>
<td>3.97</td>
<td>0.18 ± 0.13</td>
<td>5.7</td>
<td>0</td>
<td>2.27</td>
<td>3.7</td>
</tr>
<tr>
<td>$\tau^- \to e^-\pi^-K^-$</td>
<td>2.62</td>
<td>0.64 ± 0.23</td>
<td>5.6</td>
<td>0</td>
<td>1.86</td>
<td>4.5</td>
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<tr>
<td>$\tau^- \to e^-K^+\pi^-$</td>
<td>4.07</td>
<td>0.55 ± 0.31</td>
<td>5.7</td>
<td>0</td>
<td>1.97</td>
<td>3.1</td>
</tr>
<tr>
<td>$\tau^- \to \mu^-K^+\pi^-$</td>
<td>2.55</td>
<td>0.56 ± 0.21</td>
<td>5.6</td>
<td>0</td>
<td>1.93</td>
<td>4.8</td>
</tr>
<tr>
<td>$\tau^- \to e^-K^-\pi^-$</td>
<td>4.00</td>
<td>0.46 ± 0.21</td>
<td>5.7</td>
<td>0</td>
<td>2.02</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Set upper limits @90%CL:

$\text{Br}(\tau \to \ell hh') < (2.0-8.4) \times 10^{-8}$

(preliminary)

$\Rightarrow$ most sensitive results

Improve our previous results by a factor of 1.8 on average

21/July/2011

K. Hayasaka
Results for $\tau \rightarrow \Lambda h/\bar{\Lambda} h$

In the signal region, no candidate event are found $\Rightarrow$ no significant excess

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
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<th>$\sigma_{syst}$ (%)</th>
<th>$N_{obs}$</th>
<th>$s_{90}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow \Lambda \pi^-$</td>
<td>4.80</td>
<td>0.21 ± 0.15</td>
<td>8.2</td>
<td>0</td>
<td>2.3</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \Lambda \pi^-$</td>
<td>4.39</td>
<td>0.31 ± 0.18</td>
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<td>0</td>
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</tr>
<tr>
<td>$\tau^- \rightarrow \bar{\Lambda} K^-$</td>
<td>4.11</td>
<td>0.31 ± 0.14</td>
<td>8.6</td>
<td>0</td>
<td>2.2</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \Lambda K^-$</td>
<td>3.16</td>
<td>0.42 ± 0.19</td>
<td>8.6</td>
<td>0</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Set upper limits@90%CL:
- $\text{Br}(\tau \rightarrow \bar{\Lambda} \pi^-) < 2.8 \times 10^{-8}$ (B-L) cons.
- $\text{Br}(\tau \rightarrow \bar{\Lambda} K^-) < 3.1 \times 10^{-8}$ (B-L) viol.
- $\text{Br}(\tau \rightarrow \Lambda \pi^-) < 3.0 \times 10^{-8}$ (B-L) cons.
- $\text{Br}(\tau \rightarrow \Lambda K^-) < 4.2 \times 10^{-8}$ (B-L) viol.

$\Rightarrow$ most sensitive results

Around x(2-3) improvement from the previous BaBar results
New Upper Limits on $\tau$ LFV Decay

90% C.L. Upper limits for LFV $\tau$ decays

$\gamma$ $lP^0$ $lS^{0}$ $lV^0$ $lll$ $lhh$ $\Lambda h$

$10^{-5}$

$10^{-6}$

$10^{-7}$

$10^{-8}$

Reach upper limits around $10^{-8}$ ~100x more sensitive than CLEO

Update using full data samples will be finalized soon!

K. Hayasaka, A. Adametz
LFV Sensitivity for future prospects

Belle II @ SuperKEKB • Super B-factory: (10~50) ab⁻¹

LFV sensitivity

- $\tau \rightarrow l\gamma$,

  Sensitivity currently limited due to background from $\tau^+\tau^-\gamma$ events
  scale as $\sim 1/\sqrt{L} \Rightarrow \text{Br} \sim O(10^{-(8-9)})$

- $\tau \rightarrow 3\text{leptons}, l+\text{meson}$

  Negligible background at 1 ab⁻¹ due to good particle identification and mass restriction to select meson
  scale as $\sim 1/L \Rightarrow \text{Br} \sim O(10^{-(9-10)})$
The MEG Experiment

$$\mu^+ \rightarrow e^+ \gamma$$
Event distribution after unblinding

**BR < 1.5 \times 10^{-11} \ @ 90\% CL**

6.1 \times 10^{-12} expected

**Nsigt = 3.0**

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 $L_{\text{sig}}/(L_{\text{RMD}}+L_{\text{BG}})$. Same numbered dots in the right and the left figure are an identical event.
• **New data:**
  
  • \(2010 \text{ data} = 2 \times 2009 \text{ data}\)

• **Better calibrations of data:**
  
  • alignments inside/among detectors
  
  • applied to both 2009 & 2010 data

• **Analysis methods:**
  
  • \(N_{BG}\) constrained by side bands
  
  • profile likelihood intervals

  *Feldman-Cousins*
The MEG Experiment

LXe Gamma-ray Detector
DC Muon Beam
COBRA SC Magnet
Drift Chamber
Timing Counter

~55 collaborators
Dominant Background Is Accidental

By the naive calculation of background above, the accidental background is found to be the dominant background source, and it will limit the experiment. First, from Eq. 2.23 we see the background rate is proportional to the instantaneous muon beam intensity. Whereas we estimated that we need $>10^7$ sec muon intensity to signal $e^+$ background $\gamma$ background must manage high rate $e^+$

good $\gamma$ resolution is most important!
3.2. The Gamma-ray Detector

The gamma-ray detector is undoubtedly the most innovative and challenging part of the experiment. Its performance is crucial for a successful search for the $\mu^+ \rightarrow e^+ \gamma$ decay. We use a gamma-ray detector of a 900 liter homogeneous volume of liquid xenon (LXe). It is placed just outside of the COBRA magnet. Gamma rays that penetrated the positron spectrometer enter the detector. They interact with LXe and generate scintillation light. The scintillation light is collected by a number of photomultipliers (PMT) surrounding the active volume of LXe to measure the total energy released by the incident gamma ray as well as the position and time of its first interaction. A conceptual figure of the gamma-ray detector is shown in Figure 3.21. Sometimes multiple gamma rays enter the detector and are measured at the same time in a high rate of low-energy gamma-ray background since the detector consists of a large volume without any segmentation. Nevertheless, we can handle those pileup events correctly because the image of the light distribution from a large number of PMTs enables us to identify and unfold those multiple events. In addition, the time distribution and waveform can also be used to identify pileup events.

The R&D works, performance of prototype detector, design and construction of final detectors are described in detail in [46], [47].

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**2.7t Liquid Xenon Photon Detector**

- Scintillation light from 900 liter liquid xenon is detected by 846 PMTs mounted on all surfaces and submerged in the xenon
- **fast response & high light yield** provide good resolutions of E, time, position
- kept at 165K by 200W pulse-tube refrigerator
- **gas/liquid circulation system** to purify xenon to remove contaminants
Monitor $E_{\gamma}$ during Run

- sub-MeV proton beam produced by a dedicated Cockcroft-Walton accelerator (CW) are bombarded on $\text{Li}_2\text{B}_4\text{O}_7$ target.

- 17.67 MeV from $^7\text{Li}$

- 2 coincident photons (4.4, 11.6) MeV from $^{11}\text{B}$: synchronization of LXe and TC

- Short runs two-three times a week

remotely extendable beam pipe of CW proton beam (downstream of muon beam line)

17.67 MeV Li peak
Stability of $E_\gamma$ Scale

- Stability range: $\pm 1\%$
- RMS: $\sim 0.3\%$
Absolute $E_\gamma$ Calibration

- negative pions stopped in liquid hydrogen target
- Tagging the other photon at $180^\circ$ provides monochromatic photons
- Dalitz decays were used to study positron-photon synchronization and time resolution:

$$\pi^- p \rightarrow \pi^0 n \rightarrow \gamma \gamma n$$

NaI crystal array on a movable stand to tag the other photon.

$$\pi^0 \rightarrow \gamma e^+ e^-$$
- **Gamma ray energy**
  - Signal PDF from the CEX data
  - Accidental PDF from the sidebands
  - Scale & resolutions verified by radiative decay spectrum
  - Systematic uncertainty on energy scale: 0.3%
Resolution for photon conversion position was evaluated by CEX run with Pb collimators.

- ~ 5mm
Low energy positrons quickly swept out

Constant bending radius independent of emission angles

solenoid

μ^+ beam

DC

emitted e^+

uniform B-field

gradient B-field

CHAPTER 3. Experimental Apparatus

Figure 3.7: Conceptual illustrations of the COBRA spectrometer compared with one with a uniform magnetic field. (a) and (c) show trajectories of positrons emitted at 88°. The uniform field makes many turns inside the detector, whereas the gradient field sweeps the positron out of the detector much more quickly. (b) and (d) show trajectories of mono-energetic positrons emitted at various angles. In the uniform field, the bending radius depends on the emission angle, whereas it is independent in the gradient field.

Figure 3.8: Rate of Michel positrons per cm^2 per second as a function of radius assuming muon decay rate of 3 \times 10^7/sec.
Drift Chambers

- 16 radially aligned modules, each consists of two staggered layers of wire planes
- 12.5μm thick cathode foils with a Vernier pattern structure
- He:ethane = 50:50 differential pressure control to COBRA He environment
- \( \sim 2.0 \times 10^{-3} X_0 \) along the positron trajectory

filled with He inside COBRA
Angular resolution can be evaluated by two ways:
1. Fitting the image of the hole
2. Subtracting the double curling track
Both show consistent results; $x \sim 4.5 \text{ mm}$ and $y \sim 3.2 \text{ mm}$.

Angular resolution is estimated by doubly curling the track. Subtracted angular residual of each turn gives intrinsic angular resolution.

---

**Positron Angle & Muon Decay Point**

- Angular resolutions were evaluated by the double turn tracks inside the DC.
- Holes of the muon stopping target.
Timing Counters

- Scintillator arrays placed at each end of the spectrometer
- Measures the impact point of the positron to obtain precise timing

APD

fine-mesh PMTs for scintillating bars

scintillating fibers

installing inside COBRA
Positron - Photon Timing

- Positron time measured by TC and corrected by ToF (DC trajectory)
- LXe time corrected by ToF to the conversion point
- RMD peak in a normal physics run corrected by small energy dependence; stable < 20ps
Improved calibration & analysis

- alignment by CR & Michel $e^+$
  - DC - B field - target - LXe
  - optical surveys
  - DC: MILLEPEDE (a la CMS)
  - target holes
  - LXe: Pb collimators
- more detailed implementation of $e^+$ correlations
Blind & Likelihood Analysis

\( (E_\gamma, E_e, T_{e\gamma}, \theta_{e\gamma}, \phi_{e\gamma}) \)

\[ \rightarrow \text{signal, acc BG, RD BG} \]

PDFs mostly from data
accidental BG: side bands
signal: measured resolution
radiative BG: theory + resolution

BG \( E_\gamma \) spectrum

Blind region

\( T_{e\gamma} \) resolution
Likelihood Fit

- fully frequentist approach (Feldman & Cousins) with profile likelihood ratio ordering

\[
\mathcal{L}(N_{\text{sig}}, N_{\text{RMD}}, N_{\text{BG}}) = \frac{e^{-N_{\text{obs}}} \prod_{i=1}^{N_{\text{obs}}} (N_{\text{sig}}S(\bar{x}_i) + N_{\text{RMD}}R(\bar{x}_i) + N_{\text{BG}}B(\bar{x}_i))}{N!} e^{-\frac{1}{2} \frac{(N_{\text{BG}} - \langle N_{\text{BG}} \rangle)^2}{\sigma_{\text{BG}}^2}} e^{-\frac{1}{2} \frac{(N_{\text{RMD}} - \langle N_{\text{RMD}} \rangle)^2}{\sigma_{\text{RMD}}^2}}
\]

\[
LR_p(N_{\text{sig}}) = \frac{\max_{N_{\text{BG}}, N_{\text{RMD}}} \mathcal{L}(N_{\text{sig}}, N_{\text{BG}}, N_{\text{RMD}})}{\max_{N_{\text{sig}}, N_{\text{BG}}, N_{\text{RMD}}} \mathcal{L}(N_{\text{sig}}, N_{\text{BG}}, N_{\text{RMD}})}.
\]
## Performance Summary

<table>
<thead>
<tr>
<th></th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma Energy (%)</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Gamma Timing (psec)</td>
<td>96</td>
<td>67</td>
</tr>
<tr>
<td>Gamma Position (mm)</td>
<td>5 (u,v), 6 (w)</td>
<td>5 (u,v), 6 (w)</td>
</tr>
<tr>
<td>Gamma Efficiency (%)</td>
<td>58</td>
<td>59</td>
</tr>
<tr>
<td>e⁺ Timing (psec)</td>
<td>107</td>
<td>107</td>
</tr>
<tr>
<td>e⁺ Momentum (keV)</td>
<td>310 (80% core)</td>
<td>330 (79% core)</td>
</tr>
<tr>
<td>e⁺ θ (mrad)</td>
<td>9.4</td>
<td>11.0</td>
</tr>
<tr>
<td>e⁺ φ (mrad)</td>
<td>6.7</td>
<td>7.2</td>
</tr>
<tr>
<td>e⁺ vertex Z/Y (mm)</td>
<td>1.5 / 1.1 (core)</td>
<td>2.0 / 1.1 (core)</td>
</tr>
<tr>
<td>e⁺ Efficiency (%)</td>
<td>40</td>
<td>34</td>
</tr>
<tr>
<td>e⁺-gamma timing (psec)</td>
<td>146</td>
<td>122</td>
</tr>
<tr>
<td>Trigger efficiency (%)</td>
<td>91</td>
<td>92</td>
</tr>
<tr>
<td>Stopping Muon Rate (sec⁻¹)</td>
<td>2.9x10⁷</td>
<td>2.9x10⁷</td>
</tr>
<tr>
<td>DAQ time/ Real time (days)</td>
<td>35/43</td>
<td>56/67</td>
</tr>
<tr>
<td>Expected 90% C.L. Upper Limit</td>
<td>3.3x10⁻¹²</td>
<td>2.2x10⁻¹²</td>
</tr>
</tbody>
</table>

Timing improvement by waveform digitizer upgrade in 2011; The e⁺ tracking slightly worse due to DC noise problem in 2011
2009 data update
2009 data update

Selection: \(|T_{e\gamma}| < 0.278\text{ns}; \ \Theta_{e\gamma} > 178.34\ \text{deg}\)

\(51 < E_{\gamma} < 55\ \text{MeV};\ \ 52.34 < E_e < 55\ \text{MeV}\)

\(N_{\text{sig}} = 3.0\ \ \rightarrow\ \ N_{\text{sig}} = 3.4\)
Likelihood Analysis

$1.7 \times 10^{-13} < \text{BR} < 9.6 \times 10^{-12}$

90% C.L.

Best Fit $\text{BR} = 3.2 \times 10^{-12}$

updated 2009 data
2010 data
Side band data analyzed consistent with expected sensitivity = $2.2 \times 10^{-12}$ @90\% C.L.
2010 data unblinded on July 5th

| $|T_{e\gamma}| < 0.28$ns; $\cos\Theta_{e\gamma} < -0.9996$

$51 < E_{\gamma} < 55$ MeV; $52.3 < E_e < 55$ MeV
Likelihood Fit - 2010 Data

\[ T_{e\gamma} \]

\[ E_e \]

\[ E_\gamma \]

\[ \theta_{e\gamma} \]

\[ \phi_{e\gamma} \]

2010 data
Likelihood Analysis

BR < $1.7 \times 10^{-12}$

90% C.L.

2010 data
## Likelihood Analysis Results

<table>
<thead>
<tr>
<th></th>
<th>BR(fit)</th>
<th>LL 90%</th>
<th>UL 90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>$3.2 \times 10^{-12}$</td>
<td>$1.7 \times 10^{-13}$</td>
<td>$9.6 \times 10^{-12}$</td>
</tr>
<tr>
<td>2010</td>
<td>$-9.9 \times 10^{-13}$</td>
<td>--</td>
<td>$1.7 \times 10^{-12}$</td>
</tr>
<tr>
<td>2009+2010</td>
<td>$-1.5 \times 10^{-13}$</td>
<td>--</td>
<td>$2.4 \times 10^{-12}$</td>
</tr>
</tbody>
</table>

**combined result**

(2009+2010 expected UL = $1.6 \times 10^{-12}$)

- **systematic errors** (in total 2% in UL) include:
  - relative angle offsets
  - correlations in $e^+$ observables
  - normalization
Profile Likelihood Curves

Note these curves are not directly used to derive the U.L. which are obtained in a frequentist approach.
MEG summary

• 2009+2010 data consistent w/ no signal

• New physics is now constrained by 5× tighter upper limit:
  \[ \text{BR} < 2.4 \times 10^{-12} \text{ @90\% C.L.} \]
  (Preprint will be posted at arXiv today)

• MEG is accumulating more data this and next year to reach \( O(10^{-13}) \) sensitivity;
  So stay tuned!

• Detector improvements/upgrades
Resources shared between COMET and Mu2e

What is COMET?
- 8GeV proton beam
- 5T pion capture solenoid
- 3T muon transport (curved solenoids)
- Muon stopping target
- Electron tracker and calorimeter

Experimental Goal of COMET
- J-PARC E21
- 10^{11} muon stops/sec for 56 kW proton beam power.
- C-shape muon beam line and C-shape electron transport followed by electron detection system.
- Stage-1 approved in 2009.

Mu2e @FNAL
- μ → e conversion at 5 × 10^{-17}
- ~1/390 × \mu^+ → e^+γ (Al)

CLFV in further future
- \mu → e conversion
- μ^+ → e^+γ (Al)
Conclusion

- CLFV & EDM experiments are low energy probes for new physics as powerful as LHC
- MEG is now exploring TeV-scale physics; EDM experiments will follow within next few years
- More to come in the next decade