μ⁺ → e⁺ γ 探索実験 MEG II

現状と今後の見込み

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on behalf of MEG II collaboration

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MEG II: in search of $\mu^+ \rightarrow e^+\gamma$

- An intensity frontier experiment
- Upgraded from MEG experiment
- To get definitive evidence for BSM

![Map of PSI and CERN](image)

MEG result (2016)

$\mathcal{B}(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13}$

@90% C.L.

(while $5.3 \times 10^{-13}$ expected)

- × 2 intensity muon beam
- × 2 resolution everywhere
- × 2 efficiency

Search for $\mu^+ \rightarrow e^+\gamma$ down to

$6 \times 10^{-14}$

(90% C.L. sensitivity)
Physics of $\mu^+ \to e^+\gamma$

- **Charged Lepton Flavor Violation**
  - Practically forbidden in SM by tiny neutrino masses.
  - Never observed yet.

- But we know ‘flavors’ are violated in SM.

- Why not in physics beyond SM?
  1. No reason to be conserved.
  2. Contribution from the known FV is unavoidable via radiative corrections in the new physics.

- Why charged lepton?
  1. No SM contribution, no theoretical uncertainty.
  2. Probably, connected to the mystery of neutrino.

- Many theoretical predictions are within experimental reach
  - SUSY-GUT, SUSY-seesaw, leptoquarks, etc.

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Sep. 19, 2019 @ JPS 2019 Autumn
YUSUKE UCHIYAMA
Experimental requirements

- High intensity DC $\mu^+$ beam
- High resolution detector for energy, timing, and direction of $\gamma$ & $e^+$.

\[ R_{BG} \propto R_\mu^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta \omega/4\pi \cdot \delta t \]

Accidental BG
Time, direction & energies are random, but dangerous at high intensity.

Accidental back-to-back
accidentally
coincident
Liquid xenon photon detector
($\varepsilon_\gamma \sim 70\%, \sigma_E/E \sim 1\%$)

Pixelated timing counter
($\sigma_t \approx 35 \text{ ps}$)

Cylindrical drift chamber
($\sim 1.6 \times 10^{-3} X_0$, $\sigma_p \sim 100 \text{ keV}$)

Radiative decay counter
(identify high-energy BG $\gamma$ events)

Muon stopping target
(140$\mu$m-thick scintillating film)

● $\mu^+$: World’s **most intense DC** muon beam @ PSI
● $\gamma$: Detect with **liquid xenon** scintillation detector
● $e^+$: Detect with **gradient B-field** spectrometer
  (drift chamber & timing counter inside)
Thin-wall SC solenoid
(gradient B-field: 1.3→0.5 T)

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Continuous $\mu^+$ beam
($7 \times 10^7 \mu^+$/s)
Liquid xenon photon detector
Radiative decay counter (RDC)
Cylindrical drift chamber (CDCH)
Pixelated timing counter (pTC)
MEG II detectors constructed
Stopping target & monitoring CCD cameras
Electronics & TDAQ
# MEG II timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam</th>
<th>Magnet</th>
<th>pTC</th>
<th>RDC (downstream)</th>
<th>RDC (upstream)</th>
<th>CDCH</th>
<th>LXe</th>
<th>Electronics</th>
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</table>

- **Beam**: 7 × 10^7 s^-1 verified
- **Magnet**: In use in engineering runs
- **pTC**: Improved field measurement
- **RDC (downstream)**: Performance demonstrated
- **RDC (upstream)**: R&D (18pT12-1)
- **CDCH**: Construction
- **LXe**: Modification/tuning/calibration
- **Electronics**: 1st prototype test

- **MEG II run**
- **MEG final result**
- **MEG II 1st result?**

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Sep. 19, 2019 @ JPS 2019 Autumn
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2018 run & issues

- We performed a successful engineering run in Oct. – Dec. 2018 with all the detectors & MEG II intensity beam.

Major issues

- Drift chamber
  - Severe problem in the electrostatic stability → only 3 outer-most layers were operational.
  - Critical problem of wire breaking happened again.

- LXe detector
  - Performance (especially the energy resolution) has not yet be demonstrated.
  - Unexpectedly large degradation of photo-sensors (MPPC & PMT) observed in beam.

- Electronics
  - Schedule delay → only limited number of channels were available.
  - Noise reduced version (final version) not yet tested.
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Focus in this talk

→ See 17aT12-4,5 19pT14-6,7,8
Drift chamber HV

After closing chamber, we tested HV.

- During HV ramp-up, currents oscillate → sometimes permanent short.
- Inner layers cannot reach the nominal voltage.
- Wire tension was not enough.
  - Tension is controlled by the length of wires.
  - We set +3.8 mm elongation (40% of elastic limit) in assembly (2018)
  - relatively weak tension to suppress wire breaking.

\[ \sim 1450V \] is required to get \( G \sim 5 \times 10^5 \)
Drift chamber HV

After the commissioning,

- Outer layers of several sectors showed bunch of short circuits.

⇒ 2 cathode wires broke!

- First breaking since 2017 Aug.
- Even in dry environment

During the run

- we can apply HV only to outer 3 layers.

The fundamental problem is still the wire-breaking

~1450V is required to get G~5 × 10^5
アルミと銀の境界 + 水分 + 張力 = 腐食による断線

- 陰極ワイヤ：40 or 50 μm 銀コーティングアルミニウムワイヤ
- チェンバーを封じ、張力も抑えたからもう起きないと期待していた。
Strategy & measures (1)

- Short term (for this year)
  1. Open the chamber and remove the broken wires.
  2. Stretch the chamber to get the electrostatic stability at nominal HV.
  3. Stretch more to let weak wires break.

- Results
  - Good stability achieved by elongation of 1.8 mm (+5.6 mm from no-tension length, 70% of elastic limit)
  - Further 30 cathode wires broke during the additional stretch 3 weeks at +6 mm
    In total ~65 cathode wires have broken
  - Simulation study shows no impact on chamber performance.

The operation took 5 months
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- 切れるやつはもう全部切った（建設時に腐食が進行していたやつ）。これ以上腐食が進むことも、断線が起きることもないだろう。
- HV問題も解決した。

今年のランで安定したオペレーションが確認されれば、このままMEG IIに使用可能。

一方、100%断線が起きない確証は得られていない。一本断線が起きたら、実験終了。
リスクが大きすぎる
Strategy & measures (2)

- Long term risk hedge

**Build another chamber with different cathode wire**

- It takes at least ~2 years → start as soon as possible, otherwise useless.
- Revisiting design requires further R&D, too late.
- Only way to go is just changing cathode wire.

- A review meeting was held with PSI/INFN joint review committee (by gas-detector experts incl. Uno-san from KEK) in 5-6th Sep.
- About to submit budget request to INFN
Alternative wires?

- Several candidates have been investigated.
- From performance point of view, Al is still preferable.
- The committee suggests to expand the candidates, incl. back-up of back-up

- Present first candidate: **bare aluminum wire**
  - The main issue is soldering (tension is supported by soldering in our chamber)
  - "**C-SOLDER™**" shows good quality of soldering on Al.
    C-Solder is **new tin-based soldering alloys** which enable the joining of various **carbon materials** (carbon fibers or carbon nanotube fibers), **ceramics**, and **aluminum**.

Further tests from various viewpoints are necessary before final decision, but looks promising!
Next step

Engineering run this autumn – winter

- Final tests of detector stability/performance with (still) limited number of electronics.
  - Drift chamber test in beam at nominal HV
  - LXe detector detailed sensor tests and performance test with 55 MeV γ from π0
  - Test final design electronics in beam → mass production by next summer

- Test new production target
  - 30 – 50% surface muon yield increase

Very important step to start physics run from next year
Status

Ready
Summary & prospects

- All the detectors were upgraded from MEG
  - to make maximum use of the highest intensity DC muon beam to date.
  - Full engineering run this year.
    - Still have to fight with a few issues: demonstrate CDCH stability, LXe energy resolution, finalize electronics.

- Physics data acquisition from 2020 for (at least) 3 years to reach a sensitivity $6 \times 10^{-14}$.
  - MEG limit will be exceeded in a few months.

- Build another more robust drift chamber by 2021.
## Low-mass drift chambers

<table>
<thead>
<tr>
<th></th>
<th>Gas</th>
<th>Cell size</th>
<th>Sense wire</th>
<th>Field wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO II</td>
<td>Ar:C\textsubscript{2}H\textsubscript{6} 50:50</td>
<td>14 mm</td>
<td>20-\textmu m Au-W</td>
<td>110-\textmu m Au-Al,</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>110-\textmu m Cu/Be</td>
</tr>
<tr>
<td>BESIII</td>
<td>He:C\textsubscript{3}H\textsubscript{8} 60:40</td>
<td>12–16.2 mm</td>
<td>25-\textmu m Au-W</td>
<td>110-\textmu m Au-Al</td>
</tr>
<tr>
<td>Belle II</td>
<td>He:C\textsubscript{2}H\textsubscript{6} 50:50</td>
<td>6–18 mm</td>
<td>30-\textmu m Au-W</td>
<td>126-\textmu m Al</td>
</tr>
<tr>
<td>COMET-Phase I</td>
<td>He:iC\textsubscript{4}H\textsubscript{10} 90:10</td>
<td>16–16.8 mm</td>
<td>25-\textmu m Au-W</td>
<td>126-\textmu m Al</td>
</tr>
<tr>
<td>KLOE</td>
<td>He:iC\textsubscript{4}H\textsubscript{10} 90:10</td>
<td>20–30 mm</td>
<td>25-\textmu m Au-W</td>
<td>81-\textmu m Ag-Al</td>
</tr>
<tr>
<td>MEG II</td>
<td>He:iC\textsubscript{4}H\textsubscript{10} 85:15</td>
<td>6.6–9 mm</td>
<td>20-\textmu m Au-W</td>
<td>40-\textmu m Ag-Al</td>
</tr>
</tbody>
</table>

**KLOE** used same type of wire without any problem for **>10 years**

Constructed under 50% R.H., never observed salt formation.

<table>
<thead>
<tr>
<th>Type</th>
<th>(X_0) (mm)</th>
<th>((X)_{\text{wires}}^{\text{wire}}) ((10^{-3} X_0))</th>
<th>((X)_{\text{tot}}^{\text{total}}) ((10^{-3} X_0))</th>
<th>(\theta_{\text{wires}}^{\text{MCS}}) (mrad)</th>
<th>(\theta_{\text{tot}}^{\text{MCS}}) (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al (5056)</td>
<td>89</td>
<td>0.72</td>
<td>1.5</td>
<td>5</td>
<td>7.6</td>
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<tr>
<td>Ti</td>
<td>36</td>
<td>1.26</td>
<td>2.1</td>
<td>6.8</td>
<td>9</td>
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<tr>
<td>CuBe</td>
<td>14.7</td>
<td>2.58</td>
<td>3.4</td>
<td>10.1</td>
<td>11.7</td>
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<tr>
<td>Stainless Steel (302)</td>
<td>17.8</td>
<td>2.2</td>
<td>3</td>
<td>9.3</td>
<td>11</td>
</tr>
</tbody>
</table>

Other material than Al is **not acceptable** from the resolution point of view.

**Bare Al wire** could be a better alternative, but difficulty in soldering.

(Naturally coated by Al\textsubscript{2}O\textsubscript{3})
Possibilities

- Al/Au 40 and 50μm
  - requirement: only if insensitive to humidity
- Al or Ti 50μm
  - requirement: effective soldering or gluing procedure
- Ti/Au 50μm
  - not yet found a good producer
    - DISCARDED
- Cu 40 and 50μm
  - pros: standard use in other chambers
  - cons: large impact on experiment sensitivity
    - DISCARDED
Drift cell configuration

U-layer

V-layer

cathode mesh (40μm)
cathode wire (50μm)
Lepton flavor violation

Low scale

B(μ → eγ) \sim 10^{-11} - 10^{-14}

Ultra-high scale

Force unification
Matter unification
Charge quantization

GUT

Flavor violation from quark Yukawa

SUSY

Flavor violation from neutrino Yukawa

Seesaw

Neutrino mass
Leptogenesis

TeV scale

Spacetime–internal sym. unification
Darkmatter?
Solution for hierarchy problem?

Low scale

Lepton flavor violation

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top-down
Other reasons

$\mu \rightarrow e\gamma$ provides the most stringent limit on the LFV Higgs decay $\text{BR}(h \rightarrow \mu e) < 10^{-8}$

(CMS limit: $\text{BR}(h \rightarrow \mu e) < 3.5 \times 10^{-4}$)

Strong correlation b/w observed anomalies. If new particle couples to both muon and electron it induces sizable $\mu \rightarrow e\gamma$. 

$\mu \rightarrow e\gamma$
MEG result (2009 – 2013)

\[ R_{BG} \propto R_{\mu}^2 \cdot \delta E_e \cdot (\delta E_\gamma)^2 \cdot \delta \omega/4\pi \cdot \delta t \]

- Search for \( \mu^+ \rightarrow e^+\gamma \) in \( 1.7 \times 10^{13} \) muon decays.
- No excess was found, and new upper limit was set:

\[ \mathcal{B}(\mu^+ \rightarrow e^+\gamma) < 4.2 \times 10^{-13} \text{ (90\% C.L.)} \]

(while \( 5.3 \times 10^{-13} \) expected)

This is the tiniest upper limit for any particle's BR.

\( \times 30 \) improvement from the prev. experiment
Readout electronics

- New DAQ/Trigger system being developed: WaveDAQ system
  - Used for all MEG-II detectors in common
  - Dense & compact system to cope with increased # of channels.
  - Away from VME crates
  - No pre-amplifier at detector side
  - Custom multi-functional readout board: WaveDREAM
    - Analog FE (programmable shaper & amplifier), SiPM bias-voltage supply, waveform sampling (DRS4), digitization, discriminator, FPGA-based trigger in one module
  - Synchronization accuracy < 20 ps (over different crate modules)