Muon $g-2$/EDM at J-PARC

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TRIUMF
on behalf of the J-PARC $g-2$/EDM Collaboration
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University of Alberta
Edmonton

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Natural Sciences and Engineering Research Council, Canada
TRIUMF, Canada’s National Laboratory for Particle and Nuclear Physics
The muon’s static dipole moments

- The magnetic and electric dipole moments $\mu$ and $d$ of are defined in terms of the particle’s mass, charge, and spin $S$, with proportionalities $g$ and $\eta$:

\[
\vec{\mu} = g \left( \frac{e}{2m} \right) \vec{S}, \quad \vec{d} = \eta \left( \frac{e}{2m} \right) \vec{S}
\]

- For a Dirac particle $g \equiv 2$, but radiative corrections add an anomaly $a$:

\[
\mu = (1 + a) \left( \frac{e\hbar}{2m} \right), \quad a \equiv \frac{g-2}{2}
\]

- For a muon with velocity $\beta$ perpendicular to a magnetic field $B$ and electric field $E$, there will be cyclotron motion at frequency $\omega_c$ while the spin will rotate at frequency $\omega_s$, with difference $\omega_a$, added to EDM rotation at frequency $\omega_\eta$:

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

\[
\omega_a, \quad \omega_\eta
\]

from Gorringe and Hertzog, Prog. in Part. Nucl. Phys. (in press)
Results of BNL E821

\[
\begin{align*}
\mu_{\mu}^{E821} &= 116\ 592\ 091(54)(33) \times 10^{-11} \\
\mu_{\mu}^{SM} &= 116\ 591\ 803(1)(42)(26) \times 10^{-11} \\
\Delta \mu_{\mu} &= \mu_{\mu}^{exp} - \mu_{\mu}^{SM} = 288(63)(49) \times 10^{-11}
\end{align*}
\]

A. Hoecker and W.J. Marciano, PDG Review of Particle Properties (September 2014)

- \( \mu_{\mu} \) differs from SM predictions by \( \sim 3.6\sigma \)

- Motivation for improvements in the SM prediction, and better experiments
  - FNAL E989
  - J-PARC E34

K. Hagiwara et al. (HLMNT), J. Phys. G 38, 085003 (2011)

G.W. Bennett et al. (E821), Phys. Rev. D 73, 072003 (2006) (corrected)
### Anomalous moment $a_\mu$ in SM

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Value ($10^{-11}$)</th>
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<tbody>
<tr>
<td>QED (leptons)</td>
<td>$116 , 584 , 718.95 \pm 0.08$</td>
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<tr>
<td>Electroweak</td>
<td>$153.6 \pm 1$ (quark triangle loops)</td>
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<tr>
<td>HVP (leading order $\alpha^2$) (hadronic loop corrections)</td>
<td>$(e^+e^- \rightarrow \text{hadrons}) , 6 , 923 \pm 42(\text{exp}) \pm 3(\text{QCD})$</td>
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<td>$(\tau \rightarrow \nu_\tau + \text{hadrons}) , 7 , 015 \pm 42(\text{exp}) \pm 19(\text{Ispin}) \pm 3(\text{QCD})$</td>
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<td>Hadronic (higher order $\alpha^3$)</td>
<td>$7 \pm 26$ ($\text{Hlbl}$)</td>
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<tr>
<td>Total $a_\mu$, SM</td>
<td>$(e^+e^-) , 116 , 591 , 803 \pm 1(\text{EW}) \pm 42(\text{loH}) \pm 26(\text{hoH})$</td>
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</tbody>
</table>

- Theoretical uncertainties are dominated by leading order hadronic vacuum polarization and hadronic light-by-light scattering contributions.
  - A. Hoecker and W.J. Marciano, PDG Review of Particle Properties (September 2014)
Compare: Fermilab and J-PARC

**Fermilab (similar to BNL)**

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

- eliminate effect of $E$-field via “magic” momentum:
  - $\gamma^2 = 1 + a^{-1}$
  - $p_\mu = 3.09$ GeV/c required
- very uniform $B$
- electric quadrupole field focusing
- $B = 1.45$ T
- $\rho = 7$ m
- periodic calorimeters with some tracker modules

**J-PARC**

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

- eliminate effect of $E$-field via $E = 0$
- very uniform $B$ in compact region
- weak $B$ field focusing, no $E$ focusing – must use “ultra-cold” beam
  - polarization reduced to 50%
  - allows spin flipping
- choose $p_\mu = 0.3$ GeV/c
- $B = 3$ T
- $\rho = 0.33$ m
- uniform tracker detection along stored orbit (EDM sensitivity)

Both experiments follow time dependence of muon polarization by detecting the asymmetric PV weak decay $\mu \rightarrow e\nu\bar{\nu}$.
J-PARC $g-2$ schematic

- 3 GeV proton beam (333 uA)
- Surface muon beam (28 MeV/c, $\sim 10^8$/s)
- Resonant laser ionization of muonium for ultra-cold $\mu^+$ ($\sim 10^6 \mu^+$/s)
- Muonium production (300 K, 25 meV $\Rightarrow$ 2.3 keV/c)
- Muon reacceleration (thermal to 300 MeV/c)
- Muon storage ring (3T, r = 33 cm, 1 ppm local)
Muonium is emitted into vacuum from silica nanostructures (aerogels, powders)
- aerogels developed for J-PARC $g$–2 ultra-cold muon source
- laser ablation of holes in aerogel provided $\times 10$ increase in yield
- muonium emission measurements done at TRIUMF
Surface muons to ultra-cold muons

- Surface $\mu^+$ from $\pi^+$ decay at rest
  - $E_k = 3.4 \text{ MeV}, \ p = 27 \text{ MeV}/c$
  - $\Delta p/p = 0.05 \text{ rms}, \Delta p = 1.3 \text{ MeV}/c$
  - $\Delta p_x/p = 0.04, \Delta p_y/p = 0.08$
- Thermalization as $\text{Mu} (\mu^+ e^-)$
  - $E_k = 0.025 \text{ eV}, \ p = 2.3 \text{ keV}/c$
  - $\Delta p/p = 0.42 \text{ rms}, \Delta p = 1 \text{ keV}/c$
  - “ultra-cold” compared to surface $\mu^+$
- Thermal diffusion of $\text{Mu}$ into vacuum
  - $\mu^+$ remains ultra-cold
- Ionization
  - $1S \rightarrow 2P \rightarrow \text{unbound} (122 \text{ nm}, 355 \text{ nm})$
- Acceleration
  - $E$ field, RFQ, linear structures
  - to $E_k = 212 \text{ MeV}, \ p = 300 \text{ MeV}/c$
  - adds to $p_z$ but not significantly to $\Delta p$
Spin manipulation via $\mu^+e^-$ precession

- Spin reversal is an important tool in polarization experiments
- Muonium polarization in aerogel target or vacuum will rotate in transverse field
  - $0.14 \text{ MHz/mT} \Rightarrow 2\pi$ rotation in $0.6 \mu s$ at $0.119 \text{ mT}$
  - Muon beam consists of 2 pulses separated by $0.6 \mu s$ (at 25 Hz repetition)
    - Polarizations are added for fields at multiples of $0.119 \text{ mT}$
- Selecting ionization time selects direction of polarization

Simulation of Mu time distribution in vacuum for J-PARC beam.
Laser ionization of Mu

- **Two steps**
  - Lyman $\alpha$ 1S→2P at 122 nm
  - 2P→unbound at 366 nm

- **Lyman $\alpha$**
  - two-photon resonance four-wave mixing in Kr
  - pump with 212.55 nm
  - generate 122 nm via difference mixing with 820 nm
  - goal is 100 $\mu$J in 2 ns pulse with 80 GHz width at 25 Hz

### 122 nm, $\mu$J

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<tr>
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<th>20</th>
<th>40</th>
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### 355 nm, mJ

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Calculated ionization efficiencies (2 cm² area)

### $\omega_{\text{Ly-}\alpha} = 2 \omega_1 - \omega_2$

<table>
<thead>
<tr>
<th>$\omega_1$</th>
<th>$\omega_2$</th>
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<tbody>
<tr>
<td>815~850 nm</td>
<td>212.55 nm</td>
</tr>
<tr>
<td>121.5~122.2 nm</td>
<td>212.55 nm</td>
</tr>
</tbody>
</table>

**Ionization of Mu with 820 nm light:**
- Firstly 212.55 nm
- Then 122 nm
- Finally 366 nm

**Conversion efficiency:**
- For 122 nm: 40, 70, 60, 50, 80, 40, 100, 200, 100, 50, 20, 40, 60, 80, 100, 120
- For 355 nm: 50, 100, 150, 200, 250, 300, 350, 400
Ultra-cold muon acceleration

Requirements

- fast acceleration to reduce decay losses ($\tau_\mu = 2.2$ $\mu$s at rest)
- small emittance growth to enable injection and capture by storage ring

<table>
<thead>
<tr>
<th>Energy</th>
<th>$\beta$</th>
<th>5.6 keV</th>
<th>0.34 MeV</th>
<th>5.1 MeV</th>
<th>42.3 MeV</th>
<th>200 MeV</th>
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<tbody>
<tr>
<td></td>
<td>$\beta$</td>
<td>0.01</td>
<td>0.08</td>
<td>0.3</td>
<td>0.7</td>
<td>0.94</td>
</tr>
</tbody>
</table>

- Bunching Section
- Low-$\beta$
  - RFQ (324 MHz)
  - High capture efficiency
- Middle-$\beta$
  - Interdigital-H (324 MHz)
  - High shunt impedance
  - DAW (1300 MHz)
  - External coupling structure for Middle-$\beta$
- High-$\beta$
  - Disk loaded structure (1300 MHz)
  - High gradient (4 structures)
Muon storage ring

- **Superconducting solenoid**
  - cylindrical iron poles and yoke
  - vertical $B = 3$ Tesla, <1 ppm locally
  - storage region $r = 33.3 \pm 1.5$ cm, $h = \pm 5$ cm
  - tracking detector vanes inside storage region
  - storage maintained by static weak focusing
    - $n = 1.5 \times 10^{-4}$, $rB_z(z) = -n zB_z(r)$ in storage region

- **Spiral injection**
  - transfer line from end of linac with downward deflection
  - hole in upper yoke for beam entrance
    - permits entry, shields beam from field
  - pulsed radial field on injection
    - reduces vertical momentum to match a trapped orbit

---

**Figure 7.1:** Outline of three-dimensional injection scheme. A radial fringe field deflects the vertical component of the beam momentum to the horizontal component. Pulsed radial magnetic field removes the residual vertical motion down to $10^{-5}$ [rad], and then weak focusing field keeps the beam inside storage area.

**Figure 7.2:** Schematic representation of spiral injection for our case. A solenoid magnet is suitable. A radial fringe field, shown as $B_R$, deflects the vertical component of the beam momentum to the horizontal component.
J-PARC $g-2$ statistics goals (Stage 1)

Statistical uncertainties

- **Goals**
  - $\Delta \omega_a / \omega_a = 0.36$ ppm (0.163/\(\text{PN}^{1/2}\))
  - $\Delta d_\mu = 1.3 \times 10^{-21}$ e \cdot cm
  - $\Delta d_e < 1.05 \times 10^{-27}$ e \cdot cm

- **Running time**
  - measurement only: $2 \times 10^7$ s

- **Muon rate from H-line**
  - 1MW, SiC target: $3.2 \times 10^8$ s^{-1}

- **Conversion efficiency to ultra-slow muons**
  - Mu emission (S1249), laser ionization
  - lose polarization: 100% $\rightarrow$ 50%
  - $2.15 \times 10^{-3}$ (Stage 2 goal is 0.01)

- **Acceleration efficiency including decay**
  - RFQ, IH, DAW, and high-$\beta$: 0.52

- **Storage ring injection, decay, kick**
  - 0.92

- **Stored muons**
  - $3.3 \times 10^5$ s^{-1}

- **Detected positrons ($\epsilon = 0.12$)**
  - $4.0 \times 10^4$ s^{-1}

Further development of aerogel microstructure planned to optimize this fraction.
Summary

- The BNL E821 measured value of the muon magnetic moment $a_\mu$ may be an indication of physics beyond the Standard Model.
  - it needs to be verified with increased precision (FNAL E989)
  - it deserves to be verified in an independent experiment (J-PARC E34)
- The J-PARC method has systematic uncertainties different from BNL E821.
  - smaller and more precise magnetic storage field
  - compact detector with tracking capability
  - flip spin to analyze asymmetry rather than decay time distribution
  - ultra-cold muon beam using muonium in vacuum as an ion source
- R&D phase evolving to construction phase with a growing collaboration (136 members, 8 countries).
**Goals for the next generation of \( g-2 \)**

- Reduced experimental uncertainties (x4), coupled with a modest (x1.5) reduction for the SM prediction, will decrease the uncertainty in the difference by x2. With the same central values, the significance grows to 7–8 \( \sigma \).
- Regardless of the central value, this precision will discriminate among possible extensions to the SM, in a way complementary to LHC discoveries.
Decay positron tracking detector

- Detect $e^+$ at higher range of energies (200–290 MeV/c)
  - $A<0$ for lower energies
  - want typically one turn
- Radial vanes of axial and radial Si strips
- Core of lead-tungsten to absorb multiple turns

### Figure of merit

$$fom = \frac{dN(e^+)/dp_L}{(NA^2)^{1/2}}$$

### Specifications

<table>
<thead>
<tr>
<th>Item</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial volume</td>
<td>240mm (radial) x 400 mm (axial)</td>
</tr>
<tr>
<td>Number of vane</td>
<td>48</td>
</tr>
<tr>
<td>Sensor technology</td>
<td>Single-sided Silicon strip sensor (p-on-n)</td>
</tr>
<tr>
<td>Strip</td>
<td>axial-strip : 100mm pitch, 72mm long, 1024 ch radial-strip: 188mm pitch, 98mm long, 384 ch</td>
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<tr>
<td>Sensor dimension</td>
<td>74 mm x 98 mm x 0.32mm</td>
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<tr>
<td>Number of sensor</td>
<td>1152 (12 sensors per vane)</td>
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<td>Number of channel</td>
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## Proposed timeline

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Now to Fall 2019
Identifying Mu in vacuum

- A multi-step process of:
  - $\mu^+$ thermalization, $\mu^+e^-$ formation.
  - $\mu^+e^-$ escapes into voids in evacuated silica nanostructure ($\sim100\%$).
  - $\mu^+e^-$ migrates (“diffuses”) to nearby material boundary ($\sim$ few %).

- Identify and characterize by:
  - time and position ($y,z$) correlations of muon decays from $e^+$ tracking (drift chambers).

- Muons decay in:
  - the target, as $\mu^+e^-$ and $\mu^+$.
  - vacuum, in flight, as $\mu^+e^-$.
  - surrounding materials ($\mu^+e^-$ or $\mu^+$).

- Provides image of decay locations in $(y,z)$, as a function of time.
Mu in vacuum: 2010 and 2011

- Aerogel samples
  - all high uniform and optically transparent
  - different preparations
    - hydrosopic nature of surfaces
  - different densities: 27–180 mg/cm³

- Observations
  - no obvious dependence on density or preparation
  - speed larger than thermal?

- Partial yields \(\sim 0.003\)
  - into regions 1–3, distance 10–40 mm from aerogel surface
  - normalized to all muon decays observed
    - some care required to interpret yield expected with different beams and targets

The PAC commends the excellent progress that the g-2 collaboration has made in all areas and recommends that Stage-1 approval should be granted.

The realization of the experiment still requires significant advances for the chosen experimental technology. Most importantly, the intensity of the cold muon source needs to be improved by almost a factor 10. In addition to the design and R&D the collaboration has provided a set of milestones that can be used to monitor the progress of the g-2 project. These milestones appear well suited to guide the development of the project towards Stage-2 approval (CDR, section 1.7):

**M1** Demonstration of the ultra-cold muon production with the required conversion efficiency leading to an intensity of $1 \times 10^6 \mu^+$/s.

**M2** Muon acceleration tests with the baseline configuration of low-$\beta$ muon LINAC, i.e. RFQ, and IH-LINAC.

**M3** Tests of the spiral injection scheme.

**M4** Production of a prototype magnet and development of the field monitor with the required precision.

**M5** Demonstration of rate capability of the detector system for decay positron detection.

The PAC emphasizes the importance of rapid progress on the first milestone, to increase the intensity of the ultra-cold muon production. This goal should be pursued by the collaboration with the highest priority.
Independent *simulations* based on a diffusion model showed emission increase of ~5 for a surface with a structure of size ~0.2 mm.

How could that structure be created in the delicate aerogel material?
Results of 2013 data

- Used a model-independent approach to estimate yields.
- For 0.3 mm structure, observed 11 times yield previously reported from 2011 data, 8 times yield found in similar flat target in 2013.
- Model-independent approach cannot independently estimate total yield or partial yield near target for laser ionization estimates.
  - ➔ apply diffusion model analysis.

Table 1  Yield of Mu in the vacuum region 1–3. For all laser processed samples, the diameter of the structure is 270 μm.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Laser-ablated structure (pitch)</th>
<th>Vacuum yield (per 10^3 muon stops)</th>
</tr>
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<tbody>
<tr>
<td>Flat</td>
<td>none</td>
<td>3.72 ± 0.11</td>
</tr>
<tr>
<td>Flat (Ref. [7])</td>
<td>none</td>
<td>2.74 ± 0.11</td>
</tr>
<tr>
<td>Laser ablated</td>
<td>500 μm</td>
<td>16.0 ± 0.2</td>
</tr>
<tr>
<td>Laser ablated</td>
<td>400 μm</td>
<td>20.9 ± 0.7</td>
</tr>
<tr>
<td>Laser ablated</td>
<td>300 μm</td>
<td>30.5 ± 0.3</td>
</tr>
</tbody>
</table>

Preliminary analysis for laser ablated (pitch = 0.3 mm) aerogel:
- much better signal to background enables more reliable diffusion model comparison
  - simultaneous fit to 3 vacuum regions at T=322 K shown
- best fit emission velocities correspond to $322 \pm 5$ (stat) K
- $D=870 \pm 20$ cm$^2$ s$^{-1}$, $\chi^2 = 168/140$ (p=5%)
- total yield into vacuum: 0.10 per stopped $\mu^+$ (from simulation with model) for TRIUMF beams
- fit of yield into vacuum regions V1-V3: 0.030 per stopped $\mu^+$, similar to model independent analysis