muEDM at PSI: An attractive possibility to extend even further the intensity frontier program

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\[ \text{set } E \equiv aBc\beta \gamma^2 \]

\[ R = 0.14 \text{ m} \]

Prescursur: \( \sigma(d_\mu) < 3 \cdot 10^{-21} \text{ ecm} \)

Final: \( \sigma(d_\mu) < 6 \cdot 10^{-23} \text{ ecm} \)
Motivations: Search for EDMs

• The Standard Model of particle physics: A great triumph of the modern physics but not the ultimate theory

• Low energy precision physics: Rare/forbidden decay searches, symmetry tests, precision measurements very sensitive tool for unveiling new physics and probing very high energy scale

• Baryogenesis, the creation of more matter over anti-matter, requires additional CP violation (CPV) beyond the SM

• These additional CPV underlying interactions would also result in Electric Dipole Moments (EDMs) of fundamental particles at the current experimental sensitivity, well above the SM predictions
muEDM: Definition

Magnetic moment $\left( \mu = \frac{g q h}{4mc} \sigma \right)$

Electric moment $\left( d = \frac{\eta q h}{4mc} \sigma \right)$

A discovery of a muon EDM indicates CP violation invoking CPT theorem
muEDM dedicated search: Current status

- EDMs of fundamental particles are intimately connected to the violation of time invariance and the combined symmetry of charge and parity
- The different EDM searches are sensitive to different, unique combinations of underlying CPV sources

Quite poor current direct limit
\[ d_\mu < 1.5 \times 10^{-19} \text{ ecm (CL 90\%)} \]
Impressive limits on the electron EDM deduced from measurements using atoms or molecules, e.g., thorium oxide molecules $d_e < 1.1 \times 10^{-29} \text{ cm (CL 90\%)}$ lead to $d_\mu < 2.3 \times 10^{-27} \text{ cm (CL 90\%)},$ which is many orders of magnitude better than the direct limit $d_\mu.$

- $m_\mu/m_e$: naive rescaling assumes minimal flavor violation (MFV), that is a model dependent assumption.

- The muon plays an exceedingly prominent role in unveiling path towards BSM. All substantial evidence found in laboratory experiments for a departure from SM physics involves the muon:
  - $g-2$ experiment at FNAL ($a = (g-2)/2 \rightarrow 4.2\sigma$)
  - LFU in B-meson decays ($3.1\sigma$, more than $5\sigma$ evidence when combining all LFU observable in B-meson decays)
  - Deficit in the 1st row unitarity of the CKM matrix may be interpreted as LFU violation (about $4\sigma$)
muEDM direct search: Why now?

- FNAL/JPARC g-2 experiments aims at $d_\mu \sim O(10^{-21}) \text{ ecm (via g-2)}$

- Direct muEDM search at PSI in stages:
  - Precursors: $d_\mu < 3 \times 10^{-21} \text{ ecm}$
  - Final: $d_\mu < 6 \times 10^{-23} \text{ ecm}$
Few scalings model-independent predictions

- $\text{BR}(\ell_i \to \ell_j \gamma) \textbf{vs.} (g - 2)_\mu$

\[
\begin{align*}
\text{BR}(\mu \to e\gamma) & \approx 3 \times 10^{-13} \left( \frac{\Delta a_{\mu}}{3 \times 10^{-9}} \right)^2 \left( \frac{\theta_{e\mu}}{10^{-5}} \right)^2 \\
\text{BR}(\tau \to \mu\gamma) & \approx 4 \times 10^{-8} \left( \frac{\Delta a_{\mu}}{3 \times 10^{-9}} \right)^2 \left( \frac{\theta_{\ell\tau}}{10^{-2}} \right)^2
\end{align*}
\]

- EDMs assuming “Naive scaling” $d_{\ell_i}/d_{\ell_j} = m_{\ell_i}/m_{\ell_j}$

\[
\begin{align*}
d_e & \approx \left( \frac{\Delta a_{\mu}}{3 \times 10^{-9}} \right) 10^{-28} \left( \frac{\phi_e^{CPV}}{10^{-4}} \right) \text{ e cm}, \\
d_\mu & \approx \left( \frac{\Delta a_{\mu}}{3 \times 10^{-9}} \right) 2 \times 10^{-22} \phi_\mu^{CPV} \text{ e cm}.
\end{align*}
\]

- **Main messages:**
  - $\Delta a_{\mu} \approx (3 \pm 1) \times 10^{-9}$ requires a nearly flavor and CP conserving NP
  - Large effects in the muon EDM $d_\mu \approx 10^{-22} \text{ e cm}$ are still allowed.
Reminder: g-2 in numbers and experimental approaches

Anomalous magnetic moment (g-2)

\[ a_\mu = \frac{(g-2)}{2} = 11 659 208.9 (6.3) \times 10^{-10} \text{ (BNL E821 exp)} \]

\[ a_\mu = 11 659 182.8 (4.9) \times 10^{-10} \text{ (standard model)} \]

\[ \Delta a_\mu = \text{Exp} - \text{SM} = 26.1 (8.0) \times 10^{-10} \sim 4\sigma \text{ anomaly} \]

In uniform magnetic field, muon spin rotates ahead of momentum due to \( g-2 = 0 \)

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

BNL E821 approach \( \gamma = 30 \) \( (P=3 \text{ GeV/c}) \)

J-PARC approach \( E = 0 \) at any \( \gamma \)

Continuation at FNAL with 0.1ppm precision
Proposed at J-PARC with 0.1ppm precision
EDM search: From the “frequency” approach…

$$\vec{\omega} = \frac{q}{m} \left[ a \vec{B} - \left( \alpha + \frac{1}{1 - \gamma^2} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right] + \frac{q}{m} \eta \left( \vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right)$$

- i.e. FNAL: The decay positrons are recorded using calorimeters and straw tube trackers inside the storage ring.
- The sensitivity to a muon EDM is limited by the resolution of the vertical amplitude, proportional to $\zeta$, of the oscillation in the tilted precession plane.
- i.e. J-PARC: even if the technique is different the sensitivity to an EDM is limited by the resolution of the vertical amplitude.
...to the frozen-spin technique

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

- The frozen-spin technique uses an Electric field perpendicular to the moving particle and magnetic field, fulfilling the condition:
  \[ a \vec{B} = \left( a - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}_f}{c} \]

- Without EDM, \( \omega = 0 \), the spin follows the momentum vector as for an ideal Dirac spin-1/2 particle, while with an EDM it will result in a precession of the spin with \( \omega_e \parallel E \)

- The sensitivity to a muon EDM is given by the asymmetry up/down of the positron from the muon decay
EDM: From the “frequency” approach to the frozen-spin technique

• Putting everything together, here a summary:
The sensitivity to a muon EDM is given by the asymmetry up/down of the positron from the muon decay. Positron are emitted predominantly along the muon spin direction.

\[ A(t) = \frac{N_\uparrow(t) - N_\downarrow(t)}{N_\uparrow(t) + N_\downarrow(t)} = \alpha \sin \left( \frac{2d_\mu}{\hbar} t \right) \approx \alpha p \frac{2d_\mu}{\hbar} t \]

The slope gives the sensitivity of the measurement:

\[ \sigma(d_\mu) = \frac{\hbar \gamma^2 a_\mu}{2pE_f \sqrt{N} \gamma \tau_\mu \alpha} \]

- \( p \) := initial polarization
- \( E_f \) := Electric field in lab
- \( \sqrt{N} \) := number of positrons
- \( \tau_\mu \) := lifetime of muon
- \( \alpha \) := mean decay asymmetry
The general experimental idea

- Muons enter the uniform magnetic field
- A radial magnetic field pulse stops them within a weakly focusing field where they are stored
- Radial electric field ‘freezes’ the spin so that the precession due to the MDM is cancelled

\[ E_f \approx \frac{g - 2}{2} B c \beta \gamma^2 \]
muEDM final at PSI: Frozen spin and longitudinal injection

- $\mu^+$ from Pion-decay $\rightarrow$ high polarization $p \approx 95$
- Injection through superconducting channel
- Fast scintillator triggers pulse
- Magnetic pulse stops longitudinal motion of $\mu^+$
- Weakly focusing field for storage
- Thin electrodes provide electric field for frozen spin
- Pixelated detectors for $e^+$—tracking

$p=125$ MeV/c [muE1]
muEDM Precursor at PSI: Proof-of-principle of the frozen spin technique

Develop key technologies and design the final instrument
• Full MC model
• Full FEM model
• Analysis and DAQ
• Nested electrode system with a minimal material budget for the frozen-spin technique
• Pulsed magnetic field to kick muons on a stable orbit
• Injection channel made of a superconducting shield

Perform a first EDM measurement using existing infrastructure and solenoid at PSI
• Develop magnetic-field correction coils and field measurement device
• Develop dedicated positron and muon detectors
• Demonstrate injection
• Demonstrate for the first time electric-field tuning to frozen-spin condition
• First dedicated frozen-spin EDM measurement
First meeting in person in Pisa

- First discussion of tasks and potential interest
- Theoretical seminar (Paride Paradisi)
- Material available at the link: https://indico.psi.ch/event/12975/
Foreign interested institutes

• (apart PSI, ETH Zurich, INFN):
  • University of Zurich, University of Geneve
  • University of Liverpool, University of London (UCL), University of Manchester, University of Sussex
  • Mainz, Mainz PRiSMA, Universitat Dortmund TU
  • Shanghai University, Tsung-Dao Lee Institute
  • Argonne National Laboratory, Brookhaven National laboratory
A tentative schedule

1. Full proposal for both phases to CHRIISP committee
2/a Magnet call for tender / precursor design fix
b Precursor ready for assembly/commissioning
3/c Technical design report / frozen spin demonstration
d First data for precursor muEDM
4. Magnet delivered, characterized and accepted
5. Successful commissioning / start of data taking
6. End of data acquisition for muEDM
Key milestones of the precursor

• Demonstrate the injection

• Demonstrate for the first time electric-field tuning to frozen spin condition

• And then...having detectors to prove it and eventually to perform the first measurement of muEDM with this technique
  
  • Plastic scintillators coupled to SiPM (Muon tagging, Top/bottom asymmetry and eventually positron tracking - at the first stage to keep the detector complexity at the minimum)

  • PTC feasibility study: muon tracking (to prove that the wanted muon tracks are the selected ones) [not excluded as positron tracker but other options could be more competitive]
Beam-line at PSI for the precursor in piE1

- Surface muon beam at 28 MeV/c
- Muon rate $\sim 3 \times 10^6$
- Test bed for development
- Demonstration of storage and detection of $g-2$/EDM, e.g. with PSC magnet $\phi = 200\,\text{mm}$
  - the larger the bore the better for instrumentation
Beam measurements at PSI for the precursor in piE1

- Horizontal Emittance: 200 \(\pi\) mm mrad
- Vertical Emittance: 270 \(\pi\) mm mrad
- Beam rate about 2 \(\times\) 10\(^6\) s\(^{-1}\)
- Acceptance phase space:
  - High transmission through channel 6%
  - Injection efficiency about 2%
  - Expected \(e^+\) detection rate 2kHz
- Moderate E field 3kV/cm
The “muEDM” magnet and the injection scheme

- The PSC magnet: Up to 5 T (3 T needed for muEDM)
- CAD view of the injection SC line, pulsed coils, HV electrodes, Grounds and support structure
Outlook

- A very attractive experiment with strong scientific motivations
- The main challenges: Beam related aspects and B and E fields, systematics and the analysis
- Quite stimulating to face with these new scientific tasks
- Large room for leading and shaping the experiment at different and complementary levels

- ERC (consolidator) just granted. It represents the base on which start to build the rest
Thank you for your attention!
Back-up
Sensitivity: Very preliminary

\[
\sigma = \frac{\hbar \gamma a_\mu}{(2PE_f \sqrt{N} \tau_\mu \alpha)} < 6 \times 10^{-23} \text{ ecm}
\]

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<th>Value</th>
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DC muon beams. Future prospects: HiMB

- **Aim:** $O(10^{10} \text{ muon/s})$; Surface (positive) muon beam ($p = 28 \text{ MeV/c}$); DC beam
- **Time schedule:** $O(2027)$
- **Key elements:** Slanted Target and optimised beam line (higher capture efficiency and large space acceptance transport channel)
Slanted target: First test on 2019 and since then in operation

- Expect ~30-60% enhancement
- Measurements successfully done in different experimental areas in fall 2019
- Increased muon yield CONFIRMED!
- To be seen: impact of higher thermal stress on long term stability of target wheel
The muCool project at PSI

- Aim: low energy high-brightness muon beam
- Phase space reduction based on: dissipative energy loss in matter (He gas) and position dependent drift of muon swarm
- Increase in brightness by a factor $10^{10}$ with an efficiency of $10^{-3}$
- Longitudinal and transverse compression (1st stage + 2nd stage): experimentally proved
- **Next Step**: Extraction into vacuum

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**μSR (solid state physics)**
muonium (spectroscopy, gravitational interaction...)
muon experiments (μEDM, g-2...)

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\[
\vec{v}_{\text{drift}} = \frac{\mu E}{1 + \left(\frac{\omega}{\nu_{\text{col}}}\right)^2} \left[\hat{\vec{E}} + \frac{\omega}{\nu_{\text{col}}} \hat{\vec{E}} \times \hat{\vec{B}} + \left(\frac{\omega}{\nu_{\text{col}}}\right)^2 \left(\hat{\vec{E}} \cdot \hat{\vec{B}}\right) \hat{\vec{B}}\right]
\]

→ Transforms a standard $\mu^+$ beam into a high-brightness low-energy $\mu^+$ beam
Few numbers

• Precision achieved in the studies of magnetic dipole moments

\[
\Delta \left( a_e^{\text{SM}} - a_e^{\text{exp}} \right) \approx 10^{-12} \\
\Delta \left( a_\mu^{\text{SM}} - a_\mu^{\text{exp}} \right) \approx 10^{-9}
\]

• Sensitivity to new physics scales like the lepton mass squared

\[ a_f^{\text{NP}} \sim \frac{m_f^2}{\Lambda^2} \]

• Muon is a more sensitive probe (but electron is becoming relevant…)

\[ \frac{\Lambda_\mu}{\Lambda_e} \sim \frac{m_\mu}{m_e} \sqrt{\frac{\Delta a_e}{\Delta a_\mu}} \sim 6 \]
Dirac’s relativistic theory predicted muon magnetic moment “g” = 2

Experiment suggested that g-factor differs from the expected value of 2

Standard Model prediction: $a_{\text{SM}} = a_{\text{QED}} + a_{\text{Had}} + a_{\text{Weak}} + a_{\text{NP}}$

BNL E821 result: 3.3σ deviation from SM prediction

FNAL First Result: April 2021 [using RUN1 with statistics similar to BNL statistics]

RUN1-3 (already collected): ~8x BNL statistics. Aiming at ~20x BNL statistics
NP effects are encoded in the effective Lagrangian

\[ \mathcal{L} = e \frac{m_\ell}{2} \left( \bar{\ell}_R \sigma_{\mu\nu} A_{\ell\ell'} \ell'_L \ell'_L + \bar{\ell}'_L \sigma_{\mu\nu} A^{*}_{\ell'\ell} \ell_R \ell \right) F^{\mu\nu} \quad \ell, \ell' = e, \mu, \tau, \]

- **Branching ratios of** \( \ell \to \ell'\gamma \)

\[ \frac{\text{BR}(\ell \to \ell'\gamma)}{\text{BR}(\ell \to \ell'\nu_\ell \bar{\nu}_{\ell'})} = \frac{48\pi^3\alpha}{G_F^2} \left( |A_{\ell\ell'}|^2 + |A_{\ell'\ell}|^2 \right). \]

- **\( \Delta a_\ell \) and leptonic EDMs**

\[ \Delta a_\ell = 2m_\ell^2 \text{Re}(A_{\ell\ell}), \quad \frac{d_\ell}{e} = m_\ell \text{Im}(A_{\ell\ell}). \]

- "Naive scaling":

\[ \frac{\Delta a_\ell}{\Delta a_{\ell'}} = \frac{m_\ell^2}{m_{\ell'}^2}, \quad \frac{d_\ell}{d_{\ell'}} = \frac{m_\ell}{m_{\ell'}.} \]
Back-up

- **LFV operators @ dim-6**

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2_{\text{LFV}}} \mathcal{O}^{\text{dim-6}} + \ldots .
\]

\[\mathcal{O}^{\text{dim-6}} \ni \bar{\mu}_R \sigma^{\mu\nu} H e_L F_{\mu\nu}, \ (\bar{\mu}_L \gamma^\mu e_L) (\bar{f}_L \gamma^\mu f_L), \ (\bar{\mu}_R e_L) (\bar{f}_R f_L), \ f = e, u, d\]

- $\ell \rightarrow \ell' \gamma$ probe ONLY the dipole-operator (at tree level)
- $\ell_i \rightarrow \ell_j \bar{\ell}_k \ell_k$ and $\mu \rightarrow e$ in Nuclei probe dipole and 4-fermion operators
- When the dipole-operator is dominant:

\[
\begin{align*}
\text{BR}(\ell_i \rightarrow \ell_j \bar{\ell}_k \ell_k) & \approx \alpha \times \text{BR}(\ell_i \rightarrow \ell_j \gamma) \\
\text{CR}(\mu \rightarrow e \text{ in } N) & \approx \alpha \times \text{BR}(\mu \rightarrow e \gamma)
\end{align*}
\]

\[
\frac{\text{BR}(\mu \rightarrow 3e)}{3 \times 10^{-15}} \approx \frac{\text{BR}(\mu \rightarrow e\gamma)}{5 \times 10^{-13}} \approx \frac{\text{CR}(\mu \rightarrow e \text{ in } N)}{3 \times 10^{-15}}
\]

- Ratios like $Br(\mu \rightarrow e\gamma)/Br(\tau \rightarrow \mu\gamma)$ probe the NP flavor structure
- Ratios like $Br(\mu \rightarrow e\gamma)/Br(\mu \rightarrow eee)$ probe the NP operator at work
Could the spatial resolution of single electrons be improved?

**Ar:CH₄ 90:10 → Dᵣ = 208 μm/√cm**

→ σ = 24 μm

**Ar:iButane 95:5 → Dᵣ = 211 μm/√cm**

→ σ = 24 μm

Smaller pads/pixels could result in better resolution!

At Nikhef the GridPix was invented.

**Improving Micromegas: GridPix**

Standard charge collection:
- Pads of several mm²
- Long strips (l~10 cm, pitch ~200 μm)

**Instead:** Bump bond pads are used as charge collection pads.
GridPix

Timepix

Number of pixels: 256 × 256 pixels
Pixel pitch: 55 × 55 μm²
Chip dimensions: 1.4 × 1.4 cm²
ENC: ~ 90 e⁻

Limitations: no multi-hit capability, charge and time measurement not possible for one pixel.
Each pixel can be set to one of these modes: TOT = time over threshold (charge)
Time between hit and shutter end.