Muon Spin Force

Ting Gao
University of Minnesota

Based on 2308.01356 with M.Pospelov and Y.Ema

Constraints on

Muon Spin Force

as a possible explanation to the muon g-2 anomaly

so...

- What is the muon spin force?
- How is it related to the muon g-2 anomaly?
- Does existing experiments exclude it?
- If not, will a future experiment provide a definitive test on it?

Muon spin-vertical direction coupling

Assume there is a light scalar field which has scalar coupling with nucleons and axial vector/pesudoscalar coupling with the muon

$$\mathcal{L}_{\text{eff}} = \ldots + \frac{1}{2}(\partial_\nu \phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - g_S\phi(\bar{n}n + \bar{p}p) + \frac{g_A^{(\mu)}}{2m_\mu}\partial^\alpha\phi\bar{\mu}\gamma_\alpha\gamma_5\mu - g_P^{(\mu)}\phi\bar{\mu}i\gamma_5\mu.$$

In the non-relativistic limit, this turns out to be a force acting on the muon spin

$$H^{(\mu)} = \frac{g_S(g_A^{(\mu)} + g_P^{(\mu)})}{4\pi \times 2m_\mu}(\boldsymbol{\sigma}^{(\mu)} \cdot \boldsymbol{\nabla})\frac{\exp(-m_\phi r)}{r} = \Delta E_{(\mu)}(\mathbf{s} \cdot \mathbf{n})$$

Small for individual nucleon-muon pair, but can be enhanced by the large number of atoms in the Earth to produce a non-negligible effect.

muon spin force as an explanation to the muon g-2 anomaly

- Muon g-2 anomaly: the $\Delta a_\mu \simeq 2.5 \times 10^{-9}$ discrepancy between SM prediction on g-2 and the experimental result, corresponding to 4.2σ (more recently, exceeding 5σ).
- Hadronic vacuum polarization might be responsible, or new physics might be responsible
- A muon spin force modifies the spin dynamics of the muon and can be interpreted as a contribution to muon g-2:

$$\left(\frac{\mathrm{d}\boldsymbol{s}}{\mathrm{d}t}\right)_{\text{rest frame}} = \boldsymbol{s}\times(\mu\boldsymbol{B}-\Delta E_{(\mu)}\mathbf{n}) \quad \rightarrow \quad \boldsymbol{\Omega}_{\gamma=29.3} = \frac{q}{m}\left(a_\mu \boldsymbol{B} - \frac{m}{\gamma q}\Delta E_{(\mu)}\mathbf{n}\right)$$

  This possibility has been discussed before by Ryan Janish & Harikrishnan Ramani 2006.10069, Prateek Agrawal et al 2210.17547, Hooman Davoudiasl & Robert Szafron 2210.14959.
- $|\Delta E_{(\mu)}| = 6 \times 10^{-14}$eV will explain the muon g-2 anomaly

Isotope experiments

A number of isotope experiments have been done to constrain the nuclear spin force

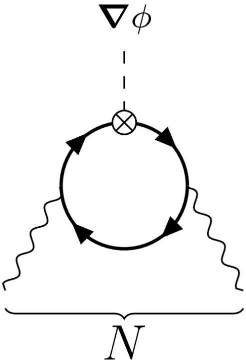
$$H_i = -\mu_N g_i (\mathbf{I}\cdot\mathbf{B}) + \Delta E_i (\mathbf{I}\cdot\mathbf{n})$$

Current best limits are

$$|\Delta E_{\rm Hg}| = \left|\Delta E_{201} - \Delta E_{199}\,\rho_{\rm Hg}\right| < 3.0\times 10^{-21}\,{\rm eV} \quad \text{(UW experiment)}$$
$$|\Delta E_{\rm Xe}| = |\Delta E_{129} - \Delta E_{131}\,\rho_{\rm Xe}| < 1.7\times 10^{-22}\,{\rm eV} \quad \text{(USTC experiment)}$$

Muon spin force can induce nuclear spin force via loop transfer.

Consequences at 1-loop, constraints on pseudoscalar coupling



$$\mathcal{L}_{eff} = \frac{e^2 \nabla\phi}{4\pi^2 m_\mu} \cdot \left(g_P^{(\mu)} \mathbf{B} A_0 + \frac{g_A^{(\mu)}}{12 m_\mu^2} \mathbf{B}\, \nabla^2 A_0 \right).$$

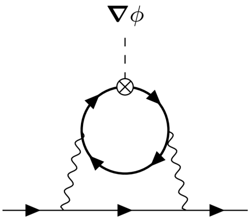
- Pseudoscalar and axial vector couplings are equivalent at tree level, but have different consequences in loops.
- Nuclear charge well approximated by a uniform distribution.
- Magnetic field distribution is uncertain because no nuclear model reliably explains where the nuclear magnetic dipole moment comes from.
- We model the magnetic field to be coming from valance neutron + uniformly polarized nucleus

$$\left|\frac{\Delta E_{\mathrm{Hg}}}{\Delta E_{(\mu)}}\right| = 1\times 10^{-6}; \quad \left|\frac{\Delta E_{\mathrm{Xe}}}{\Delta E_{(\mu)}}\right| = 3\times 10^{-6} \text{ for } g_P^{(\mu)},$$

$$\left|\frac{\Delta E_{\mathrm{Hg}}}{\Delta E_{(\mu)}}\right| = 2\times 10^{-8}; \quad \left|\frac{\Delta E_{\mathrm{Xe}}}{\Delta E_{(\mu)}}\right| = 4\times 10^{-9} \text{ for } g_A^{(\mu)}.$$

Pseudoscalar coupling is ruled out by a few orders of magnitude, constraint on axial coupling is uncertain due to nuclear uncertainty.

Consequences at 2-loop, constraints on axial vector coupling



- Pseudoscalar coupling contribution is suppressed at 2-loops
- Axial vector coupling can be important

$$\mathcal{L}_{\rm eff} = \sum_{i=u,d,s,e} \frac{g_A^{(i)}}{2m_\mu} \partial_\alpha \phi \times \bar{\psi}_i \gamma^\alpha \gamma_5 \psi,$$

$$g_A^{(i)} = -g_A^{(\mu)} \times \frac{3}{4} \left(\frac{\alpha}{\pi}\right)^2 Q_i^2 \log(\Lambda_{\rm UV}^2/\Lambda_{\rm IR}^2),$$

- Induced axial coupling with quarks can be transferred to the nucleus

Quarks —(lattice QCD / axial charge)→ Nucleon —(nucleon spin / expectation values)→ Nucleus

- Result relatively consistent among various models

$$\Delta E_{\rm Xe} = (3-7)\times 10^{-8} \times \Delta E_{(\mu)} \times \frac{\log(\Lambda_{\rm UV}^2/\Lambda_{\rm IR}^2)}{\log(m_\tau^2/m_p^2)} \quad \rightarrow \quad |\Delta E_{(\mu)}| < 6\times 10^{-15} \text{eV}$$

- Kind of stronger than the muon g-2 requirement, but this result could be undermined by nuclear uncertainty at 1-loop.

Direct detection: a possible setup

Direct detection is possible with muon spin resonance in weak magnetic field using stopped μ^+.

Direct measurement in the muon's rest frame requires detecting the rotation angle

$$\Delta\psi = \frac{\Delta E_{(\mu)} t}{\hbar} \implies \Delta\psi(t = \tau_\mu) = 2 \times 10^{-4}$$

Can be achieved with

- $N_{(\mu)} > 1/(\Delta\psi)^2 \sim 10^8$ muons $= 10^5$muons/second $\times\ 10^3$seconds
- Liquid or gaseous target to stop the muons
- Uniform vertical magnetic field in the range $5 - 50$Gs with a possibility of reversing direction
- Co-magnetometer to monitor the magnetic field

All can be achieved with current experimental techniques.

Summary

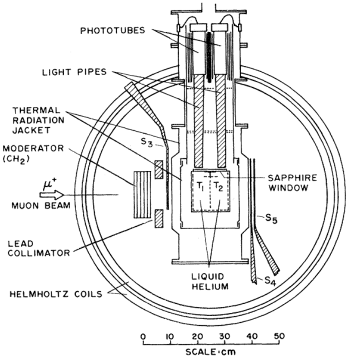
- The existence of a muon spin force of the size $|\Delta E_{(\mu)}| = 6 \times 10^{-14}$eV could explain the muon g-2 anomaly
- The muon spin force can be indirectly constrained by nuclear experiments, the constraint
  - strongly rules out the pseudoscalar type of muon spin force.
  - is uncertain for axial coupling due to significant nuclear uncertainty.
- The muon spin force can be directly probed by μSR experiments using stopped muons

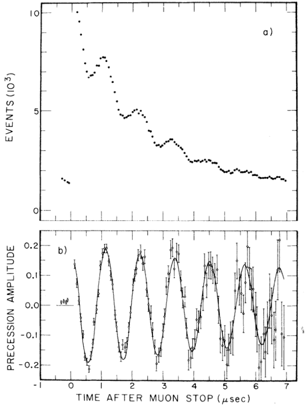
Thank you!

Back up slides

Existing experiments using similar setup

An experiment using stopped muons was done half century ago using magnetic field ∼66Gs to measure the magnetic moment of μ^+. (T. W. Crane et al PhysRevLett.33.572)





Their result is $\Omega = 2\pi \times (13.58 \pm 0.02\text{kHz/G}) \times B$, about two orders of magnitude weaker than our requirement.