Constraints on muon spin force from co-magnetometer experiments

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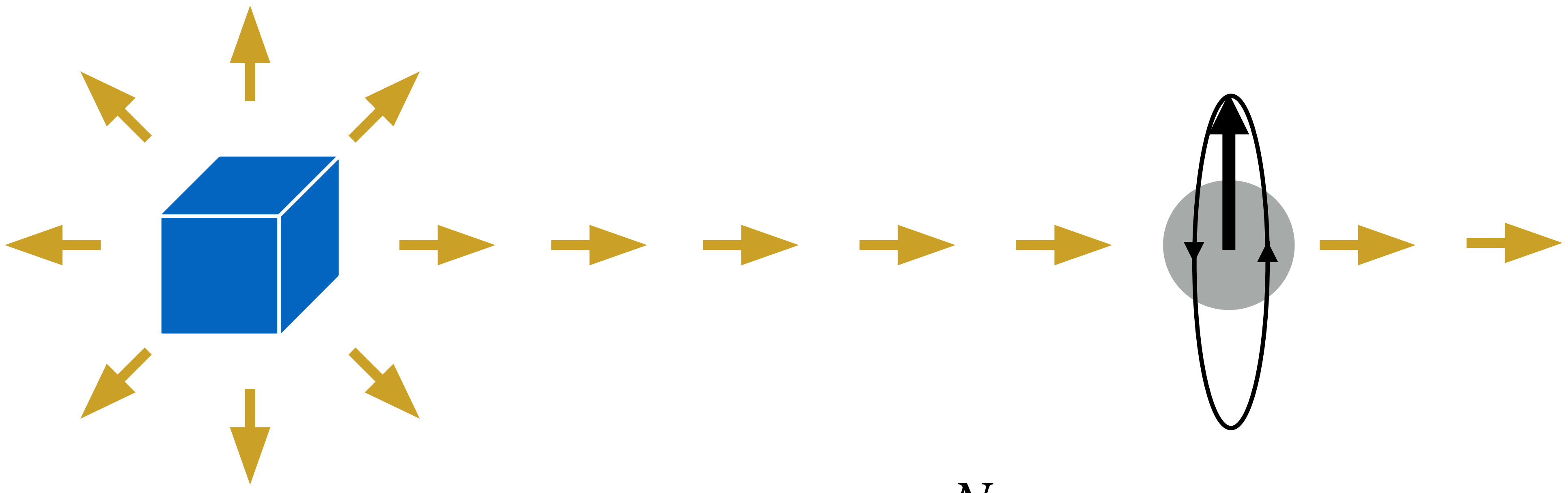
Based on **2307.xxxxx** with Ting Gao and Maxim Pospelov

Spin-mass coupling

- Spin-mass coupling mediated by light CP-violating scalar:

$$\mathscr{L} = g_s \phi\, \bar{\psi}_1 \psi_1 + \frac{g_p}{m} (\partial_\alpha \phi)\, \bar{\psi}_2 \gamma^\alpha \gamma_5 \psi_2 \quad \Rightarrow \quad V(r) = \frac{g_s g_p}{8\pi m} \left(\frac{m_\phi}{r} + \frac{1}{r^2} \right) e^{-m_\phi r}\, \vec{\sigma}_2 \cdot \hat{r}\,.$$

- Acts as "pseudo" magnetic field:



$$\text{“}\vec{B}_\phi\text{”} = -\vec{\nabla}\phi, \quad \phi = \frac{g_s N_1}{4\pi r} e^{-m_\phi r}\,.$$

Muon spin-mass coupling

- Muon spin-mass coupling: additional spin rotation to storage ring experiment.

$$\mathscr{L} = g_s \phi \bar{N} N + \frac{g_p}{m_\mu} \partial_\alpha \phi \, \bar{\mu} \gamma^\alpha \gamma_5 \mu$$

$$\vec{\Omega} = \frac{e}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E} + \underline{\frac{1}{\gamma}\frac{m}{e}\vec{b}}\right], \quad b = \frac{g_p |\vec{\nabla}\phi|}{m_\mu}.$$

- Muon g-2 may be explained if $b = \gamma \frac{eB}{m_\mu} \Delta a_\mu \sim 120\,\mathrm{Hz}$. [Davoudiasl+ 22; Agrawal+ 22]

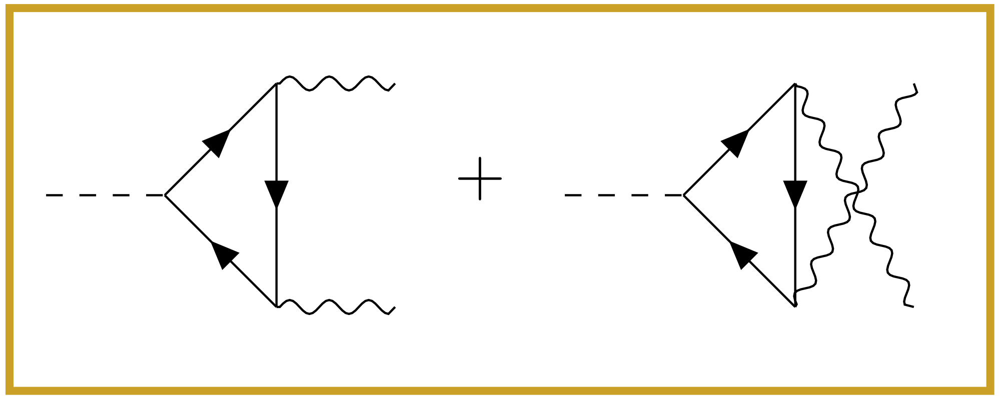
(Effect would be bigger at J-PARC due to smaller γ.)

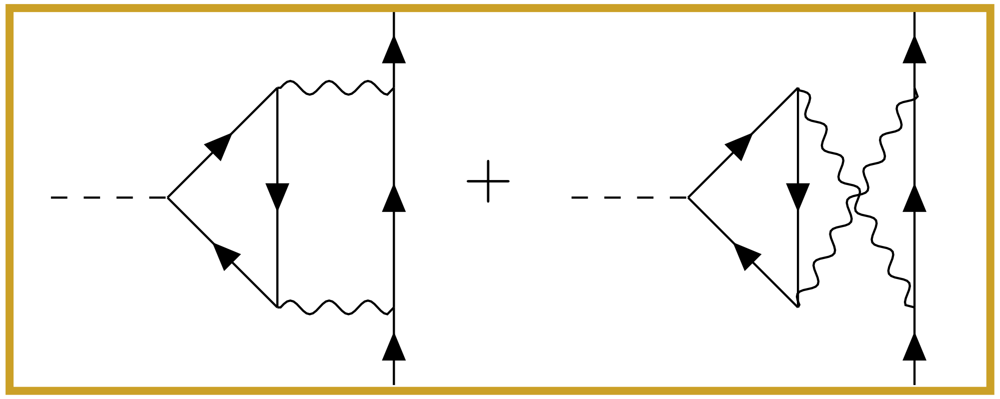
A way of constraining this coupling in the laboratory?

Muons at loop level

- By closing muon loops, several different spin-mass couplings are generated.

$$\frac{g_p}{m_\mu}\partial_\alpha\phi\,\bar{\mu}\gamma^\alpha\gamma_5\mu$$





$$-\frac{e^2 g_p}{24\pi^2 m_\mu^3}(\partial_\nu\phi)\tilde{F}^{\nu\alpha}(\partial^\mu F_{\mu\alpha})$$

$$\parallel$$

$$-\frac{e^2 g_p}{24\pi^2 m_\mu^3}\rho_N\vec{\nabla}\phi\cdot\vec{B}_N$$

$$-\frac{3g_p}{4m_\mu}Q^2\left(\frac{\alpha}{\pi}\right)^2\log\left(\frac{\Lambda^2}{m_\mu^2}\right)(\partial_\alpha\phi)\bar{\psi}\gamma^\alpha\gamma_5\psi$$

- These couplings probed by the co-magnetometer experiments.

Co-magnetometer experiments

- Co-magnetometer technique is key to suppress noise from the magnetic field.

$$\mathscr{H} = \vec{\sigma}_N \cdot \left(\mu_N \vec{B} + \underbrace{\chi_N \vec{g}}_{\propto \vec{\nabla}\phi}\right) \quad \Longrightarrow \quad \vec{\Omega}_{N_1} - \frac{\mu_{N_1}}{\mu_{N_2}}\vec{\Omega}_{N_2} = \vec{g}\left(\chi_{N_1} - \frac{\mu_{N_1}}{\mu_{N_2}}\chi_{N_2}\right).$$

(Evaluation of χ_N requires the nuclear physics input.)

- Recent $^{129}\mathrm{Xe} - {}^{131}\mathrm{Xe}$ result: [Zhang+ 23]

$$|(\chi_{129} + 1.1245\,\chi_{131})\vec{g}\,| < 8.5 \times 10^{-23}\,\mathrm{eV}\,.$$

- If we use the Schmidt model to evaluate χ_N, we obtain

(The lattice result [FLAG Review 2021] used to go from quark to nucleon spin.)

$$\begin{cases} \boxed{\rho_N \vec{\nabla}\phi \cdot \vec{B}_N} \quad \Longrightarrow \quad \boxed{b < 0.44\,\mathrm{Hz},} \\[2ex] \boxed{\vec{\nabla}\phi \cdot \vec{\sigma}_N} \quad \Longrightarrow \quad \boxed{b < 0.18\,\mathrm{Hz}\,.} \end{cases}$$

This is to be compared with $b \simeq 120\,\mathrm{Hz}$ for muon g-2.

Caveat on nuclear physics

- The Schmidt model does not reproduce the nuclear magnetic dipole moments.

(still usually applied to extract constraints in the spin-mass coupling experiments.)

$$\begin{cases} \mu_{129}^{(\mathrm{Schmidt})} = \mu_n, & \mu_{129}^{(\mathrm{exp})} = 0.41\,\mu_n, \\ \mu_{131}^{(\mathrm{Schmidt})} = -0.6\,\mu_n, & \mu_{131}^{(\mathrm{exp})} = -0.36\,\mu_n\,. \end{cases}$$

- Different nuclear computations give different results:

[Klos+ 13] → $b < 1.2\,\mathrm{Hz}$,

[Ressell, Dean 97] (Bonn A) → $b < 0.56\,\mathrm{Hz}$,

[Ressell, Dean 97] (Nijmegen II) → $b < 0.49\,\mathrm{Hz}$, (from nucleon spin operator.)

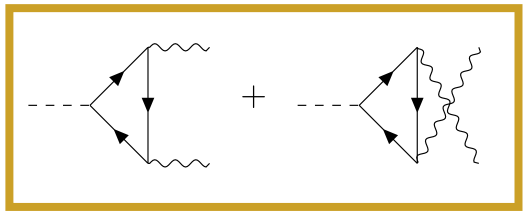
- Even a possibility of perfect cancellation, $\chi_{129} = \dfrac{\mu_{129}}{\mu_{131}}\chi_{131}$, not fully excluded.

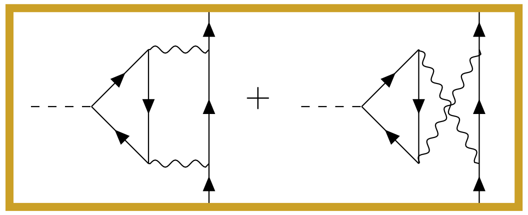
More precise input from nuclear physics desired.

Summary

- Muon spin-mass coupling motivated by muon g-2 anomaly.

- Muon loops induces operators probed by co-magnetometer experiments.





- Spin-mass coupling explaining muon g-2 anomaly is disfavored.

But

- Nuclear uncertainty exists, more precise nuclear physic input desired.