Spin-Dependent Exotic Interactions

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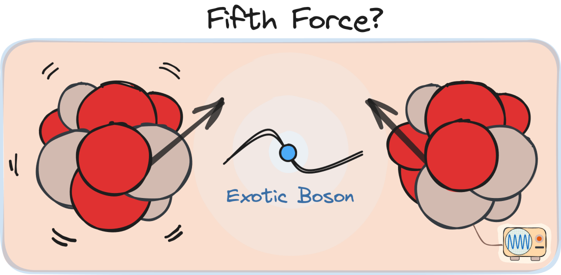
Motivations

Spin-Dependent Exotic Interactions – Who ordered that?



Exotic boson[1]:

axions	**arions**	**familons**	**majorons**	**Z′**	**paraphoton**

- Theoretical solutions to key open questions can give rise to new ultraweak interactions.
  - The strong CP problem;
  - The matter-antimatter asymmetry of the universe;
  - Dark matter.

[1] Safronova, M. S., D. Budker, D. DeMille, D. F. J. Kimball, A. Derevianko, and C. W. Clark (2018), Rev. Mod. Phys. **90** (2), 025008.

Theoretical framework

Background: spin-independent potential

- Yukawa proposed massive spin-0 bosons, the exchange of which gives rise to the Yukawa potential [2]:

$$V(r) = -g^2 \frac{e^{-Mr}}{4\pi r}, \tag{1}$$

  - V(r) is the potential energy as a function of distance r between two particles;
  - g is the dimensionless coupling constant;
  - M is the mass of the exchanged boson.

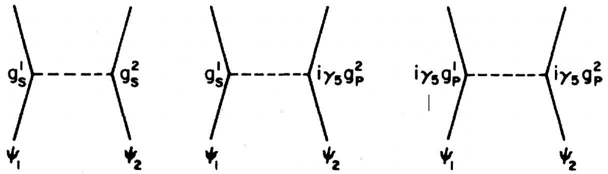
Yukawa Potential

Hideki Yukawa's prediction of the mediator particle, initially called the "meson" (now known as the pion), was confirmed with its discovery in cosmic rays in 1947.

[2] Yukawa, H. (1935), Nippon Sugaku-Buturigakkwai Kizi Dai 3 Ki **17**, 48. Zel'dovich, B.

1. Spin-dependent potentials – Moody and Wilczek [3]

Two possibilities for spin-0 bosons couplings to fundamental fermions: the scalar vertex (s) and the pseudoscalar vertex (p).



Monopole-Monopole   Monopole-Dipole   Dipole-Dipole

where ψ is the fermion field, γ_5 matrices encode the spinor structure.

$$V(r) = \frac{-g_S^1 g_S^2 e^{-m_\varphi r}}{4\pi r}\ ; \qquad V(r) = (g_S^1 g_P^2)\frac{\hat{\sigma}_2\cdot\hat{r}}{8\pi M_2}\left[\frac{m_\varphi}{r}+\frac{1}{r^2}\right]e^{-m_\varphi r}\ ;$$

$$V(r) = \frac{g_P^1 g_P^2}{16\pi M_1 M_2}\left[(\hat{\sigma}_1\cdot\hat{\sigma}_r)\left[\frac{m_\varphi}{r^2}+\frac{1}{r^3}+\frac{4\pi}{3}\delta^3(r)\right]-(\hat{\sigma}_1\cdot\hat{r})(\hat{\sigma}_2\cdot\hat{r})\left[\frac{m_\varphi^2}{r}+\frac{3m_\varphi}{r^2}+\frac{3}{r^3}\right]\right]e^{-m_\varphi r}\ .$$

[3] Moody, J. Wilczek, F. New macroscopic forces? Phys. Rev. D **30**, 130-138 (1984).

Bosons interacting with fermions

1.Moody and Wilczek

1984, Moody and Wilczek introduced a general framework of hypothetical bosons and explored **3** potentials resulting from the exchange of spin-0 bosons, e.g. axion.

2.Dobrescu and Mocioiu

2006, Dobrescu and Mocioiu later expanded this framework to encompass **16 potentials**, employing a different approach based on symmetries.

3.Fadeev *et al.*

2019, Fadeev *et al.* providing a more general framework, and classify the potentials in **9** type of physical constants.

2. A complete set of forms of potentials [4]

- 15/16 depend on spin.
- Traditional exotic searches constrain V_1, V_3, V_{9+10}.

$$\mathcal{V}_1 = \frac{1}{r}\, y(r) \;,$$

$$\mathcal{V}_2 = \frac{1}{r}\, \vec{\sigma}\cdot\vec{\sigma}\,'\, y(r) \;,$$

$$\mathcal{V}_3 = \frac{1}{m^2\, r^3}\left[\vec{\sigma}\cdot\vec{\sigma}\,'\left(1 - r\frac{d}{dr}\right) - 3\left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left(\vec{\sigma}\,'\cdot\hat{\vec{r}}\right)\left(1 - r\frac{d}{dr} + \frac{1}{3}r^2\frac{d^2}{dr^2}\right)\right] y(r) \;,$$

$$\mathcal{V}_{4,5} = -\frac{1}{2m\, r^2}\left(\vec{\sigma}\pm\vec{\sigma}\,'\right)\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\left(1 - r\frac{d}{dr}\right) y(r) \;,$$

$$\mathcal{V}_{6,7} = -\frac{1}{2m\, r^2}\left[\left(\vec{\sigma}\cdot\vec{v}\right)\left(\vec{\sigma}\,'\cdot\hat{\vec{r}}\right) \pm \left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left(\vec{\sigma}\,'\cdot\vec{v}\right)\right]\left(1 - r\frac{d}{dr}\right) y(r) \;,$$

$$\mathcal{V}_8 = \frac{1}{r}\left(\vec{\sigma}\cdot\vec{v}\right)\left(\vec{\sigma}\,'\cdot\vec{v}\right)\, y(r) \;,$$

[4] Dobrescu, B. A. Mocioiu, I. Spin-Dependent Macroscopic Forces from New Particle Exchange. J. High Energy Phys. **2006**, 005-005 (2006).

2. A complete set of forms of potentials

- 15/16 depend on spin.
- Traditional exotic searches constrain V_1, V_3, V_{9+10}.

$$
\begin{aligned}
\mathcal{V}_{9,10} &= -\frac{1}{2m\,r^2}\,(\vec{\sigma}\pm\vec{\sigma}\,')\cdot\hat{\vec{r}}\left(1-r\frac{d}{dr}\right)y(r)\;, \\
\mathcal{V}_{11} &= -\frac{1}{m\,r^2}\,(\vec{\sigma}\times\vec{\sigma}\,')\cdot\hat{\vec{r}}\left(1-r\frac{d}{dr}\right)y(r)\;, \\
\mathcal{V}_{12,13} &= \frac{1}{2r}\,(\vec{\sigma}\pm\vec{\sigma}\,')\cdot\vec{v}\,y(r)\;, \\
\mathcal{V}_{14} &= \frac{1}{r}\,(\vec{\sigma}\times\vec{\sigma}\,')\cdot\vec{v}\,y(r)\;, \\
\mathcal{V}_{15} &= -\frac{3}{2m^2\,r^3}\left\{\left[\vec{\sigma}\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\left(\vec{\sigma}\,'\cdot\hat{\vec{r}}\right)+\left(\vec{\sigma}\cdot\hat{\vec{r}}\right)\left[\vec{\sigma}\,'\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\right\} \\
&\quad\times\left(1-r\frac{d}{dr}+\frac{1}{3}r^2\frac{d^2}{dr^2}\right)y(r)\;, \\
\mathcal{V}_{16} &= -\frac{1}{2m\,r^2}\left\{\left[\vec{\sigma}\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right](\vec{\sigma}\,'\cdot\vec{v})+(\vec{\sigma}\cdot\vec{v})\left[\vec{\sigma}\,'\cdot\left(\vec{v}\times\hat{\vec{r}}\right)\right]\right\}\left(1-r\frac{d}{dr}\right)y(r)\;.
\end{aligned}
$$

People study the $V_i = f_i\mathcal{V}_i$ and set constriants for the coefficients f_i.

3.Spin-dependent potentials —Classification by physical constants [5]

Spin $S = 0$, nonrelativistic limit

$$\mathcal{L}_\phi = \phi \sum_\psi \bar{\psi} \left(g_s^\psi + i\gamma_5 g_p^\psi \right) \psi \Rightarrow$$

$$V_{ss}(\boldsymbol{r}) = \underbrace{-g_s^X g_s^Y \frac{e^{-Mr}}{4\pi r}}_{V_1|_{ss}} + \underbrace{\frac{g_s^X g_s^Y}{4} \left\{ \boldsymbol{\sigma}_X \cdot \left(\frac{\boldsymbol{p}_X}{m_X^2} \times \hat{\boldsymbol{r}} \right), \left(\frac{1}{r^2} + \frac{M}{r} \right) \frac{e^{-Mr}}{8\pi} \right\}}_{V_{4+5}|_{ss}}$$

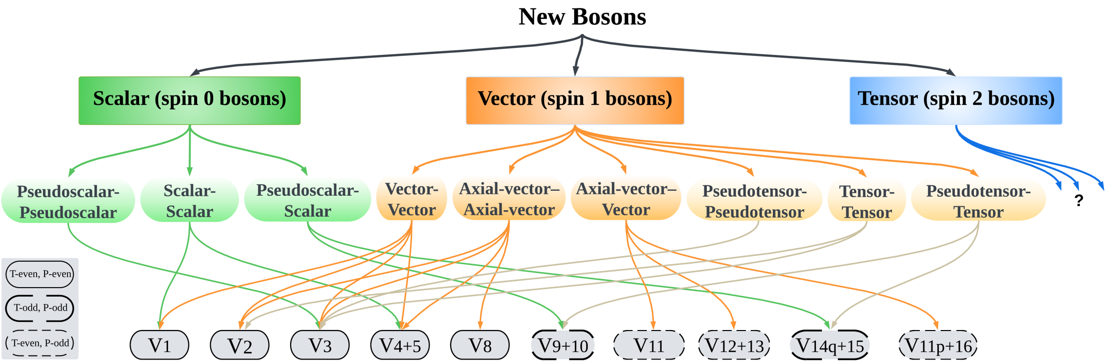
$$V_{pp}(\boldsymbol{r}) = \underbrace{-\frac{g_p^X g_p^Y}{4} \left[\boldsymbol{\sigma}_X \cdot \boldsymbol{\sigma}'_Y \left[\frac{1}{r^3} + \frac{M}{r^2} + \frac{4\pi}{3}\delta(\boldsymbol{r}) \right] - (\boldsymbol{\sigma}_X \cdot \hat{\boldsymbol{r}})(\boldsymbol{\sigma}'_Y \cdot \hat{\boldsymbol{r}}) \left[\frac{3}{r^3} + \frac{3M}{r^2} + \frac{M^2}{r} \right] \right] \frac{e^{-Mr}}{4\pi m_X m_Y}}_{V_3|_{pp}}$$

$$V_{ps}(\boldsymbol{r}) =$$
$$\underbrace{-g_p^X g_s^Y \boldsymbol{\sigma}_X \cdot \hat{\boldsymbol{r}} \left(\frac{1}{r^2} + \frac{M}{r} \right) \frac{e^{-Mr}}{8\pi m_X}}_{V_{9+10}|_{ps}}$$
$$+ \underbrace{\frac{g_p^X g_s^Y}{8} \left[\left\{ (\boldsymbol{\sigma}_X \times \boldsymbol{\sigma}'_Y) \cdot \frac{\boldsymbol{p}_Y}{m_Y}, \frac{1}{r^3} + \frac{M}{r^2} + \frac{4\pi}{3}\delta(\boldsymbol{r}) \right\} - \left\{ (\boldsymbol{\sigma}_X \cdot \hat{\boldsymbol{r}}) \boldsymbol{\sigma}'_Y \cdot \left(\frac{\boldsymbol{p}_Y}{m_Y} \times \hat{\boldsymbol{r}} \right), \frac{3}{r^3} + \frac{3M}{r^2} + \frac{M^2}{r} \right\} \right] \frac{e^{-Mr}}{8\pi m_X m_Y}}_{V_{14q+15}|_{ps} \sim \boldsymbol{q}^2 \mathcal{V}_{14} + \mathcal{V}_{15}}$$

[5] Fadeev, P. et al. Revisiting Spin-Dependent forces mediated by new bosons: Potentials in the coordinate-space representation for macroscopic- and atomic-scale experiments. Phys. Rev. A **99**, 022113 (2019).

Our review[6]

Formulation of the potentials in terms of a small number of coupling constants



[6] L. Cong*, W. Ji*, P. Fadeev, F. Ficek, M. Jiang, V. V. Flambaum, H.S. Guan, D. F. Jackson Kimball, M. G. Kozlov,Y. V. Stadnik, D. Budker. *Spin-Dependent exotic interactions*, Rev. Mod. Phys. **97**, 025005 (2025).

Experimental Search

Experimental search: 1. Dedicated source-sensor experiments

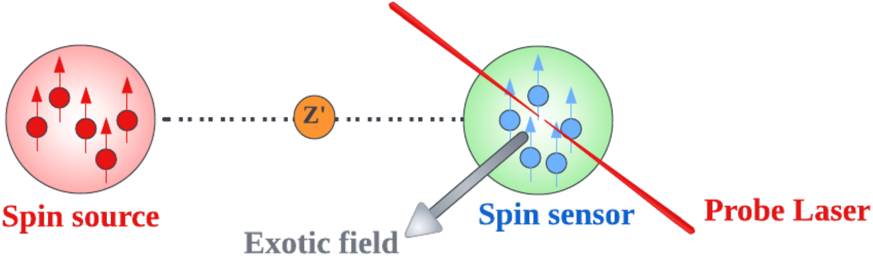


Figure: Schematic figure of a dedicated source-sensor experiments.

In source-sensor experiments, the exotic interaction typically manifests as an effective magnetic field acting on the spins of the sensor.

Source materials used in experiments for exotic forces

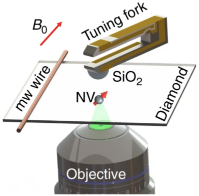
Polarized

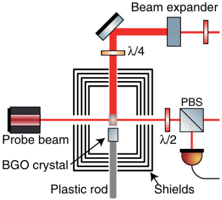
- ^{3}He
- ^{87}Rb
- $SmCo_5$
- Alnico 5
- ...

Unpolarized

- Water (with paramagnetic salts)
- SiO_2
- Tungsten
- Lead
- ...

Sensors used in experiments for exotic forces





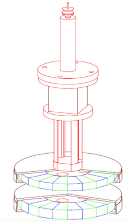


Figure: Dedicated source-sensor experiments.

From left to right, the sensors are:

- Nitrogen-vacancy (NV) centers in diamond[7]
- Neutron spin from a ^{129}Xe-^{131}Xe-Rb comagnetometer[8]
- $SmCo_5$ and Alnico in Torsion pendulum[9]

[7] Rong X, Jiao M, Geng J, et al. Constraints on a Spin-Dependent exotic interaction between electrons with single electron spin quantum sensors (2018). Phys. Rev. Lett. **121**(8): 080402.

[8] Feng Y K, Ning D H, Zhang S B, et al. Search for Monopole-Dipole Interactions at the Submillimeter Range with a ^{129}Xe-^{131}Xe-Rb Comagnetometer (2022). Phys. Rev. Lett. **128**(23): 231803.

[9] Terrano W A, Adelberger E G, Lee J G, et al. Short-range, Spin-Dependent interactions of electrons: A probe for exotic pseudo-goldstone bosons (2015). Phys. Rev. Lett. **115**, 201801.

Example a: Four orders tighter limits in the axion window [10]

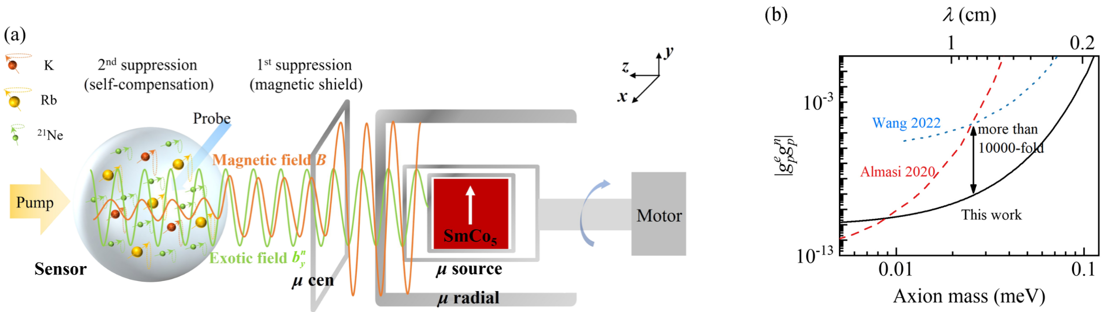


Figure: (a) Atom spins in the sensor are polarized and probed by pump/probe lasers. The white arrow represents the magnetization direction of the spin source. (b) Constraints on the coupling constant product $g_p g_p$ as a function of the new boson mass.

[10] Xu, Z., Heng, X., Tian, G., Gong, D., Cong, L., Ji, W., Budker, D., Wei, K. (2025). Constraints on Axion Mediated Dipole-Dipole Interactions. Phys. Rev. Lett. **134**, 181801.

2. Complementary experiments and observations to detect exotic spin-dependent interactions

- Precision Measurements: Spectroscopy of exotic atoms[11]

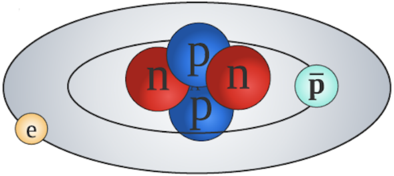


Figure: Schematic figure of an antiprotonic helium atom.

- Atomic and molecular parity-violation experiments[12]
- EDM experiments[13]

[11] Ficek, F., P. Fadeev, V. V. Flambaum, D. F. Jackson Kimball, M. G. Kozlov, Y. V. Stadnik, and D. Budker (2018), Phys. Rev. Lett. **120** (18), 183002.

[12] Antypas, D., A. Fabricant, J. E. Stalnaker, K. Tsigutkin, V. V. Flambaum, and D. Budker (2019), Nat. Phys. **15** (2), 120.

[13] Stadnik, Y. V., V. A. Dzuba, and V. V. Flambaum (2018), Phys. Rev. Lett. **120** (1), 013202.

Example b: Searching for exotic interactions between antimatter with antihydrogen

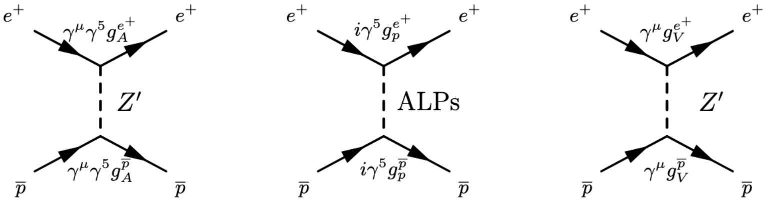


Figure: Three type Spin-Dependent exotic interactions mediated by a new boson in antihydrogen.

Example b: Searching for exotic interactions between antimatter with antihydrogen [14]

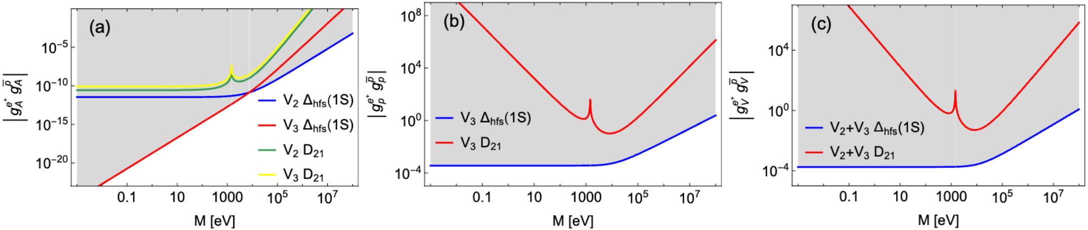


Figure: Constraints on three types of exotic interactions between antimatter.

[14] Cong, L., Ficek, F., Fadeev, P., Stadnik, Y. V., Budker, D. (2025). Searching for Exotic Interactions between Antimatter. arXiv:2503.07161.

Our review [15]

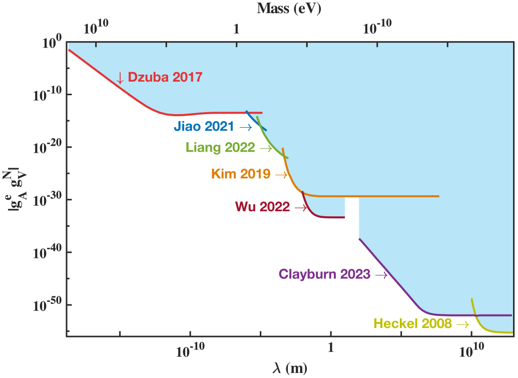
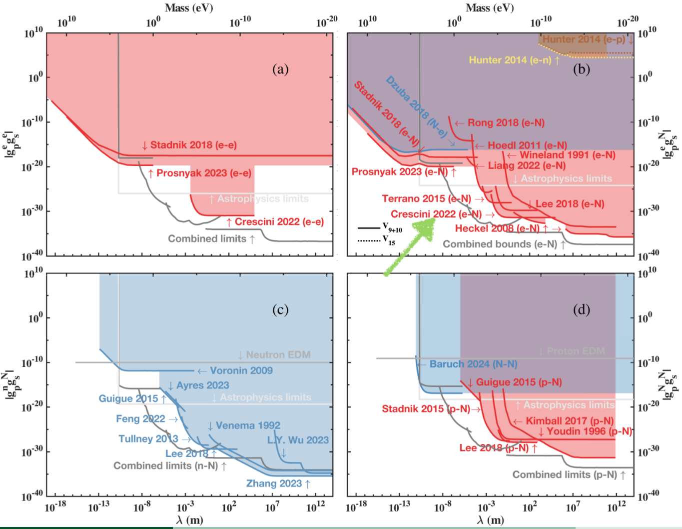


Figure: Laboratory constraints on the coupling constant product $g_A g_V$ as a function of the interaction range λ shown on the bottom x-axis. The top x-axis represents the new vector boson mass M. V_{12+13}.

[15] L. Cong*, W. Ji*, P. Fadeev, F. Ficek, M. Jiang, V. V. Flambaum, H.S. Guan, D. F. Jackson Kimball, M. G. Kozlov,Y. V. Stadnik, D. Budker. *Spin-Dependent exotic interactions*, Rev. Mod. Phys. **97**, 025005 (2025).

Constraints for pseudoscalar/scalar interaction $g_p g_s$



Conclusion

Conclusion[16]

This review aims to:

- provide a common approach;
- suggest full analysis of different types of interactions by a particular experiments;
- support experimental researchers to judge what to try to do next to advance the field;
- assitant theorists to more easily check to make sure their ideas are not yet ruled out by experiments.

[16] L. Cong*, W. Ji*, P. Fadeev, F. Ficek, M. Jiang, V. V. Flambaum, H.S. Guan, D. F. Jackson Kimball, M. G. Kozlov,Y. V. Stadnik, D. Budker. *Spin-Dependent exotic interactions*, Rev. Mod. Phys. **97**, 025005 (2025).

A website[17] collects the results:

Spin-Dependent-5th-Force-Limits

This dataset compiles search results from existing exotic particle search experiments, with a specific focus on the fifth force, particularly the spin-dependent fifth force (SDFF). It aims to provide convenience to researchers in the field.

View the Project on GitHub
Lei-Cong/Spin-Dependent-5th-Force-Limits

This project is maintained by Lei-Cong

Hosted on GitHub Pages — Theme by orderedlist

Dataset Instruction

Overview

This repository contains datasets of constraints on spin-dependent exotic interactions, also referred to as the spin-dependent fifth force (SDFF), mediated by the exchange of a single boson of mass M between fermions X and Y. The interactions are categorized into the following types:

1. Axial-vector/vector, axial-vector/axial-vector, vector/vector.
2. Pseudoscalar/scalar, pseudoscalar/pseudoscalar, scalar/scalar.
3. Tensor/tensor, pseudotensor/tensor, and pseudotensor/pseudotensor.

As a reference, one may consult the format of the exotic potentials presented in the RMP review: **Spin-Dependent Exotic Interactions**.

The repository serves as a **live** webpage designed to present the latest experimental results. For contributions or to include your new results, please feel free to contact Dr. Lei Cong (congllzu@gmail.com), Dr. Wei Ji (weiji001@uni-mainz.de), or Prof. Dmitry Budker (budker@uni-mainz.de).

Citation

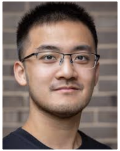
Please cite this repository as follows: DOI 10.5281/zenodo.14572652. One can copy the BibTeX file from here: **BibTeX Format**.

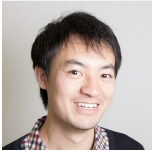
Spin-Dependent Fifth Force

[17] https://lei-cong.github.io/Spin-Dependent-5th-Force-Limits/

Collaborators

Wei  Victor  Pavel  Filip 

Derek  Dmitry  Haosen 

Min  Mikhail  Yevgeny and Lei 


Thank you