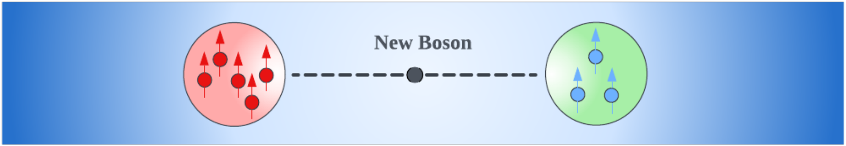
A Review: Spin-dependent Exotic Interaction

Lei Cong
congllzu@gmail.com

Supervisor: Dmitry Budker
Helmholtz-Institut Mainz, Germany

November 18, 2024

Spin-dependent Exotic Interactions – Who ordered that?



New boson[1]:

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

- Specific theoretical ideas aiming to answer unresolved key problems can produce new ultraweak interactions.
  - The strong CP problem;
  - The matter-antimatter asymmetry of the universe;
  - Dark matter;
  - The hierarchy problem;

[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.

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.

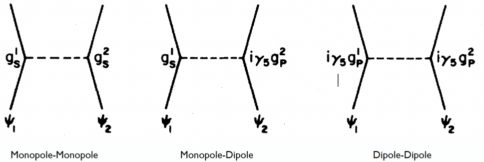
Yukawa Potential

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.

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).



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

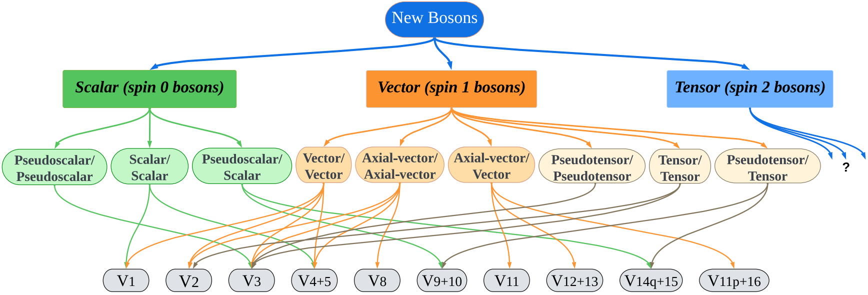
2006, Dobrescu and Mocioiu later expanded this framework to encompass **16 potentials**, employing a different approach based on symmetries.

3.Fadeev *et al.*

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

Our review[4]

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



[4] 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*, arXiv:2408.15691 (2024).

Experiment search: 1. Dedicated source-sensor experiments

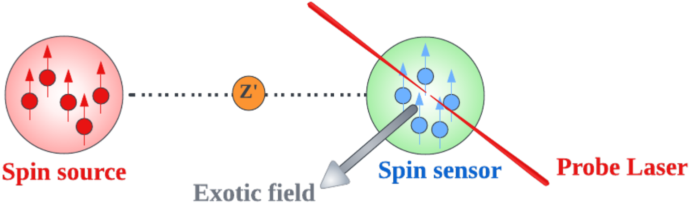


Figure: Schematic figure of a dedicated source-sensor experiments.

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

Sensors used in experiments for exotic forces

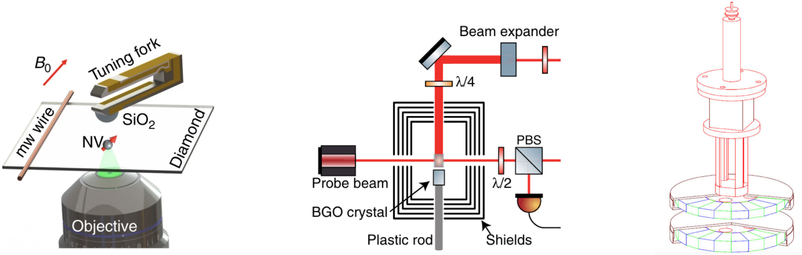


Figure: Dedicated source-sensor experiments.

From left to right, the sensors are:

- Nitrogen-vacancy (NV) centers in diamond[5]
- Neutron spin from a ^{129}Xe-^{131}Xe-Rb comagnetometer[6]
- $SmCo_5$ and Alnico in Torsion pendulum[7]

[5] 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.

[6] 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.

[7] 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.

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

- Precision Measurements: Spectroscopy of exotic atoms[8]

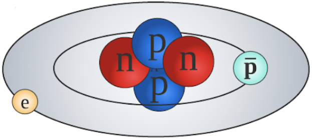


Figure: Schematic figure of an antiprotonic helium atom.

- Atomic and molecular parity-violation experiments[9]
- EDM experiments[10]

---

[8] 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.

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

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

Our review [11]

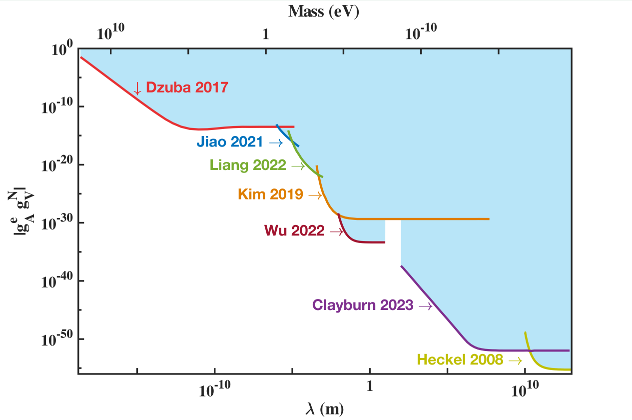


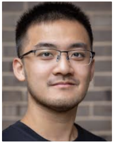
Figure: Laboratory constraintson the coupling constant product $g_A g_V$ as a function of the interaction range λ shown on the bottom x-axis. The top x-axis represents the new vector boson mass M. V_{12+13}.

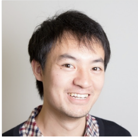
[11] L. Cong*, W. Ji*, P. Fadeev, F. Ficek, M. Jiang, V. V. Flambaum, H.S. Guan, D. F. Jackson Kimball, M. G. Kozlov,Y. V. Stadnik, D. Budker. *Spin-dependent exotic interactions*, arXiv:2408.15691 (2024).


Thank you

Collaborators

Wei  Victor  Pavel  Filip 

Derek  Dmitry  Haosen 

Min  Mikhail  Yevgeny and Lei