AXEL Experiment in Space to Search for Spin-Coupling Interactions

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Outline

- Motivations
- Principles for detecting spin-coupling interactions
- Present achievements of spin-coupling experiments
- AXEL experiment scheme
  1、Proposed design
  2、Sensitivity limit
  3、Next work
- Outlook.

Motivations

- Many theoretical frameworks suggest that there maybe a new interaction coupling to the intrinsic spins of the elementary particles. (For example, axion interaction and equivalence principle and the strong CP problem, finite-range Leitner-Okubo-Hari Dass interaction, Naik-Pradhan interaction)
- Many experiments are motivated by the following two purposes:
  1. To explore the role of spin in gravitation
  2. To search for a new interaction associated with the exchange of a light or massless boson or similar interactions (e.g., axion interaction)
- In the ArkaniHamed-Cheng-Luty-Mukohyama effective theory of gravity with ghost condensation, if the standard model fields have direct coupling with the ghost sector, there are spin couplings, and these are testable experimentally.

As reported in the opening session by Bignami “Physics in Space”

PVLAS Experiment

Zavatini et al., in Phys. Rev. Lett. 2006

reported an experimental evidence of photon-pseudoscalar interaction

- Photon Axion Interaction →
- Electron Axion Interaction →
- Spin Coupling

Equivalence Principle Study and Axion-Photon Interaction

Special relativity

$$L_I = -(\frac{1}{16\pi})\eta^{ikjl}\eta^{jl}F_{ij}F_{kl} - A_k j^k(-g)^{1/2} - \sum_I m_I \frac{ds_I}{dt}\delta(x-x_I)$$

$\chi - g$ framework

$$L_I = -(\frac{1}{16\pi})\chi^{ijkl}F_{ij}F_{kl} - A_k j^k(-g)^{1/2} - \sum_I m_I \frac{ds_I}{dt}\delta(x-x_I)$$

Galileo equivalence principle restricts χ **to:**

$$\chi^{ijkl} = (-g)^{1/2}[\frac{1}{2}g^{ik}g^{jl} - \frac{1}{2}g^{il}g^{kj} + \eta\Psi\,\varepsilon^{ijkl}]$$

Axion-Photon Interaction is proposed first in [W.-T. Ni, Phys. Rev. Lett. **38**, 301 (1977)]

Recent announcement of PVLAS group and References on Axion Interaction

- W.-T. Ni, A Nonmetric Theory of Gravity, preprint, Montana State University, Bozeman, Montana, USA (1973), http://gravity5.phys.nthu.edu.tw.
- W.-T. Ni, Bull. Am. Phys. Soc., 19, 655 (1974).
- W.-T. Ni, Phys. Rev. Lett. 38, 301 (1977)
- Peccei and Quinn, Phys. Rev. Lett. 39 (1977)
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- F. Wilczek, {\sl Phys. Rev. Lett}. **40**, 279 (1978).
- J. Kim, {\sl Phys. Rev. Lett}. **43**, 103 (1979).
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- M. Dine {\sl et al.}, {\sl Phys. Lett}. **104B**, 1999 (1981).
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- S. L. Cheng, C. Q. Geng and W.-T. Ni, {\sl Phys. Rev.} **D52** 3132 (1995) and references therein.
- Zavatini et al., Phys. Rev. Lett. 2006 (PVLAS experiment)

The principle of measuring spin-mass interaction.

For a magnetic moment $\vec{m}$ in a magnetic field $\vec{B}$

$$H_{mag} = -\vec{m} \cdot \vec{B}$$

For an electron with spin magnetic dipole moment

$$H_{mag} = -\mu_e \vec{\sigma} \cdot \vec{B}$$

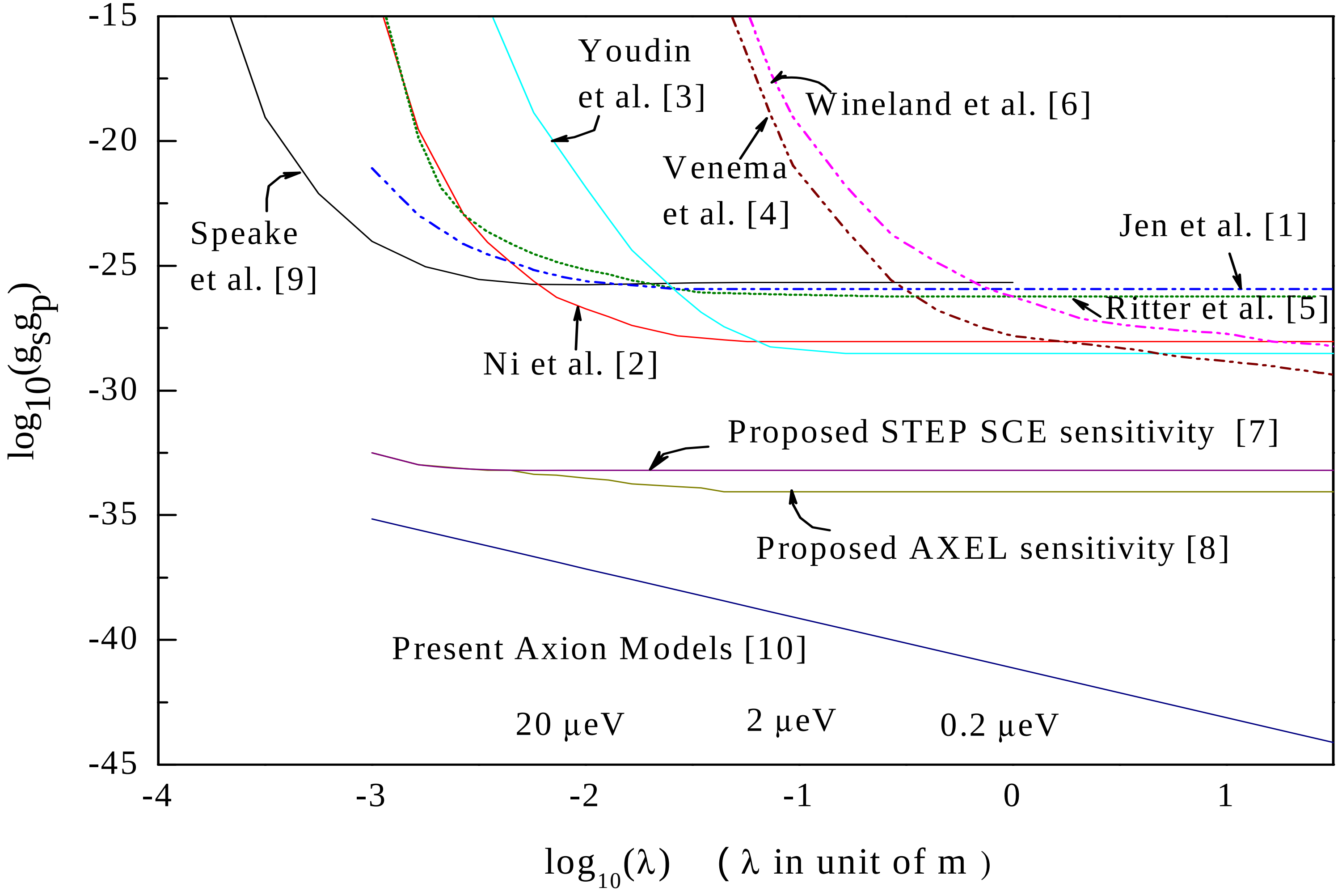
For an axion interaction, the effective field due to the mass source is:

$$H_{anom} = -\mu_e \vec{\sigma} \cdot \vec{B}_{eff}$$

$$\vec{B}_{eff} = \frac{\hbar^2}{\mu_e} \frac{g_p g_s}{8\pi m_e} \int_{V_{mass}} \left(\frac{1}{\lambda r} + \frac{1}{r^2}\right) \exp\left(-\frac{r}{\lambda}\right) \hat{r}$$

The mass-spin coupling potential can be interpreted as a coupling between ***intrinsic spin*** and an ***effective magnetic field with nonmagnetic (axion) origin.***

The magnetic interaction and the spin-mass interaction has the same effect but they are different interactions, so it is a challenge to reduce the magnetic interaction due to the residual magnetic field from the mass or spin sources.



Current limits on spin-mass coupling from various experiments for axion-type interactions

References on Spin-Coupling Exp.

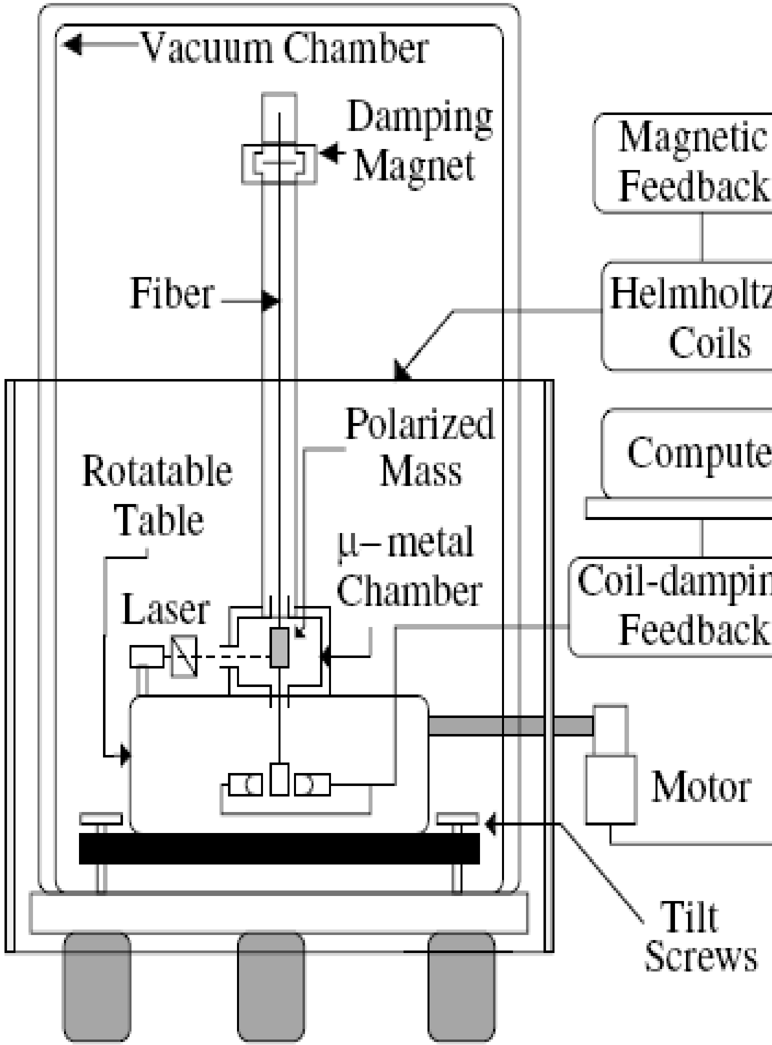
- [1] T.-H. Jen et al., in: N. Sato, T. Nakamura (Eds.), Proceedings of the Sixth Marcel Grossmann Meeting on General Relativity, 1992, p. 489
- [2] W.-T. Ni et al., Phys. Rev. Lett. 82 (1999) 2439
- [3] A.N. Youdin et al., Phys. Rev. Lett. 77 (1996) 2170
- [4] B.J. Venema et al., Phys. Rev. Lett. 68 (1992) 139
- [5] Ritter R C, Winkler L I and Gillies G T 1993 Phys. Rev. Lett. **70** 701
- [6] Wineland D J et al 1991 Phys. Rev. Lett. **67** 1735
- [7] ESA SCI(93) 4, STEP report on the phase A study, 1993
- [8] W.-T. Ni, Search for New forces using SQUID's with paramagnetic salts, CD-ROM Proceedings for the International Workshop on Gravitation and Astrophysics, November 17-19, 1997
- [9] Trenkel C. Private Communication.
- [10] C. Trenkel, G. D.Hammond, A. Pulido-Patón, C. C. Speake, in preparation

Two kinds of experimental methods

- Measuring the force on the mass (for example, using an unpolarized mass on the torsion pan)

- Measuring the force on the spin (for example, using dc SQUIDs to sense the induced magnetization change due to the spin-coupling forces on the paramagnetic materials)

Torsion balance experiment



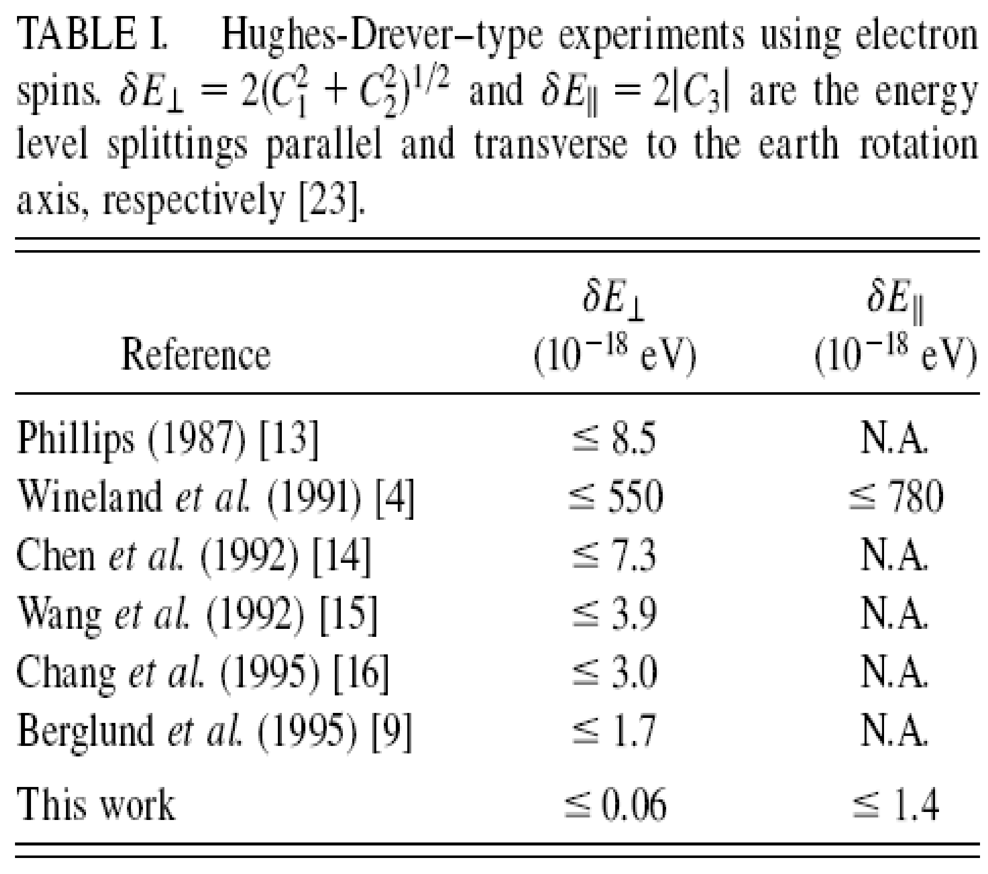
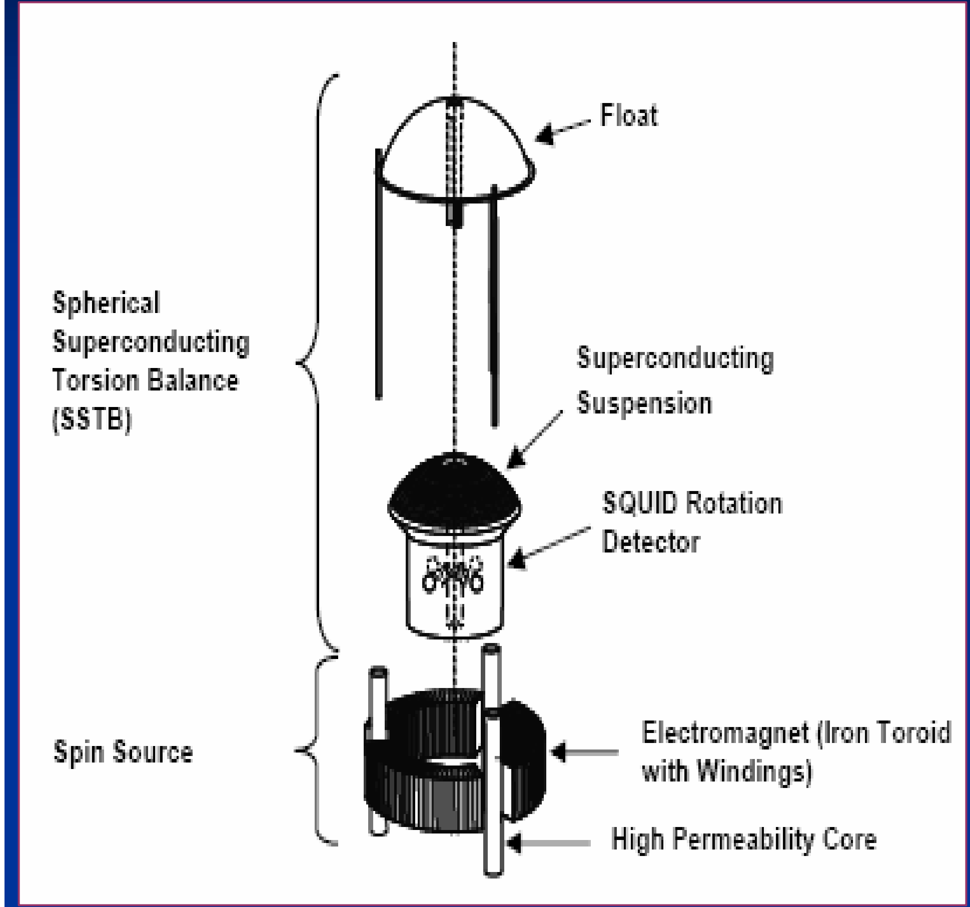


TABLE I. Hughes-Drever–type experiments using electron spins. $\delta E_{\perp} = 2(C_1^2 + C_2^2)^{1/2}$ and $\delta E_{\parallel} = 2|C_3|$ are the energy level splittings parallel and transverse to the earth rotation axis, respectively [23].

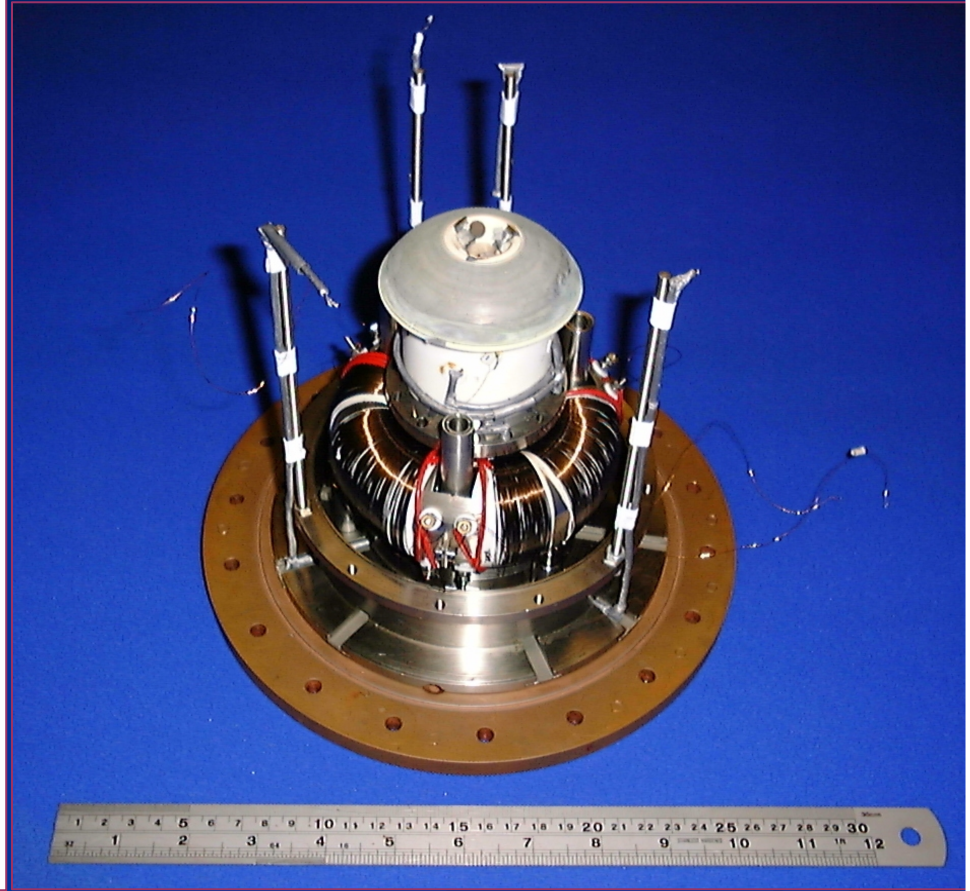
Reference	$\delta E_{\perp}$ (10^{-18} eV)	$\delta E_{\parallel}$ (10^{-18} eV)
Phillips (1987) [13]	≤ 8.5	N.A.
Wineland *et al.* (1991) [4]	≤ 550	≤ 780
Chen *et al.* (1992) [14]	≤ 7.3	N.A.
Wang *et al.* (1992) [15]	≤ 3.9	N.A.
Chang *et al.* (1995) [16]	≤ 3.0	N.A.
Berglund *et al.* (1995) [9]	≤ 1.7	N.A.
This work	≤ 0.06	≤ 1.4

Eötwash group	< 0.12	< 0.44

Measuring force using superconducting torsion balance (Birmingham University)



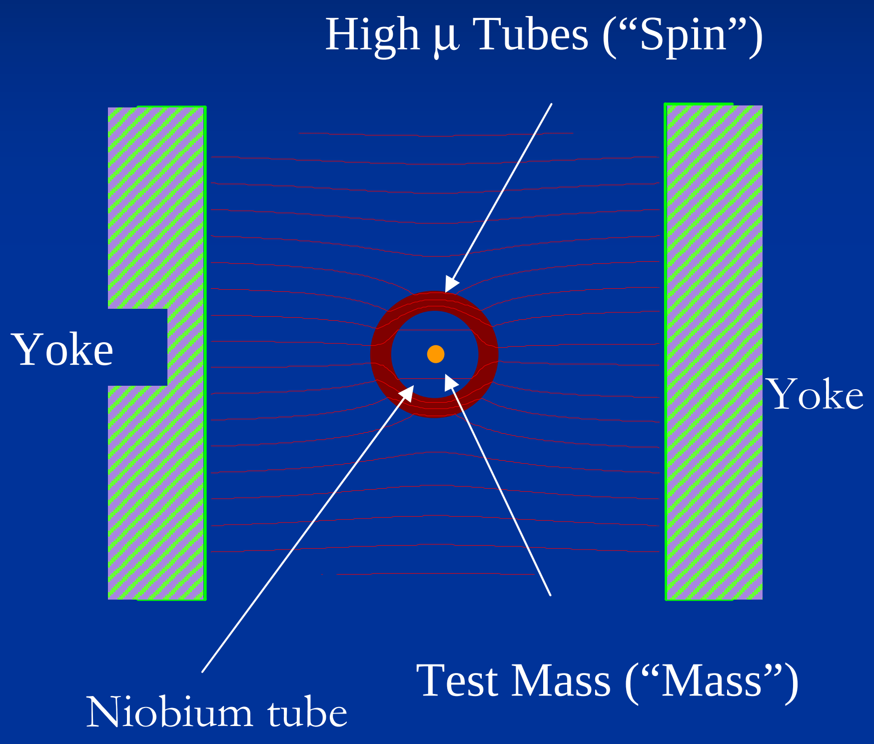
Assembly of Torsion Balance and Spin Sources



The photo of Torsion Balance and Spin Sources

The Spin Source - Birmingham Experiment

For the **spin source** we use high permeability hollow tube of thickness 1.5 mm



Spin-mass interaction limit:

$$\lambda = 1 \text{ mm}, g_s g_p \approx 1 \times 10^{-24}$$

Unique feature of the design of the spin source :

90 G External field (~0.65 A)

800 G Inside the μ -metal

5 G residual field immediately inside the μ -metal tube

The Nb tube (1 mm) inside the μ -metal shield the magnetic field to < 10^{-10}G

- The magnetic field associated with the spins is used to cancel the magnetic field that polarized them.
- The orientation of the aligned spins can be reversed electronically, rather than mechanically.

Measuring the force on the spin ---using dc SQUIDs to sense the induced magnetization change due to the spin-coupling forces on the paramagnetic materials

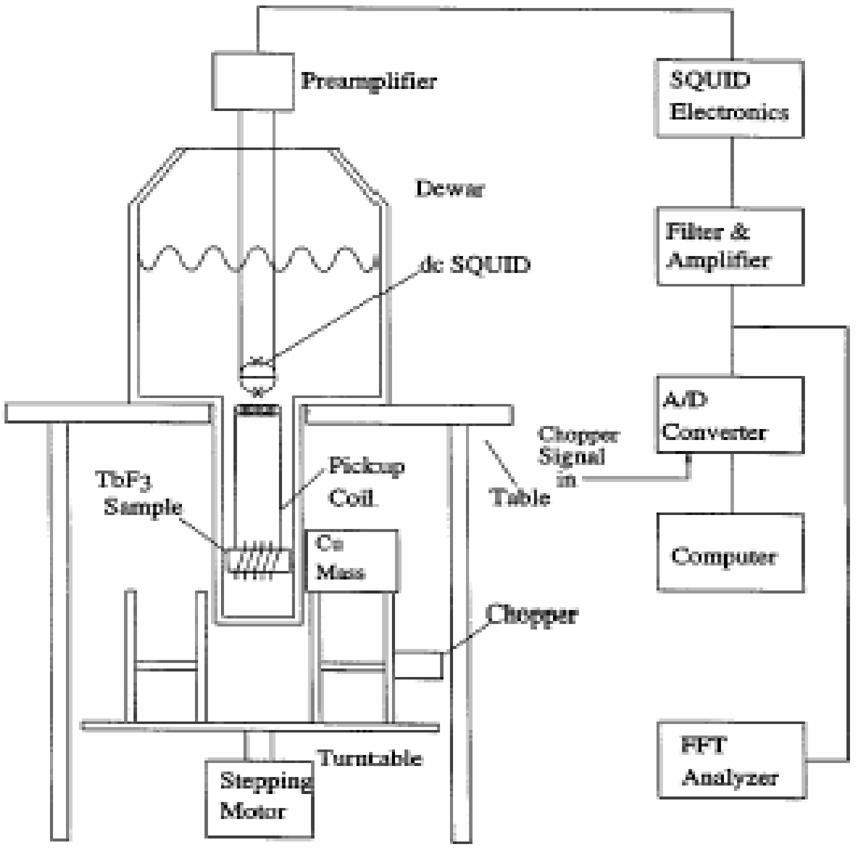


FIG. 2. Schematic for spin-coupling experiment.

Spin-mass interaction experiment

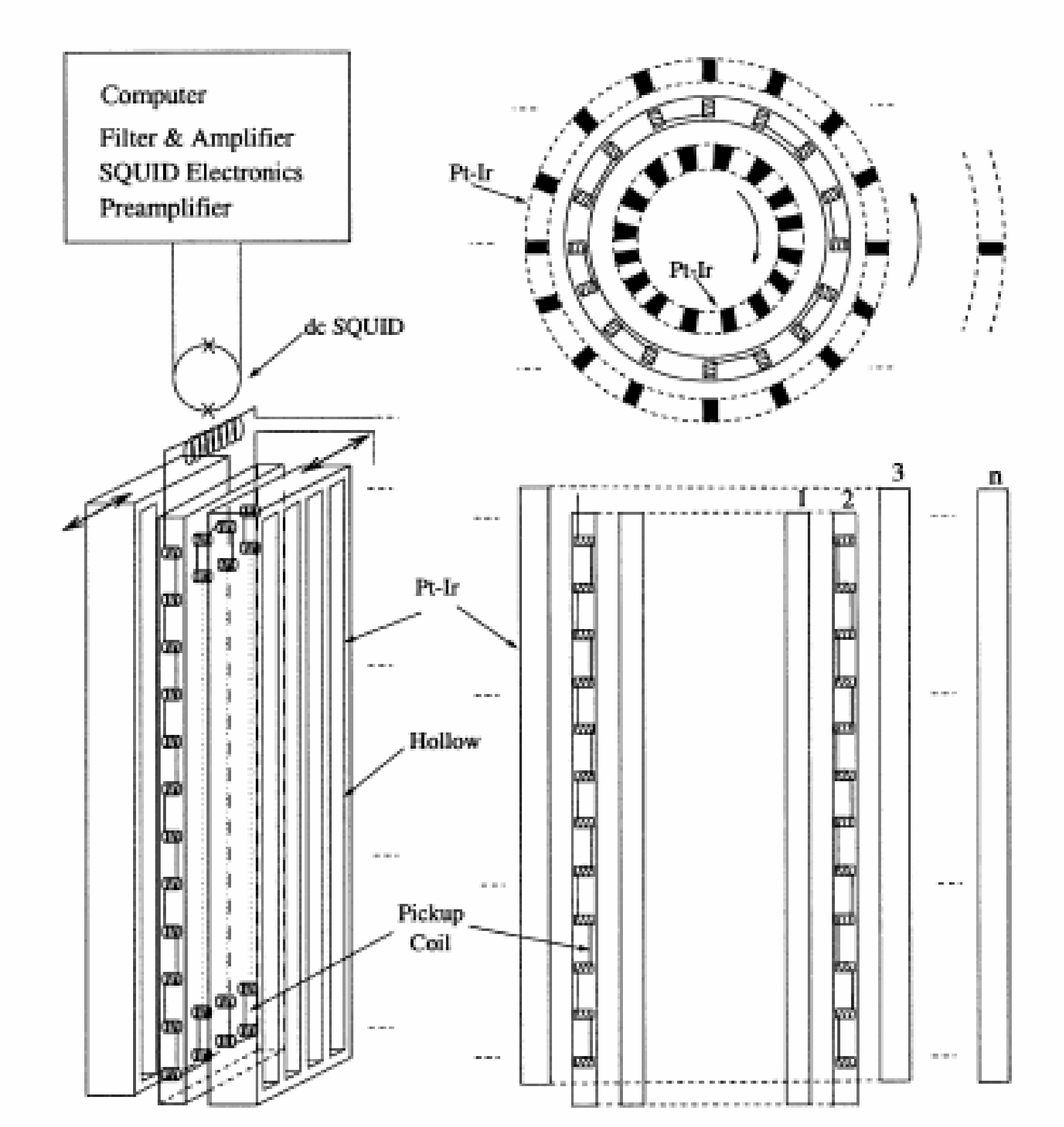
$$\lambda > 30mm, \frac{g_p g_s}{\hbar c} = (0.14 \pm 0.67) \times 10^{-28}$$

Spin source:

Paramagnetic salt: TbF_3

Mass source: Copper mass

AXEL experiment using magnetic sensors

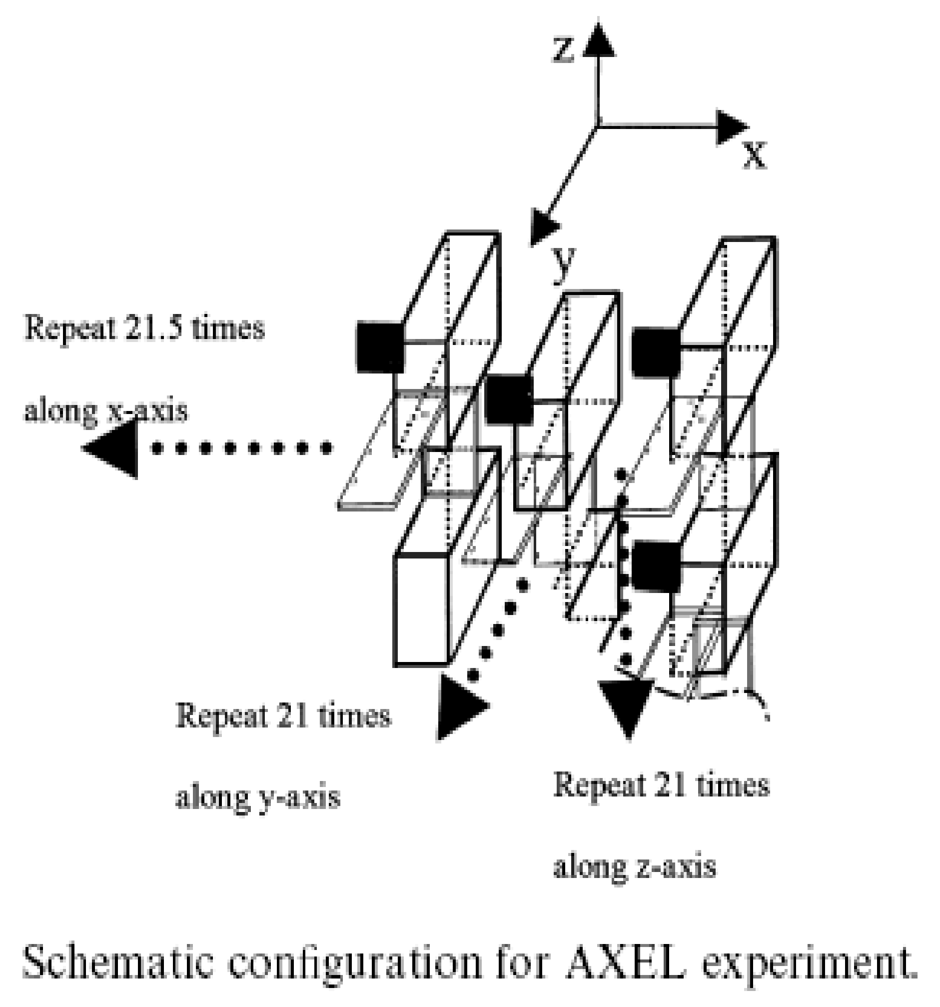


AXEL: AXial Experiment at Low temperature

- Spins source: paramagnetic salts near Curie temperature(TbF_3)
  Masses: Pt-Ir mass
- Detect the force on the spins using multiple-element paramagnetic sensors coupled to DC SQUIDs to detect the spin-coupling forces.
- The change of the spin-coupling forces on the electron spins due to the motion of the masses induces magnetization change

Schematic for a spin-coupling experiment *W.-T. Ni, Physica B (2000) 2137*

Geometric optimization of the source and detector configurations for the AXEL spin-coupling experiment



Schematic configuration for AXEL experiment.

- The array configuration is composed by 21 sensor layers and 22 source layers. Every sensor layer is sandwiched by two source layers. And each layer is a 21 × 21 array.

- The sensitivity for $g_s g_p$ can reach 6.3×10^{-33} for $\lambda = 1$ mm and $< 1.4 \times 10^{-34}$ for $\lambda > 10$ mm

Yu-Chu M. Li, Wei-Tou Ni, Physica B (2000) 2139-2140

The sensitivity is limited by thermodynamic magnetization fluctuation noise ΔM (in SI unit),

$$(\Delta M^2) = 4\tau_M kT\mu_0\chi V/(1 + 4\pi^2\tau_M^2 f^2), \tag{1}$$

where τ_M is the magnetic (spin) relaxation time. For frequency f below $(2\pi\tau_M)^{-1}$, the magnetization fluctuation noise ΔM is proportional to $\chi^{1/2}\tau_M^{1/2}$. Since, the signal is proportional to χ, the signal-to-noise ratio is proportional to $\chi^{1/2}\tau_M^{-1/2}$. The paramagnetic materials near Curie temperature have high susceptibilities. Shorter relaxation time is preferred. TbF_3 with $\chi = 2$ and $\tau_M \sim 1$ ns at 4.2 K is good for this purpose. Both planar and cylindrical configurations are good for implementation in the earth-bound laboratories. The cylindrical configuration is especially good for space experiment, since rotation can be inertial and does not induce vibrations. With multiple-layer array configuration of total sensor volume 10^{-3} m^3, magnetization-noise-limited performance and one year integration time, the sensitivity can be enhanced by more than five orders of magnitude and will be comparable to the goal of SCE experiment of STEP [5].

In Brief

The experimental sensitivity is limited by the thermodynamic magnetization fluctuation noise $\varDelta M$ as follows:

$$\left\langle \varDelta M^{2} \right\rangle = 4\tau_{M} kT \mu_{0} \chi V \big/ (1 + 4\pi^{2}\tau^{2}{}_{M} f^{2})$$

For TbF_3, the susceptibility is 2 at 4.2 K, and the relaxation time is 1 ns. Hence, it is well-suited for this purpose.

Merits of the AXEL scheme:

1. It is less sensitive to vibration effects. To minimize the vibration noise, sensors and spin-coupling sources rotate with different speed in space.
2. Ground laboratory version of the experiment can be performed first and yet give significant improvement over previous experiments.
3. The array configuration can probe smaller ranges of the interaction.

Measuring spin-spin interactions

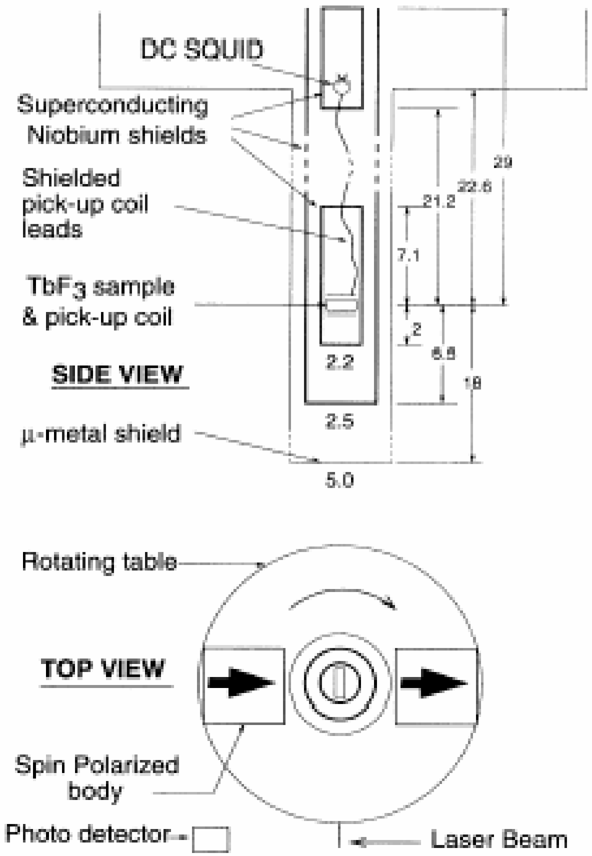


FIG. 1. The cross section and the top view of the experimental apparatus. All dimensions are given in cm. In the top view, the right polarized body is the *U* sample; the left one is the *V* sample. The spin of one of the two samples is flipped in the middle of a typical run.

Spin source: Dy_6Fe_{23}
Its compensation temperature is near room temperature. The magnetic field is compensated, but there is a net total spin (and orbital momentum).

Magnetic sensor: TbF_3
It's paramagnetic susceptibility is high at T=4.2 K which is close to and above its curie temperature 3.95 K. (the first use of this kind of sensor)

T.C. P. Chui , Wei-Tou Ni Phys. Rev. Lett. V71, (1993)

More to do for AXEL experiment study

- Optimize the cylindrical array configuration (including the numbers and the dimensions of the sensors and the spin-coupling sources)

- Calculate the theoretical spin-coupling effects for various theories.

- More detailed study of the experimental schemes in space

Outlook

- The spin coupling constant $g_p g_s$ would be improved by 5 orders of magnitude in the space AXEL experiment.
- Shorter distance toward 0.1 mm could be approached.
- The sensitivity for Spin-Spin coupling and Spin-Cosmos coupling could also be improved.
- This experiment will contribute to fundamental physics and dark matter search.

Thank you!