Search for New Forces using SQUID's with Paramagnetic Salts

Wei-Tou Ni
Center for Gravitation and Cosmology
Department of Physics, National Tsing Hua University
Hsinchu, Taiwan 30043, Republic of China

Abstract

In previous experiments, we have demonstrated the sensitivity and usefulness of using SQUID's with paramagnetic salts to explore new spin-dependent forces. These forces induce magnetization changes in the paramagnetic salts and the SQUID's detect these magnetization changes sensitively. After a brief review of the current experimental status, we explore various schemes using this method to measure mass-spin interactions, spin-spin interactions and cosmic spin interactions. Both earthbound and spacebound schemes are presented.

1. Introduction

Today, we have heard the talks on the search for fifth force, new forces and axion by E. Fishbach, H. J. Paik and S. Matsuki; and the talks on theoretical motivations for axion, and its role in inflationary universe, global string evolution and cosmology by J. E. Kim, M. Kawasaki and M. Nagasawa. Since the emphasis today in this International Workshop on Gravitation and Astrophysics is on new forces and axion as related to gravitation, particle physics, astrophysics and cosmology, I will add my talk on the search scenario for spin-dependent forces and axion using SQUID's with paramagnetic salts.

Motivated by possible P(parity), and T(time reversal) noninvariance, Leitner and Okubo [1], and Hari Dass [2] suggested some time ago the following type spin-gravity interaction

$$H_{int} = f(r)\hat{\mathbf{r}} \cdot \sigma \tag{1}$$

where $\hat{\mathbf{r}}$ is the unit vector from the massive body to the particle with spin $\hbar\sigma$. They assumed $f(r) = -AUm$ with U the gravitational potential of the massive body. With a finite range, $f(r) = -Ae^{-\mu r}mU$ can be assumed and

$$H_{int} = -Ae^{-\mu r}mU\hat{\mathbf{r}} \cdot \sigma. \tag{2}$$

In an effort to solve the strong CP problem, axion theories were proposed [3, 4, 5]. In these theories, there are monopole-dipole interactions of the form [6]

$$H_{int} = [\hbar^2(g_s g_p)/8\pi m]\sigma \cdot \hat{\mathbf{r}}(1/\lambda r + 1/r^2)exp(-r/\lambda) \tag{3}$$

together with $\sigma \cdot \sigma$ (dipole-dipole) interactions

$$H_{int} = [\hbar^3 (g_{p1} g_{p2})/16\pi c m_1 m_2][(\sigma_1 \cdot \sigma_2)(1/\lambda r^2 + 1/r^3 + (4\pi/3)\delta^3(\mathbf{r})) - (\sigma_1 \cdot \hat{\mathbf{r}})(\sigma_2 \cdot \hat{\mathbf{r}})(1/\lambda^2 r + 3/\lambda r^2 + 3/r^3)] exp(-r/\lambda). \quad (4)$$

In (3), g_s and g_p (in the following, we take g_p to be that of the electron) are the dimensionless spin-coupling constants at the scalar and pseudoscalar vertices. In (4), g_{p1} and g_{p2} are the dimensionless spin coupling constants at the pseudoscalar vertices of particles with masses m_1, m_2 and spins σ_1, σ_2 respectively; when both particles are electrons, $g_{p1}=g_{p2}=g_p$ and $m_1=m_2=m_e$. Axion also induces monople-monopole interactions of the form

$$H_{int} = -\hbar c (g_{s1} g_{s2}/4\pi r) exp(-r/\lambda). \quad (5)$$

These non-spin-dependent interactions are searched for in the fifth force experiments and the equivalence-principle experiments.

Discovery and confirmation of the quadrupole anisotropy in cosmic microwave background radiation favors cold dark matter cosmologies. Axions, other pseudoscalar Goldstone bosons and neutrinos are possible candidates for cold dark matter. Recent microlensing observations suggest that brown dwarfs are not likely to be a major constitutent of dark matter, and searching for dark matter in the form of axions or other particles becomes even more critical. To search for dark matter, it is important to experimentally determine the form of interaction in the laboratory. Earthbound and spacebound laboratory experiments to search for axion interaction complement the search for dark matter axions.

For axion interaction, the monopole-dipole (mass-spin) interaction is stronger than dipole-dipole (spin-spin) interaction in the laboratory. For the spin-spin interaction, the current limit on anomalous electron-electron spin interaction is $(1.2 \pm 2.0) \times 10^{-14}$ in terms of the interaction strength between the magnetic moments of electrons [7]. Limits on mass-spin coupling from various experiments for axion-type interaction are shown in Fig. 1. The dark matter window for axions is 1 μeV - 1 meV. There are two kinds of methods to detect the mass-spin interactions. First kind is to detect force on the mass. Second kind is to detect force on the spin. Torsion balance experiments [8-10] with unpolarized mass on the torsion pan and the STEP spin-coupling experiment [11-13] belong to the first kind. Beam balance experiment [14] and torsion balance experiments [15, 16] with polarized bodies in pans use balances to detect spin-coupling forces on the spins; magnetic resonance experiments [17-19] use pick-up coils to detect spin-coupling forces on the spins; SQUID experiment [20] uses SQUID to sense the induced magnetization change due to spin-coupling forces on paramagnetic materials. All these experiments are of the second kind.

Related to the mass-spin coupling experiments, there are cosmic spin-coupling experiments to detect possible spin-dependent cosmic spatial anisotropy. These experiments are basically in the same category of Hughes-Drever experiments [21]. For electrons, Phillips [22] used a cryogenic torsion pendulum carrying a transversely polarized magnet with superconducting shields to set a stringent upper limit of 8.5 $\times 10^{-18}$ eV for the cosmic splitting of spin states of electrons. In our laboratory, we have used a fixed room-temperature torsion balance with a magnetically-compensated $DyFe_3$ polarized mass to improve the limit. Our cumulated results set a limit of 2.96×10^{-18} eV [23-25]. Berglund et al. [26] have used the relative frequency of Hg and Cs magnetometers to monitor the potential energy level variations due to spatial anisotropy and give an upper limit of 8.3×10^{-19}eV for electron. For all of the experiments using a fixed torsion balance or fixed magnetometers, the signals to be detected have period of one sidereal day (23 hours 56 minutes 4 seconds). Now we use a rotatable torsion balance for measuring the potential spatial anisotropy, reducing the period of signals to about 1 hour (the period of rotatable table). The resolution of this method is now better than that of the fixed balance results and gives an upper limit of 7×10^{-19}eV [27]. We hope to improve this result by another order of magnitude in the near future. Hou will report on this experiment in this conference [27].

In the following, we explore various schemes using dc SQUID's to sense the magnetization change associated with spin motion for detecting the spin-coupling interactions due to ordinary unpolarized mass, polarized mass and cosmic anisotropy, with emphasis on the mass-spin interactions. Section 2 describes the basic principles of such a detection. Section 3 reports our present experimental schemes and analyzes possible methods of improvement. Section 4 discusses future outlook.

2. Basic principles

In electromagnetism, for a magnetic moment **m** in a magnetic field **B**, the Hamiltonian is

$$H_{mag} = -\mathbf{m} \cdot \mathbf{B}. \tag{6}$$

For electron spin magnetic moment, (6) becomes

$$H_{mag} = \mu_e \sigma \cdot \mathbf{B} \tag{7}$$

where $\mu_e(=|\mu_e|)$ is the *magnitude* of the electron magnetic moment. Compared with (1), the anomalous monopole-spin interaction on an electron is equivalent to a **B**-field of

$$\mathbf{B}_{eff} = \frac{1}{\mu_e} f(r)\hat{\mathbf{r}}. \tag{8}$$

For axion interaction,

$$\mathbf{B}_{eff} = \frac{\hbar^2}{\mu_e}\frac{g_s g_p}{8\pi m_e}\ (\frac{1}{\lambda r} + \frac{1}{r^2})\ exp\ (-r/\lambda)\hat{\mathbf{r}} \tag{9}$$

for the field generated by a nucleon on an electron. Integrated over the nucleons of the ordinary unpolarized mass, we have

$$\mathbf{B}_{eff} = \frac{1}{\mu_e}\hbar^2 \; \frac{g_s g_p}{8\pi m_e} \; \frac{M}{m_N} \; \frac{1}{V} \; \int (\frac{1}{\lambda r} + \frac{1}{r^2}) \; exp\; (-r/\lambda)\hat{\mathbf{r}} dV. \tag{10}$$

This effective field can be detected by measuring the induced spin magnetization using SQUID sensors while the actual magnetic field is shielded by superconducting shields. In order to have an ac measurement to suppress noise, the source mass needs to be moved periodically or quasi-periodically. A schematic for spin-coupling experiments is shown in Fig. 2. From this effective-field measurement, the dimensionless constant product $g_s g_p$ can be determined as

$$g_s g_p = \frac{8\pi m_e \mu_e m_N V}{\hbar^2 \; M I_0} B_{eff} \tag{11}$$

where I_0 is the *magnitude* of the integral in (10).

For the cosmic spatial anisotropy experiment, Hamiltonians of the forms $g_v \sigma \cdot \mathbf{v}$ and $g\sigma\cdot\mathbf{n}$ are proposed. For these Hamiltonians, the effective fields can be defined as

$$\mathbf{B}_{eff} = \frac{g_v}{\mu_e}\mathbf{v}, \tag{12}$$

and

$$\mathbf{B}_{eff} = \frac{g}{\mu_e}\mathbf{n}. \tag{13}$$

For the spin-spin interactions, the effective field on the electrons of the magnetic sensors can be similarly defined.

3. Experimental schemes

As mentioned in the last section, Fig. 2 shows a general schematic for spin-coupling experiments. The dewar is sitting on a rotating stage. The mass underneath the table is on another rotating stage. In our former $\sigma \cdot \mathbf{r}$ spin-coupling experiment, the mass is unpolarized and is rotated with a period of about 1 cycle/sec with dewar static. In our future experiment, we will set dewar in different angles or in a slowly rotating mode (0.1$\sim$2 hr per round) to average out environmental couplings. For the spin-spin coupling experiment, the mass is spin-polarized. To increase the spin-spin coupling effect, we can add another spin-polarized mass at the opposite side or use a set of spin-polarized masses with appropriate spin-orientations. For the cosmic spatial anisotropy experiment, we can remove the mass and rotate the dewar; our universe is the source.

In our cryogenic spin-coupling experiment [20], the magnetization change of the paramagnetic salt TbF_3 induced by the spin-coupling force of the copper cylinder rotating outside the dewar is sensed by a pickup coil connected to a dc SQUID. The sensitivity to the effective field B_{eff} is 43500 ϕ_o/G where ϕ_o is the magnetic flux quantum. The magnetic field is shielded by superconducting shields. From six runs, we set new limit on the axion coupling constant $g_s g_p$ (Fig. 1). Our limit for r = 10–300 mm ranges is two orders of magnitude better than previous results. For r > 30 mm, the axion coupling constant $g_s g_p$ is $(0.14 \pm 0.67)\times 10^{-28}$.

For current axion models, typical values of $g_s g_p$ are around 10^{-36} at $\lambda \sim 1$ mm. Since our current understanding of these hypothetical scalar particles is modest, stronger coupling in a large domain would be possible and needs to be explored.

Outlook for experimental improvement can be evaluated following [28]. From the fluctuation-dissipation theorem, associated with any relaxation process, there corresponds a related fluctuation. Corresponding to magnetic relaxation is the magnetization fluctuation noise ΔM (in SI unit)

$$(\Delta M^2) = 4\tau_M kT\chi V_d \Delta f/[\mu_0(1 + 4\pi^2{\tau_M}^2 f^2)] \tag{14}$$

where τ_M is the magnetic (spin) relaxation time, Δf the bandwidth and V_d the volume of the magnetic detector. For frequency f below $(2\pi\tau_M)^{-1}$, the magnetization fluctuation noise ΔM is, to a good approximation,

$$(\Delta M) = (4\tau_M kT\chi V_d \Delta f)^{1/2}/(\mu_0)^{1/2} \tag{15}$$

and is proportional to $\chi^{\frac{1}{2}}\ \tau_M^{\frac{1}{2}}$. The magnetization density **M** due to the effective field $\mathbf{B}_{eff}$, i.e.,

$$\mathbf{M} = (\mu_0)^{-1}\chi_s \mathbf{B}_{eff} \tag{16}$$

where

$$\chi_s = \xi_s \chi \tag{17}$$

is the magnetic susceptibility due to electron spin and ξ_s is the ratio of induced spin magnetization versus total induced magnetization in the normal magnetic interaction. For Fe, Co, and Ni, the magnetization is mostly due to electron spins and ξ_s is close to 1. For TbF_3, the magnetization comes from the terbium ion which has S=3, L=3 and J=6; about two thirds of the magnetic moment of the terbium ion comes from its spin and ξ_s is about 2/3.

The total magnetization of the magnetic detector induced by the effective field $\mathbf{B}_{eff}$ is

$$\mathbf{M} = \xi_s \mu_0^{-1}\chi \int_{V_d} \mathbf{B}_{eff} dV_d. \tag{18}$$

For axion-like interaction, $\mathbf{B}_{eff}$ is given by (10) and the total induced magnetization is

$$\mathbf{M} = g_s g_p \frac{\xi_s \mu_0^{-1}\chi\rho\hbar^2}{8\pi\mu_e m_e m_N}\mathbf{I} \tag{19}$$

where

$$\mathbf{I} = \int_{V,V_d} (\frac{1}{\lambda r} + \frac{1}{r^2}) exp(-\frac{r}{\lambda}) \hat{\mathbf{r}} dV dV_d. \tag{20}$$

Here ρ=M/V is the mass density of the source. For small detector, the effect field $\mathbf{B}_{eff}$ at the detector is quite homogeneous and $I = |\mathbf{I}| \approx V_d I_0$.

To obtain the magnetization-fluctuation limited resolution $R_{g_s g_p}$ for the coupling strength $g_s g_p$, we equate ΔM to $M_{rms}(= |\mathbf{M}|/\sqrt{2})$, and solve for $g_s g_p$. The bandwidth Δf is taken to be 1/(2t) where t is the observation time. The result is

$$R_{g_s g_p} = \frac{16\pi \mu_e m_e m_N}{\xi_s \hbar^2 \rho} \frac{\mu_0}{\chi} (kT)^{1/2} (\frac{\tau_M}{t})^{1/2} \frac{(V_d)^{1/2}}{I}. \tag{21}$$

In this equation, $(V_d)^{1/2}/I$ is a geometric factor which depends on the interaction searched for. For better resolution, we need to minimize this factor, or to maximize its inverse $I/(V_d)^{1/2}$, under practical size constraints for experimental setup. Numerical work is underway to optimize this geometric factor under various situations [29].

In [28], we proposed multiple-sensor spin-coupling experiments for enhancing this geometric factor. Two such configurations are shown in Fig. 3. On the left (right) diagram is a two-dimensional planar (cylindrical) array of magnetic detectors to detect the spin-coupling forces on them as the left (outer) Pt-Ir mass and the right (inner) Pt-Ir mass move to the right and to the left (rotate to the right or to the left) in the same direction or in the opposite directions. The magnetic detectors can be made of either paramagnetic salts near Curie temperature or of ultra-soft ferromagnetic materials. The spin-coupling forces on the electron spins due to masses induce magnetization in these magnetic detectors. Motion of the masses induce magnetization change which can be picked up by the coils connected to a dc SQUID. Stray magnetic field can be shielded by layers of niobium coatings on the detector array case. Both planar and cylindrical configurations are good for implimentation in the earth-bound laboratories. The cylindrical configuration is especially good for space experiment, since rotation can be inertial and does not induce vibrations. Multi-planar or multi-cylindrical configurations of magnetic sensors can also be used to enhance the geometric factor further. One aim in using these array configurations is to probe smaller ranges of the interaction. We hope to go to millimeter range and submillimeter range.

From (21), the signal to noise ratio is proportional to $\xi_s\ \chi^{\frac{1}{2}}\ \tau_M^{-\frac{1}{2}}$. To increase the signal to noise ratio, magnetic materials with large χ and short τ_M need to be considered. Paramagnetic materials near Curie temperature have high susceptibilities. Shorter relaxation time is preferred. TbF_3 with $\chi = 2$ at 4.2 K used in [7] and [20] is a good candidate. The relaxation time for TbF_3 is around 1 ns as indicated by EPR measurements [30]. If we use TbF_3 crystal with the easy magnetization axis along the sample axis, χ is increased about 3 times and we have a gain in sensitivity of 1.7. Ultra-soft ferromagnetic materials would also be good candidates for this purpose. For VITROVAC samples, the reversible permeability can exceeds 10^3 with roll off frequency reaching 1 MHz [31]. However, their noise characteristics and ultra-small field responses need to be studied further before comparisons with paramagnetic materials can be made meaningfully.

We are currently improving on the sensitivity of this experiment. With array (multiple-sensor) configuration ($V_d \approx 10^{-3}m^3$), dense mass, magnetization-noise-limited performance and longer integration time (one year), the sensitivity would be enhanced by more than 5 orders of magnitude. The sensitivity of this proposal — AXEL (Axial Experiment at Low-Tempature) is shown in Fig. 1.

4. Outlook

As shown in Fig. 1, the STEP spin-coupling experiment [11-13] proposes to search for any coupling force between spin-polarized and ordinary matter to a sensitivity of $g_s g_p = 6 \times 10^{-34}$ at a range of 1 mm or longer. So is the AXEL spin coupling experiment.

Speake's group in Birmingham is working on the development of a new superconducting torsion balance for the spin-coupling experiment using a method of first kind (detecting force on the mass). They are also aiming at significant improvement. This morning, H. J. Paik presented his proposal aiming at great improvement using superconducting accelerometers for a spin-coupling experiment with $Q=10^{8\text{-}10}$.

Optical detection of axion-photon coupling in a high magnetic field also searches for fundamental spin-coupling interactions and give significant constraints [32]. At the present, three experiments — the PVLAS experiment [33], the Fermilab experiment [34], and the Q & A experiment [35, 36] are ongoing to measure the vacuum magnetic birefringence and to search for axion-like spin coupling interactions.

Present experimental sensitivity already limit the finite-range Leitner-Okubo-Hari Dass dimensionless constant A to A<6. Significant experimental progress in laboratory and in space will reach a sensitivity of $10^{-2} - 10^{-5}$ in A. These experiments will also explore a significant parameter region in axion-like models. More understanding of the possible coupling strengths of these models are pending. Experiments reaching a range of 0.1–1 mm are encouraged to explore the dark matter window.

Significant progress will also be achieved for the spin-spin interactions and cosmic spin interactions.

We would like to thank the National Science Council of the Republic of China for supporting this work under contract No. NSC-87-2112-M007-048. We would also like to thank J. Tang for EPR linewidth measurements of TbF_3 at Argonne National Laboratory.

References

[1] J. Leitner and S. Okubo, Phys. Rev. **136** B1542 (1964).

[2] N. D. Hari Dass, Phys. Rev. Lett. **36** 393 (1976); Ann. Phys. (N. Y.) **107** 337 (1977).

[3] S. Weinberg, Phys. Rev. Lett. **40** 233 (1978); F. Wilczek, Phys. Rev. Lett. **40** 279 (1978); M. Dine, W. Fischler and M. Srednicki, Phys. Lett. **104B** 1999 (1981); M. Shifman, A. Vainshtein and V. Zakharov, Nucl. Phys. **B166** 493 (1980); J. Kim, Phys. Rev. Lett. **43** 103 (1979); H.-Y. Cheng Mod. Phys. Lett. **A2** 409 (1987).

[4] J. E. Kim, Phys. Rep. **150** 1 (1987) and references therein.

[5] S.-L. Cheng, C.-Q. Geng and W.-T. Ni, Phys. Rev. **D52** 3132 (1995) and references therein.

[6] J. E. Moody and F. Wilczek, Phys. Rev. **D30** 130 (1984).

[7] W.-T. Ni, T.C.P. Chui, S.-s. Pan and B.-Y. Cheng, Physica **B 194-196** 153 (1994).

[8] T.-H. Jen, W.-T. Ni, S.-s. Pan and S.-L. Wang, Torsion Balance Experiment Searching for Finite-Range Mass-Spin Interactions, *Proceedings of the Sixth Marcel Grossmann Meeting on General Relativity* ed. by Sato H and Nakamura T (Singapore: World Scientific) p.489 (1992).

[9] R. C. Ritter, L. I. Winkler and G. T. Gillies, Phys. Rev. Lett. **70** 701 (1993).

[10] S.-s. Pan, National Science Council Report (1993); S.-S. Pai, S.-s. Pan and W.-T. Ni, National Science Council Report (1994).

[11] ESA SCI(93)4, STEP (Satellite test of the equivalence principle) report on the phase A study (1993).

[12] N. A. Lockerbie, M3 STEP — the mission, Class. Quantum Grav. **13**, A53 (1996).

[13] D. Shaul, T. J. Sumner, G. K. Rochester and C. C. Speake, Class. Quantum Grav. **13** A107 (1996).

[14] C.-H. Hsieh, P.-Y. Jen, K.-L. Ko, Y. Li, W.-T. Ni, S.-s. Pan, Y.-H. Shih and R.-J. Tyan, Mod. Phys. Lett. **A4** 1597 (1989).

[15] Y. Chou, W.-T. Ni and S.-L. Wang, Mod. Phys. Lett. **A5** 2297 (1990).

[16] B. Heckel, reported in talk presented in *Symposium on Fundamental Physics in Space*, 16-19 October 1995, London, U.K.

[17] D. J. Wineland *et al.*, Phys. Rev. Lett. **67** 1735 (1991).

[18] B. J. Venema *et al.*, Phys. Rev. Lett. **68** 135 (1992).

[19] A. N. Youdin *et al.*, Phys. Rev. Lett. **77** 2170 (1996).

[**20**] W.-T. Ni, S.-s. Pan, H.-C. Yeh, L.-S. Hou and J. Wan, Spin Coupling Experiment using a Paramagnetic Salt with a dc SQUID, to be submitted for publication; preliminary result reported in W.-T. Ni, S.-s. Pan, H.-C. Yeh, L.-S. Hou and J. Wan, "Search for Anomalous Spin-Dependent Forces using a dc SQUID with a Paramagnetic Salt", *Proceedings of Seventh Marcel Grossmann Meeting on General Relativity* (Singapore: World Scientific) p.1625 (1996).

[**21**] V. W. Hughes, H. G. Robinson, and V. Beltran-Lopez, Phys. Rev. Lett. **4** 342 (1960); V. Beltran-Lopez, H. G. Robinson, and V. W. Hughes, Bull. Am. Phys. Soc. **6** 424 (1961); R. W. P. Drever, Phil. Mag. **6** 683 (1962); J. F. Ellena, W.-T. Ni and T.-S. Ueng, IEEE Transactions on Instrumentation and Measurement, **IM-36** 175 (1987).

[**22**] R. Phillips, Phys. Rev. Lett. **59** 1784 (1987).

[**23**] S.-C. Chen, W.-T. Ni, S.-s. Pan, G.-B. Wang, and H.-C. Yeh, "Test of spatial isotropy using polarized-bodies", *Proceedings of the Sixth Marcel Grossmann Meeting on General Relativity*, eds. H. Sato and T. Nakamura (World Scientific) p.1625 (1992).

[**24**] S.-L. Wang, W.-T. Ni and S.-s. Pan, Modern Phys. Lett. **A8**, 3715 (1993).

[**25**] Fang-Ling Chang, Hsien-Chi Yeh, Wei-Tou Ni and Sheau-shi Pan, "Improved experimental limit on the cosmological spatial anisotropy for polarized electrons", pp. 21-29, International Workshop on Gravitation and Cosmology (National Tsing Hua University) (1995).

[**26**] C. J. Berglund et. al., Phys. Rev. Lett. **75** 1879 (1995).

[**27**] L.-S. Hou and W.-T. Ni, "Test of Spatial Anisotropy for Polarized Electrons using a Rotatable Torsion Balance", these proceedings (the CD-ROM Proceedings for the International Workshop on Gravitation and Astrophysics, November 17-19, 1997, Tokyo).

[**28**] W.-T. Ni, Class. Quantum Grav. **13** A135 (1996).

[**29**] Yu-Chu M. Li and Wei-Tou Ni, "Geometric Optimization of Source and Detector Configurations for Spin-Coupling Experiments", work in progress.

[**30**] EPR linewidth measurements at Argonne National Laboratory (J. Tang) and at National Tsing Hua University (W.-T. Ni).

[**31**] G. A. Prodi, S. Vitale, M. Cerdonio and P. Falferi, J. Appl. Phys. **66** 5984 (1989).

[**32**] R. Cameron et al., Phys. Rev. **D47** 3707 (1993).

[**33**] G. Cantatore et al., Nucl. Phys. B (Proc. Suppl.) **35** 180 (1994).

[**34**] F. Nezrick, private communication.

[**35**] W.-T. Ni, S.-K. King, H.-W. Cheng, J.-T. Shy, N. Mio, K. Tsubono and T. C. P. Chui, Test of quantum electrodynamics and search for light scalar/pseudoscalar particles using ultra-high sensitive interferometers, *Proceedings of the Seventh Marcel Grossmann Meeting on General Relativity* (Singapore: World Scientific) p.1628 (1996).

[**36**] W.-T. Ni, Chin. J. of Phys., **34** 962 (1996).

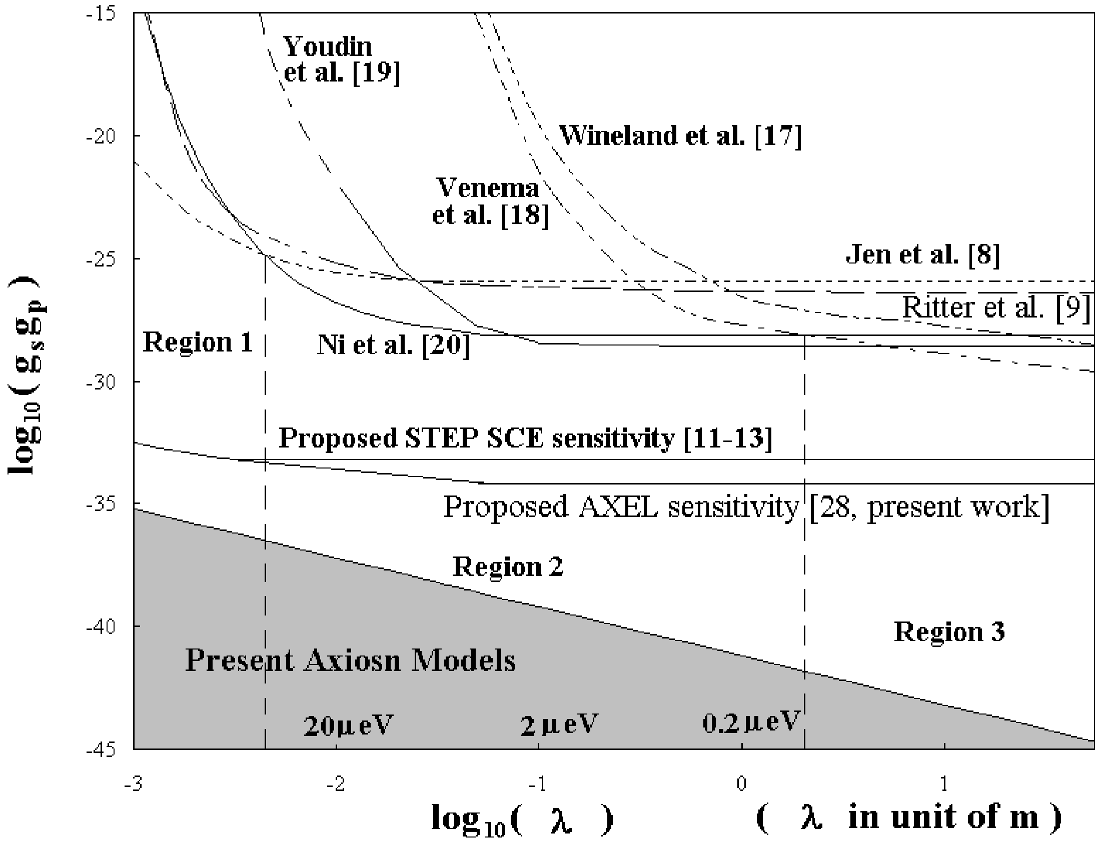

Figure 1. Limits on σ · r spin coupling from various experiments .

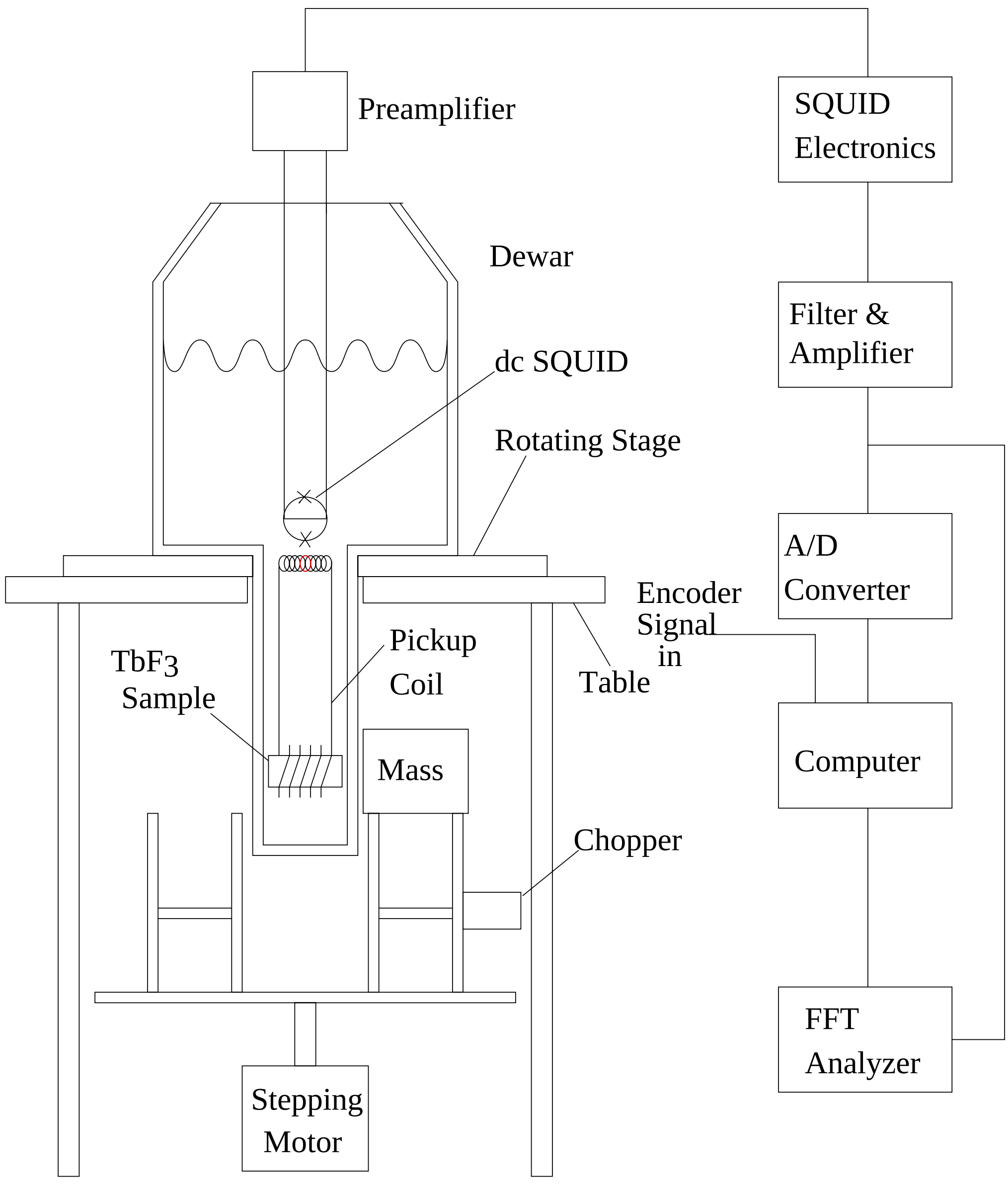

Figure 2. Schematic for spin-coupling experiments.

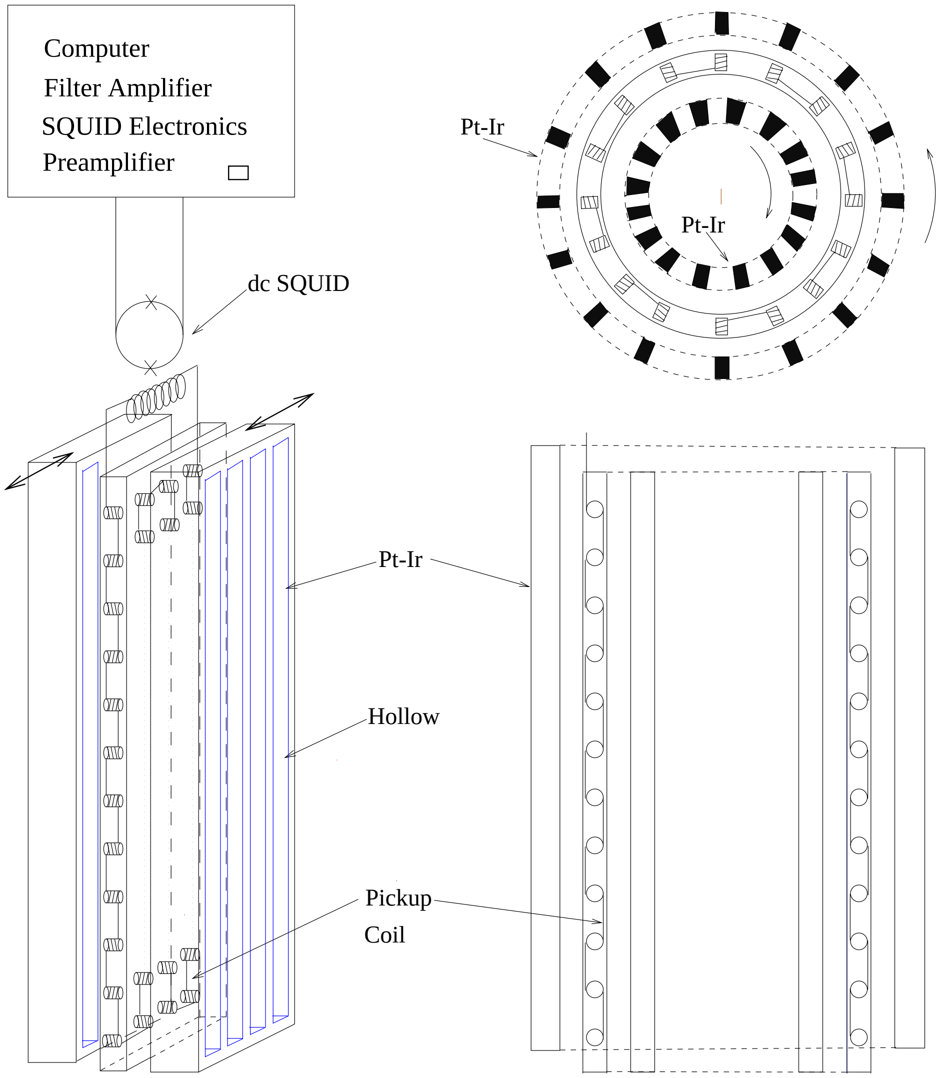

Figure 3. Schematic for a multiple-sensor spin-coupling experiment.