Tests of Lorentz Invariance with alkali-metal– noble-gas co-magnetometer

(+ other application)

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Tests of Fundamental Symmetries

- Parity violation → weak interactions
- CP violation → Three generations of quarks

Symmetry violations found before corresponding particles were produced directly

Lorentz and CPT symmetry

- Exact in standard field theory
- Can be broken in many ways by quantum gravity effects
  - ⇒ For example, Plank mass introduces an energy scale, so a particle given a Lorentz boost to $p \sim M_{\mathrm{pl}}$ should experience different physics due to quantum gravity effects.

Outline

- Lorentz Symmetry
  - ⇒ Motivations for possible violation
  - ⇒ Experimental signatures

- Development of sensitive co-magnetometer
  - ⇒ Elimination of alkali-metal spin-exchange broadening
  - ⇒ Alkali-metal noble gas co-magnetometer
  - ⇒ Limits on Lorentz-violating spin coupling

- Applications
  - ⇒ Sensitive magnetometer for detection of brain fields
  - ⇒ Nuclear spin gyroscope

Parametrizing Lorentz and CPT Violation

- Use effective field theory:

$$\mathcal{L} = -\bar{\psi}(m + a_\mu \gamma^\mu + b_\mu \gamma_5 \gamma^\mu)\psi + \qquad D = 3$$

$$\frac{i}{2}\bar{\psi}(\gamma_\nu + c_{\mu\nu}\gamma^\mu + d_{\mu\nu}\gamma_5\gamma^\mu)\overleftrightarrow{\partial}^\nu \psi \qquad D = 4$$

+ higher dimension operators

a,b - CPT-odd, dimension of energy

c,d - CPT-even, dimensionless

- Many mechanisms:
  - ⇒ spontaneous symmetry breaking: vector fields with VEV — Kostelecky *et al*.
  - ⇒ Modified dispersion relationships: $E^2 = m^2 + p^2 + \eta\, p^3/M_{Pl}$ — Jacobson, Amelino-Camelia, Myers, Pospelov, Sudarsky
  - ⇒ Non-commutative space time $[x_\mu, x_\nu] = \theta_{\mu\nu}$ — Witten, Schwartz, Pospelov

Experimental Signatures

- Spin coupling:

$$\mathcal{L} = -b_\mu \bar{\psi}\gamma_5\gamma^\mu\psi = -\boldsymbol{b}\cdot\boldsymbol{S} \qquad c.f. \qquad \mathcal{L} = e\bar{\psi}\gamma^\mu A_\mu\psi = -\frac{ge}{2m}\mathbf{B}\cdot\mathbf{S}$$

- Limiting velocities for particles different from c

$$\mathcal{L} = \frac{i}{2}\bar{\psi}c_{\mu\nu}\gamma^\mu \overleftrightarrow{\partial}^\nu\psi \qquad (c_\pi - c)/c \sim c_{00}$$

- Photon effects: vacuum dispersion, vacuum birefringence, directional dependence of the speed of light

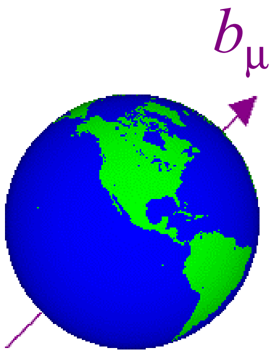
In general, spin coupling seems to be the most robust effect in most models.

Spin coupling experiments

- Vector interaction gives a sidereal signal in the lab frame
- Need a co-magnetometer to distinguish from regular magnetic fields and avoid cancellation by magnetic shields
- Assume coupling is not in proportion to the magnetic moment
- Don’t need anti-particles to search for CPT violation

$$h\nu_1 = 2\mu_1 B + 2\beta_1 (\mathbf{b}\cdot\mathbf{n}_B)$$
$$h\nu_2 = 2\mu_2 B + 2\beta_2 (\mathbf{b}\cdot\mathbf{n}_B)$$

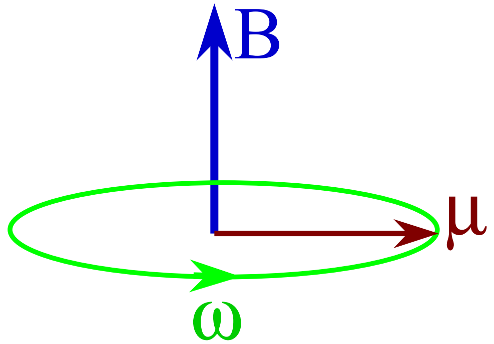
$$\frac{\nu_1}{\mu_1} - \frac{\nu_2}{\mu_2} = \frac{2}{h}\left(\frac{\beta_1}{\mu_1} - \frac{\beta_2}{\mu_2}\right)(\mathbf{b}\cdot\mathbf{n}_B)$$

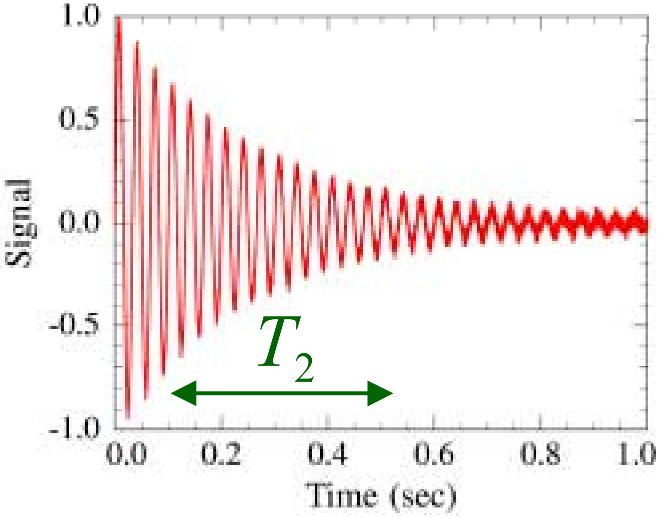


- Preferred direction b^μ could be the direction of motion relative to CMB

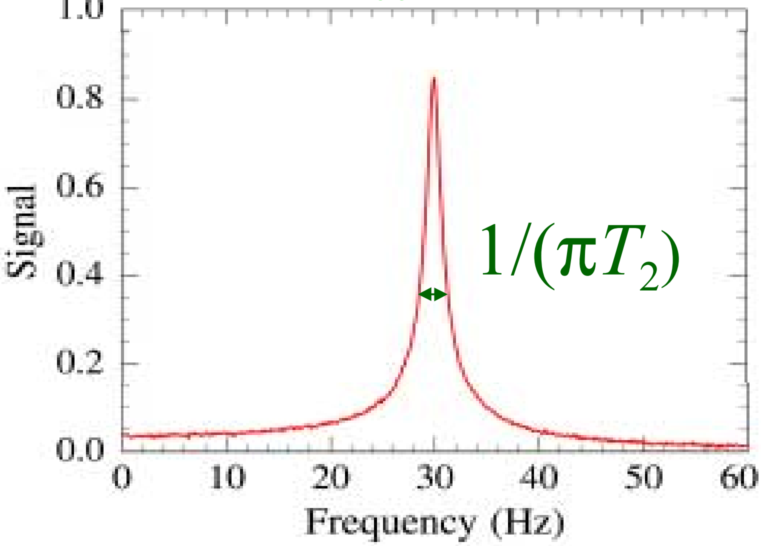
Atomic Spin Magnetometers

$$\omega = \frac{2\mu B}{\hbar}$$





FFT

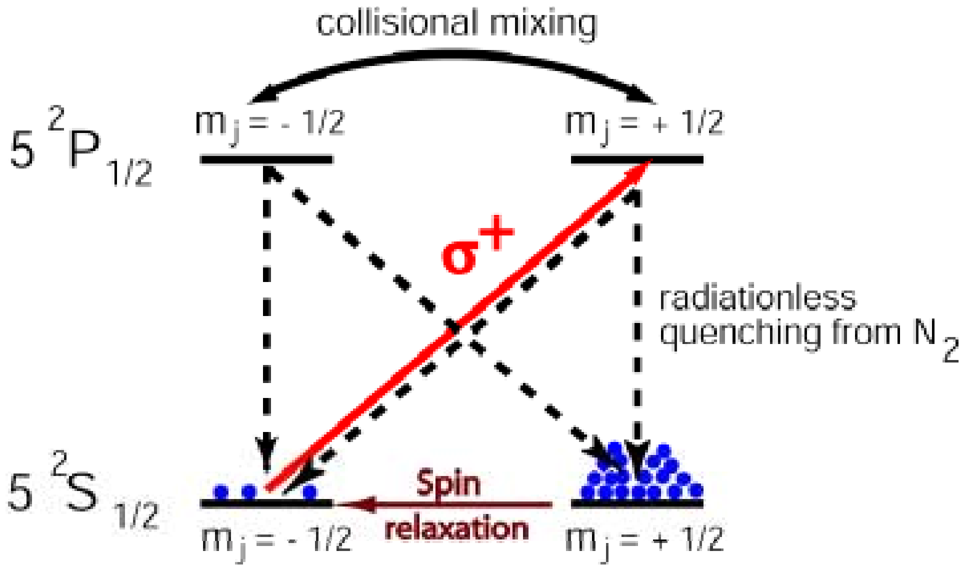


Quantum noise limit for *N* atoms: $$\delta\omega = \frac{1}{\sqrt{T_2 N t}}$$

Choice of Active Species:

Alkali metal atoms: Na, K, Rb, Cs

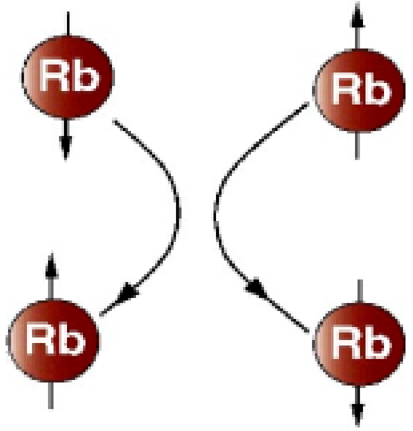
- Unpaired electron - high magnetic moment
- $^2S_{1/2}$ ground state - relatively small collisional spin relaxation rate
- Easy to polarize using optical pumping



Mechanisms of spin relaxation

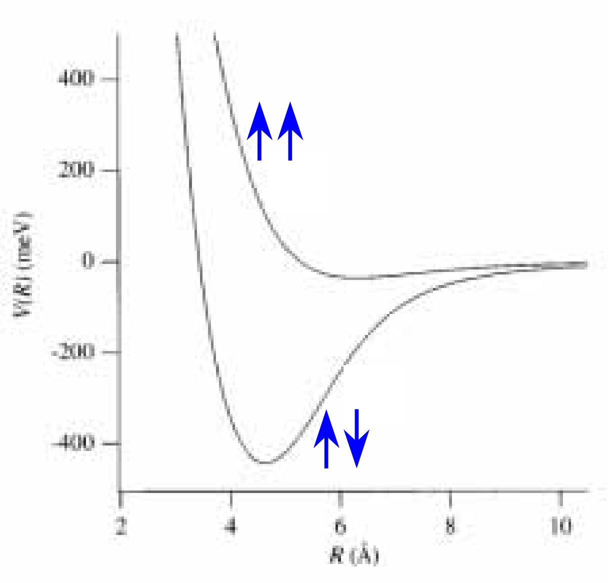
Collisions between alkali atoms, with buffer gas and cell walls

- Spin-exchange alkali-alkali collisions



$$T_2^{-1} = \sigma_{se}\,\bar{v}\,n$$

$$\sigma_{se} = 2 \times 10^{-14}\,\mathrm{cm}^2$$



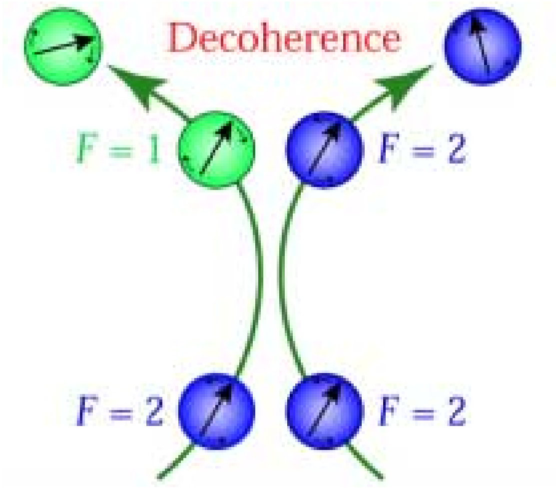
⇒ Increasing density of atoms decreases spin relaxation time

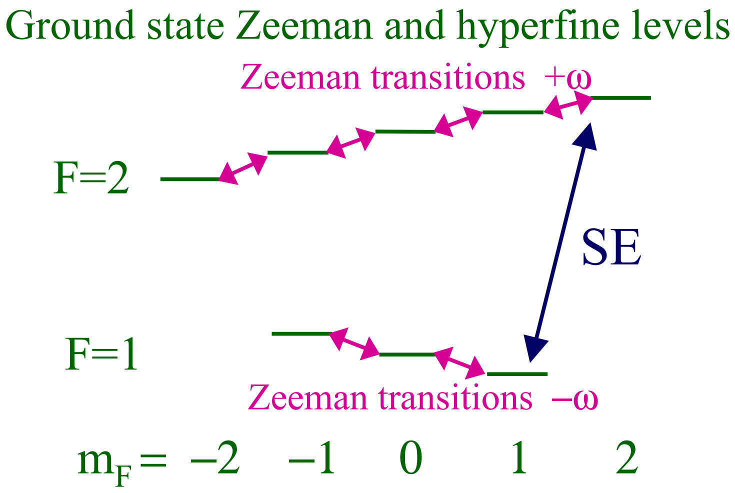
$$T_2 N = \sigma_{\mathrm{se}}\bar{v}V$$

⇒ Under ideal conditions: $\delta B \geq 1\,\mathrm{fT}\sqrt{\frac{\mathrm{cm}^3}{\mathrm{Hz}}}$

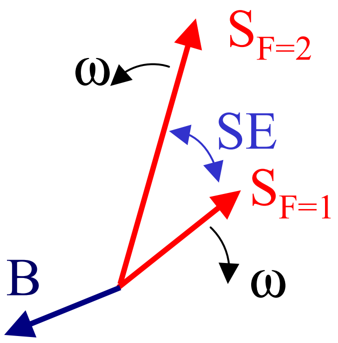
Why do spin-exchange collisions cause relaxation?

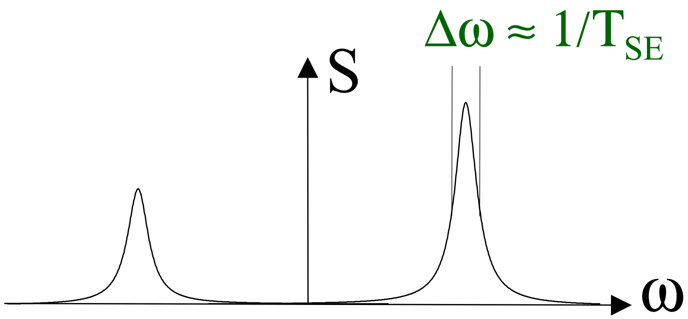
- Spin exchange collisions preserve total angular momentum
- They change the hyperfine states of alkali atoms
- Cause atoms to precess in the opposite direction around the magnetic field




Ground state Zeeman and hyperfine levels

$$\omega_{F=I\pm 1/2} = \pm \frac{g\mu_B B}{\hbar(2I+1)}$$



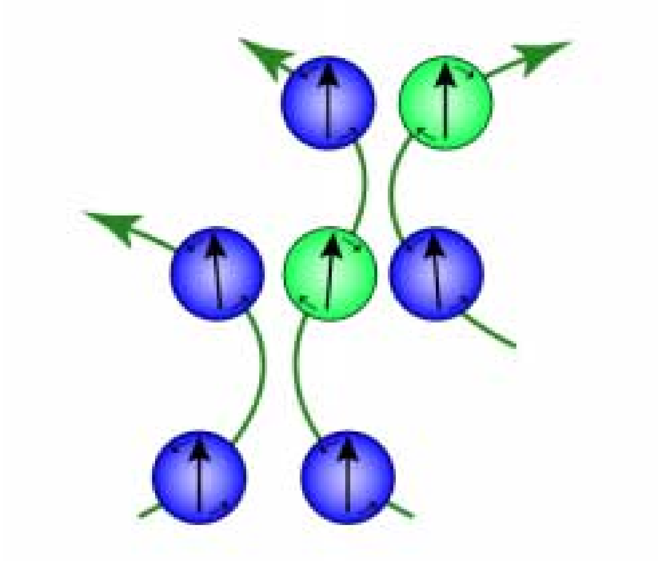

$\Delta\omega \approx 1/T_{SE}$

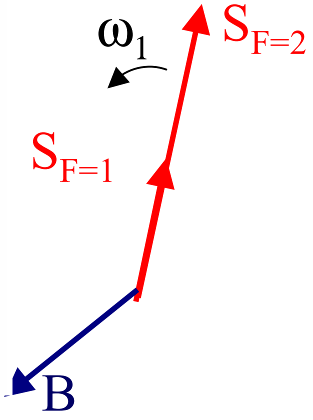
Eliminating spin-exchange relaxation

1. Increase alkali-metal density
2. Reduce magnetic field

$$\omega << 1/T_{SE}$$

Atoms undergo spin-exchange collisions faster than the two hyperfine states can precess apart





$$\omega_1 = \frac{3(2I+1)}{3+4I(I+1)}\omega = \frac{2}{3}\omega$$

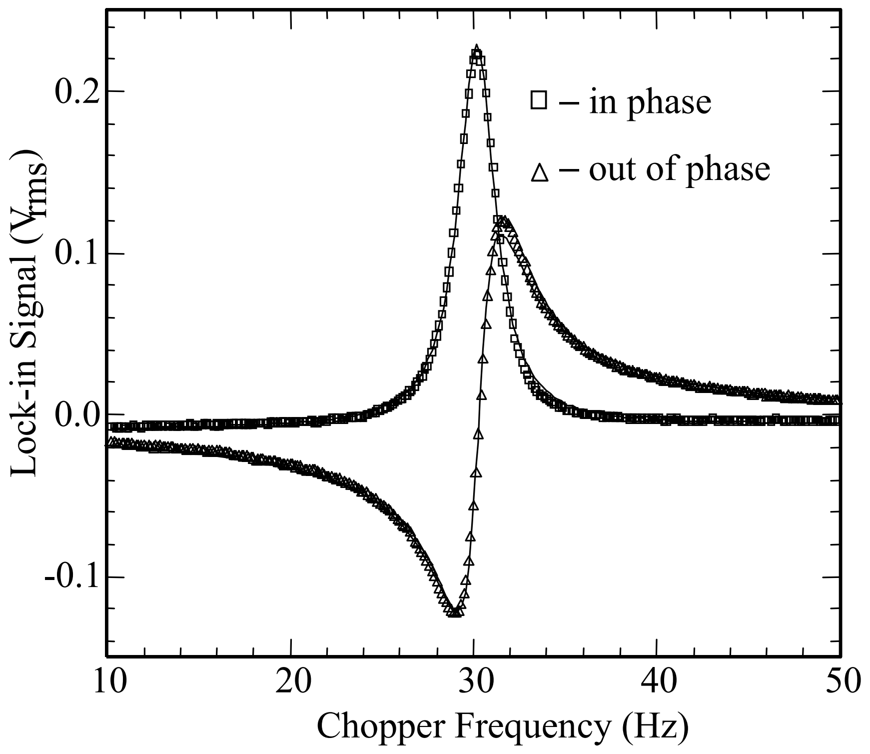
- No relaxation due to spin exchange

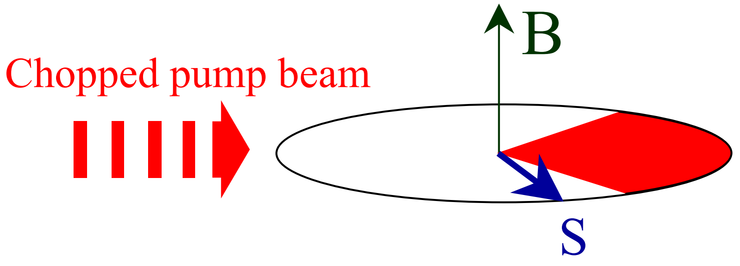
W. Happer and H. Tang, PRL **31**, 273 (1973)

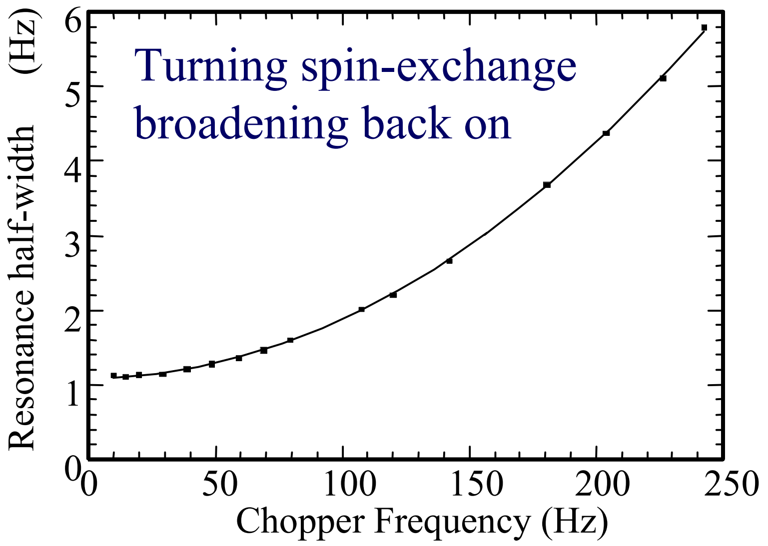
Complete elimination of spin-exchange broadening

Spin-exchange width: 3 kHz

Observed width: 1 Hz





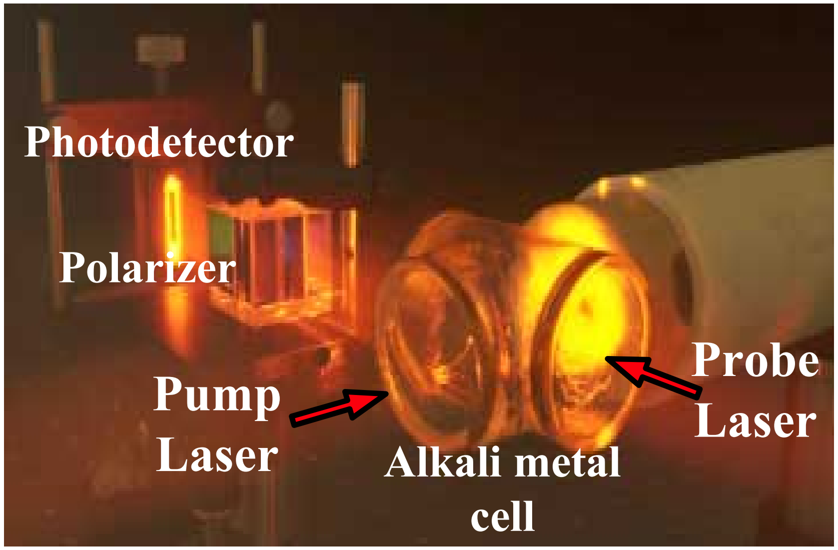


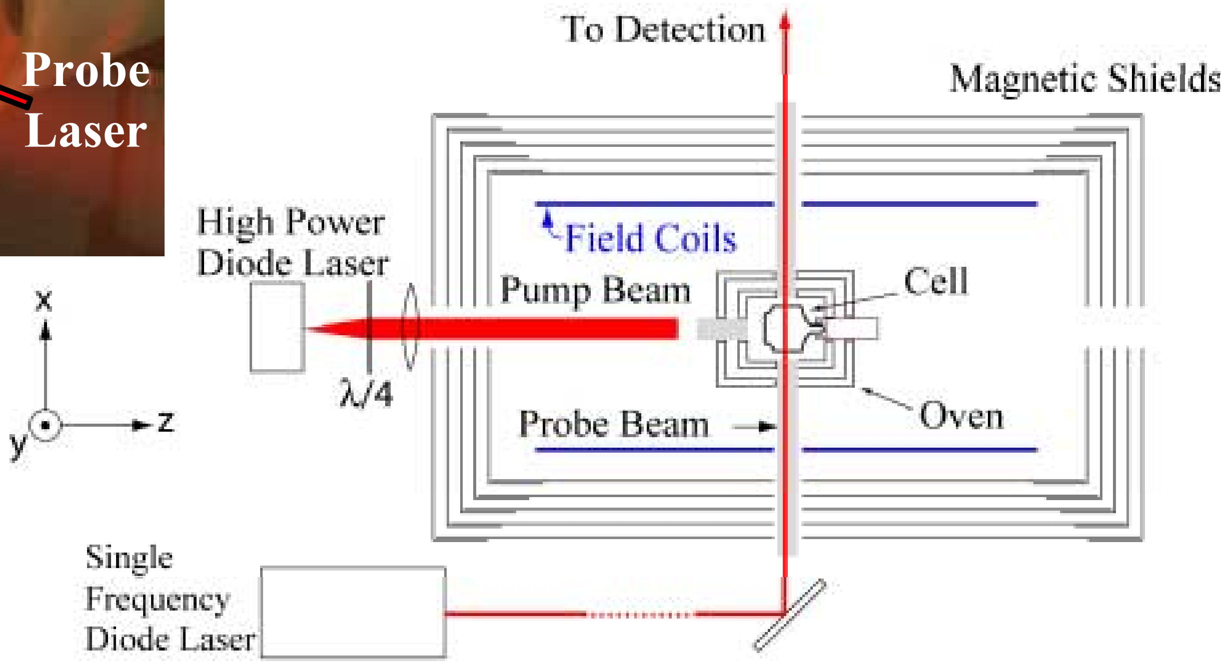
- Residual linewidth due to spin-destruction collisions

  ⇒ Convert spin angular momentum to rotational momentum of atoms

J. C. Allred, R. N. Lyman, T. W. Kornack, and MVR, Phys. Rev. Lett. **89**, 130801 (2002)

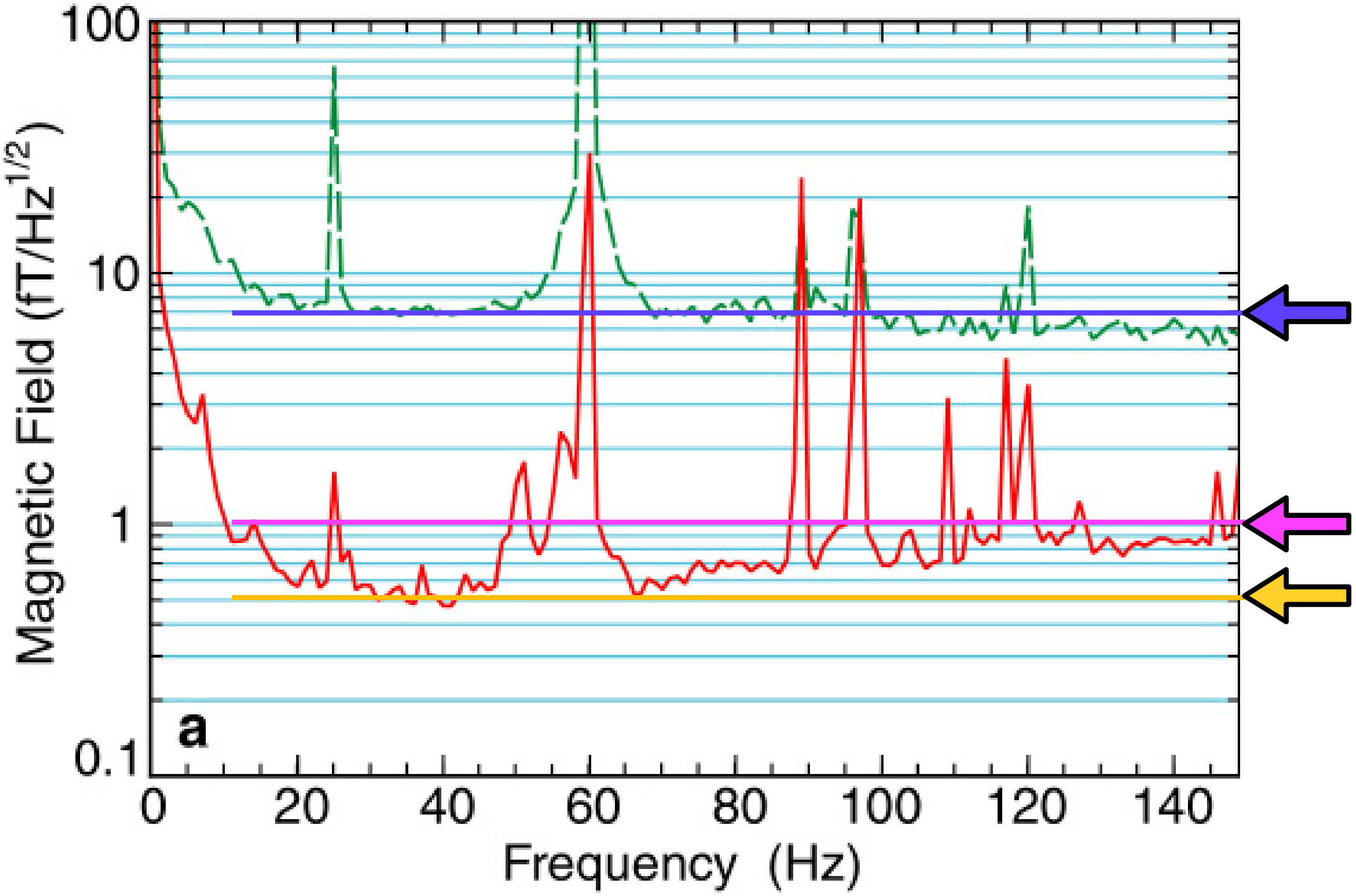
Magnetometer Schematic





- Multi-layer magnetic shields eliminate external fluctuations
- Residual fields are zeroed out with internal coils
- Cell heated to 180°C to obtain alkali density of 10^{14} cm^{-3}

Magnetometer Performance



Magnetic shield noise
7 fT/Hz$^{1/2}$

Best SQUID

Gradiometer Sensitivity
0.5 fT/Hz$^{1/2}$

Volume : 0.3 cm^3
Baseline: 3 mm

- Fundamental sensitive limit at 5 aT/$\sqrt{\text{Hz}}$

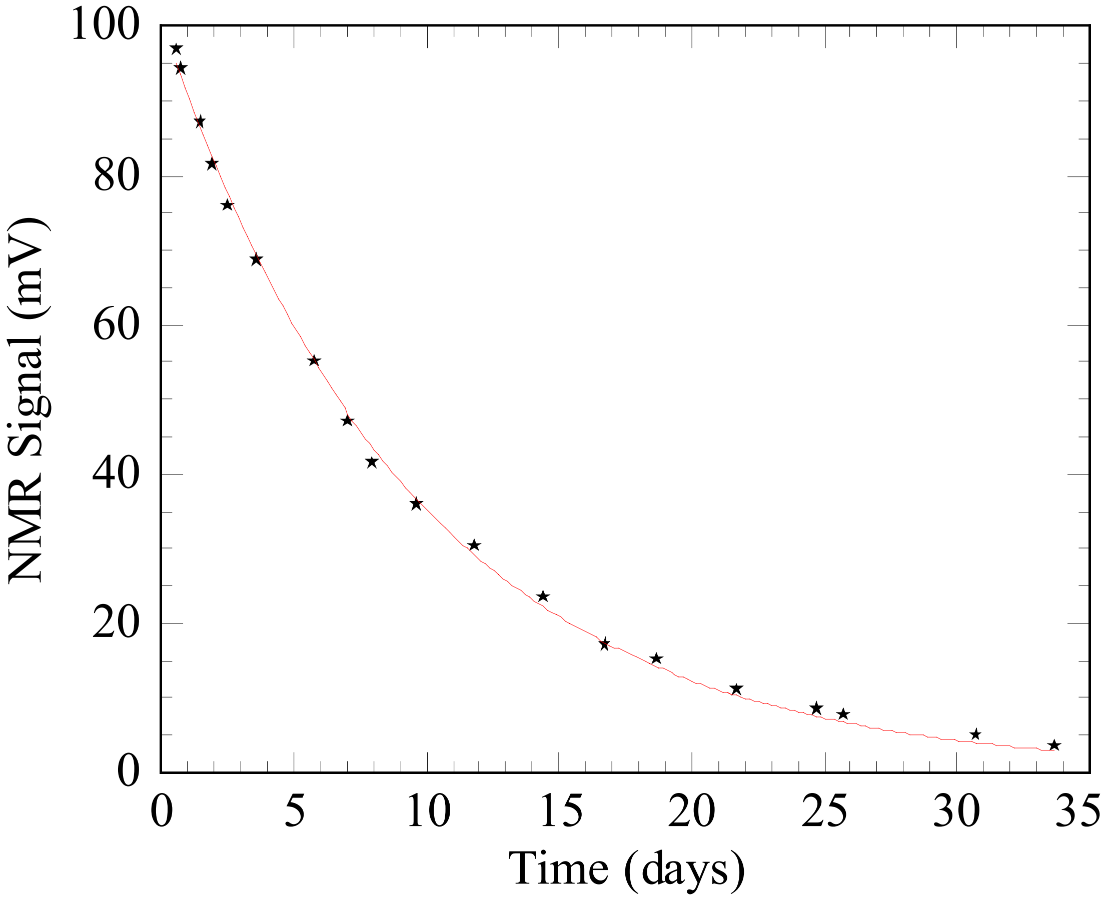
Previously best atomic magnetometer : ~1.8 fT/Hz$^{1/2}$ with a volume 1800 cm^3

I. K. Kominis, T. W. Kornack, J. C. Allred and MVR, Nature **422**, 596 (2003)

^{3}He Co-magnetometer

- Simply replace ^{4}He buffer gas with ^{3}He
- ^{3}He is polarized by spin-exchange

$\Rightarrow T_1 \sim 300$ hours



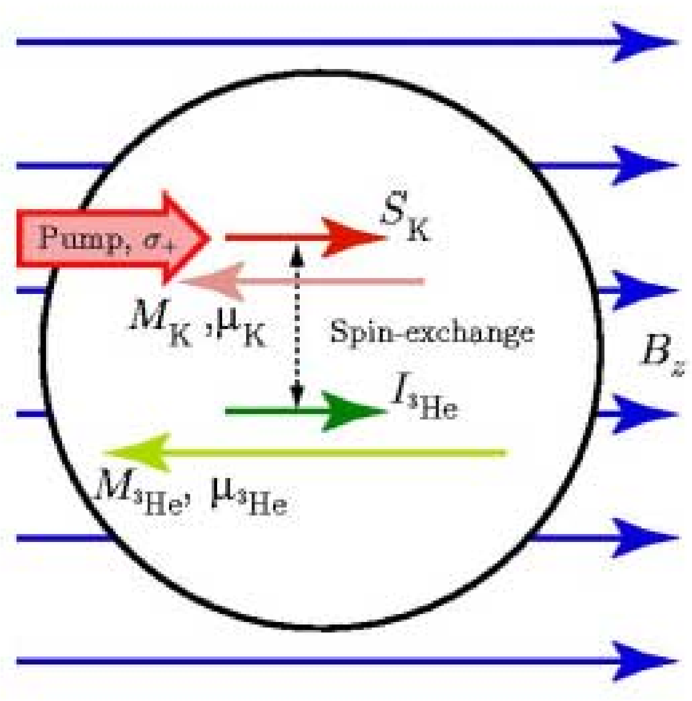
^{3}He Co-magnetometer

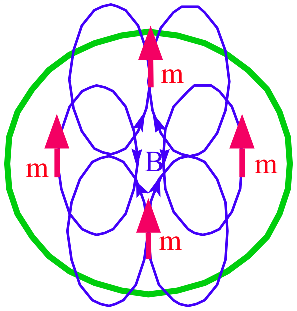
1. Replace ^{4}He with ^{3}He ($I = 1/2$)
2. ^{3}He nuclear spin is polarized by spin-exchange collisions with alkali metal
3. Polarized ^{3}He creates a magnetic field felt by K atoms

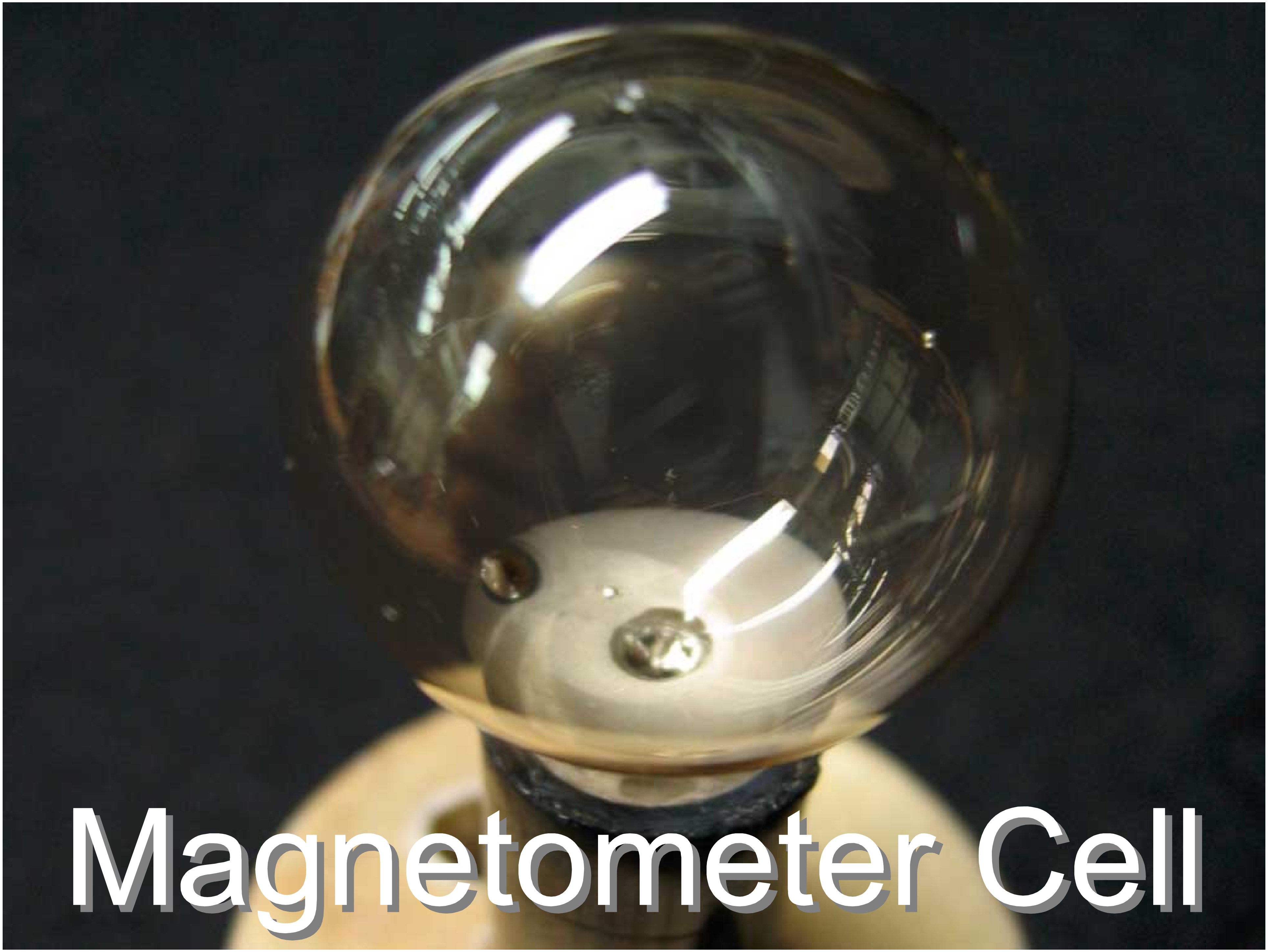
$$B_K = \frac{8\pi}{3}\kappa_0 M_{He}$$

4. Apply magnetic field B_z to cancel field B_K
   - ⇒K magnetometer operates near zero field
5. In a spherical cell dipolar fields produced by ^{3}He cancel
   - ⇒^{3}He spins experience a uniform field B_z
   - ⇒Suppress relaxation due to field gradients

$$T_1^{-1} = D\frac{|\vec{\nabla} B_x|^2 + |\vec{\nabla} B_y|^2}{B_z^2}$$

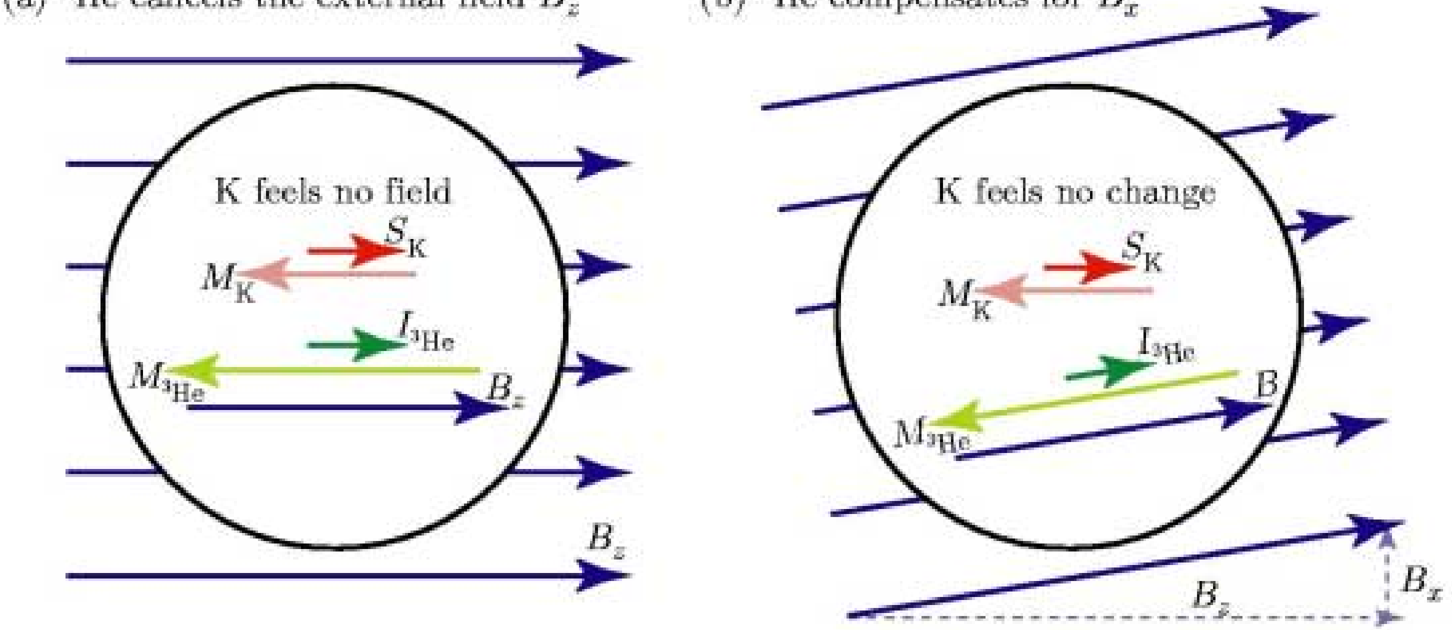




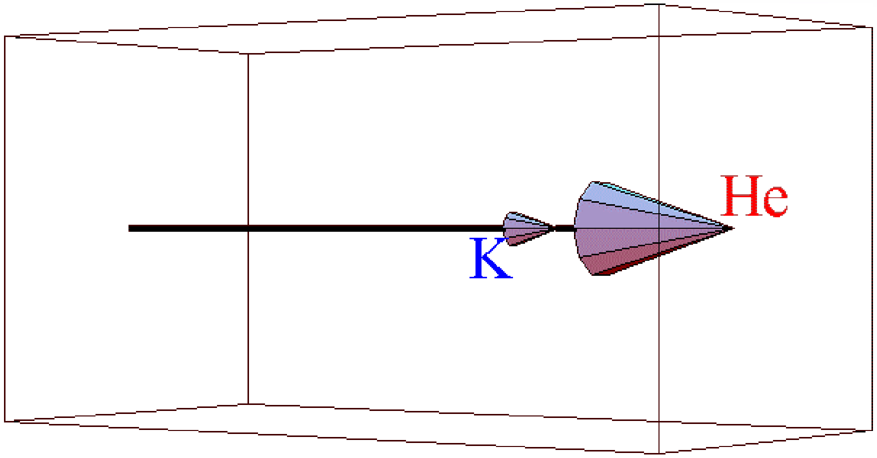


Magnetometer Cell

Magnetic field self-compensation

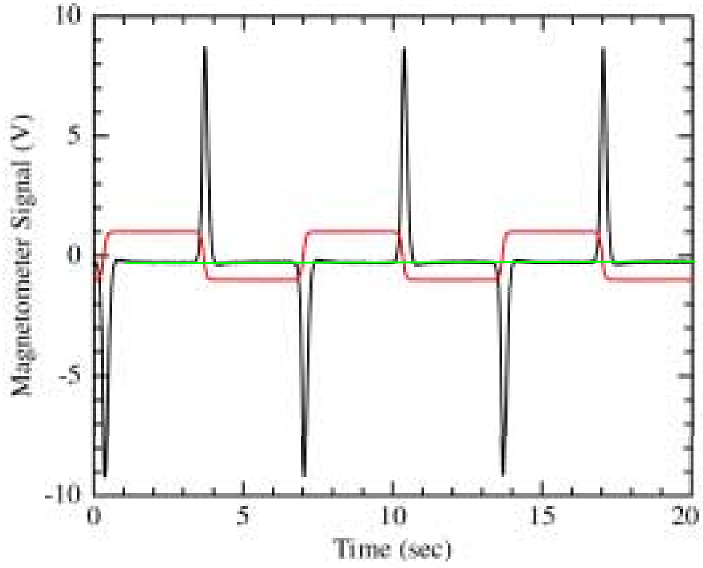

(a) ^{3}He cancels the external field B_z

(b) ^{3}He compensates for B_x

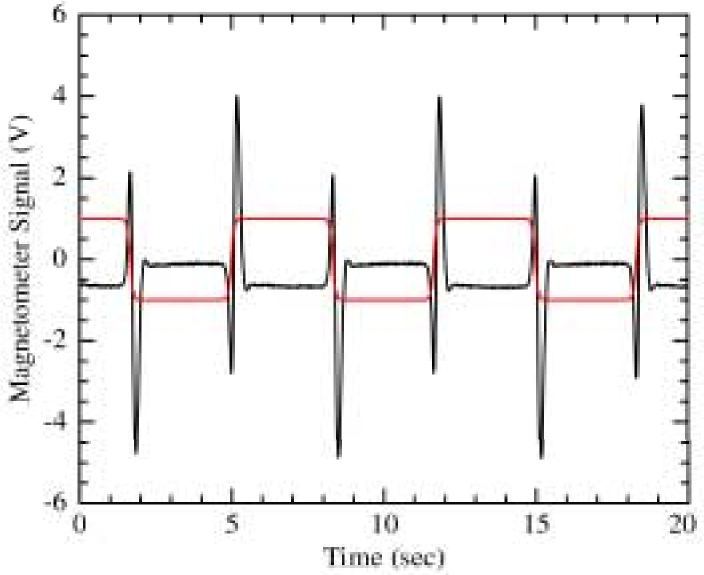


Magnetic field compensation

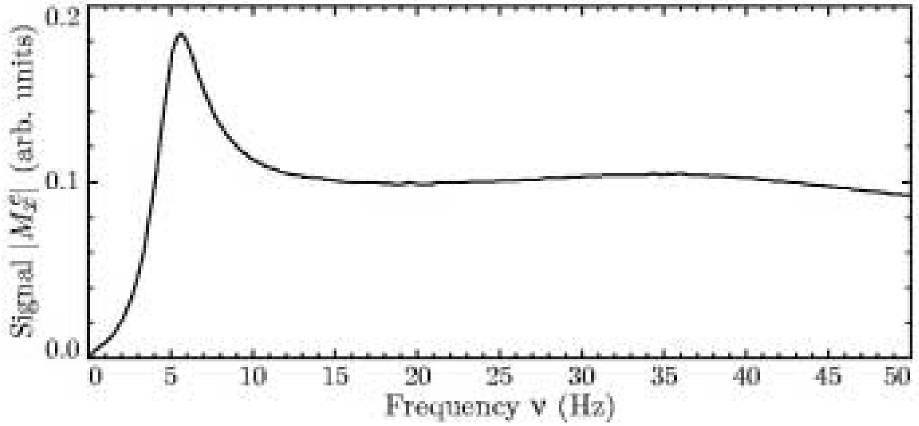
Compensated



Slightly uncompensated



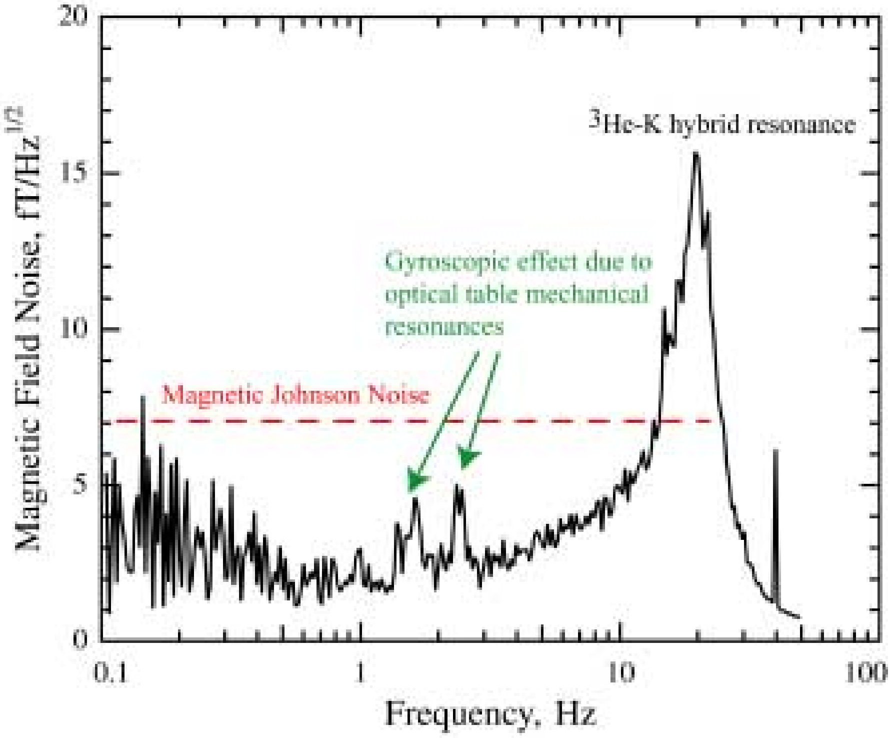
Frequency Response



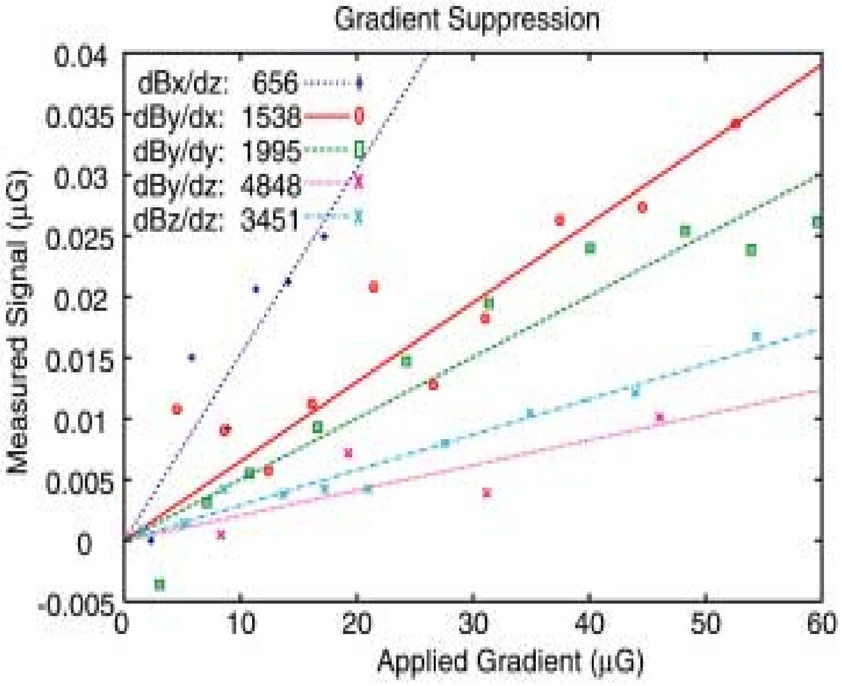
T.W. Kornack and MVR,
PRL 89, 253002 (2002)

Cancellation of magnetic field effects

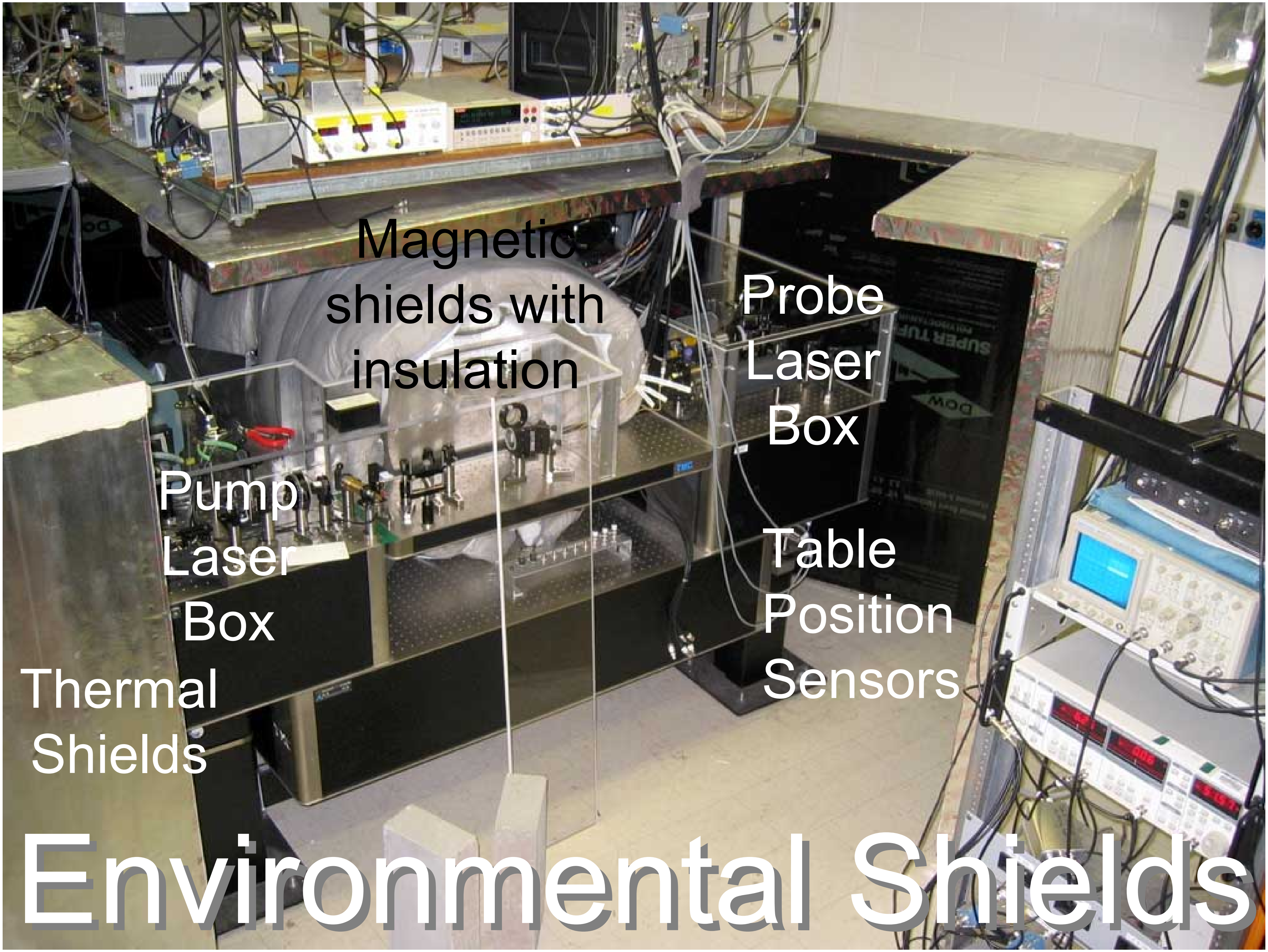
Noise Compensation



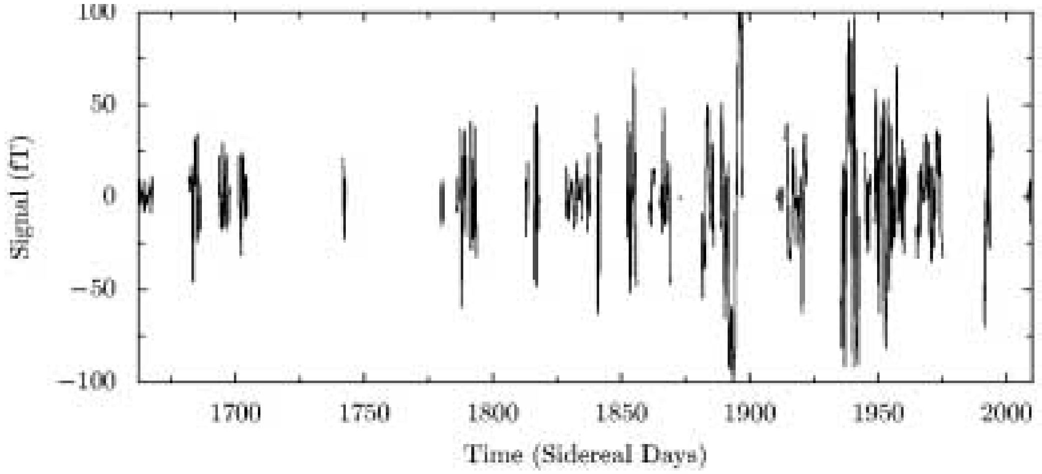
Gradient Compensation

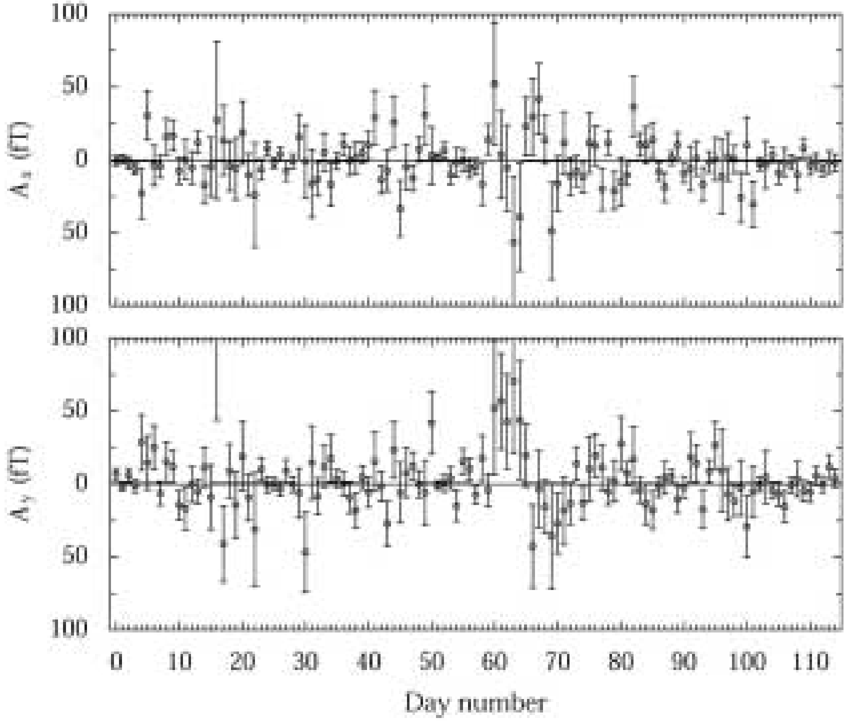


Environmental Shields

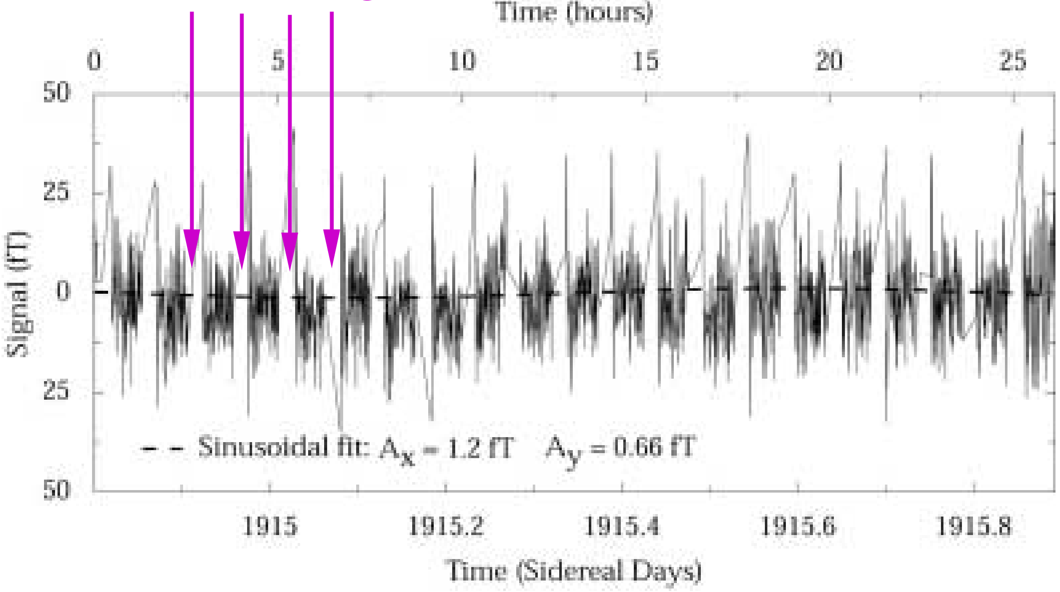


Development Run Data





Periodic zeroing of fields



$$S = A_x \sin(\Omega t) + A_y \cos(\Omega t)$$

Ω - sidereal Earth rotation rate

$$A_x = -0.76 \pm 0.74 \text{ fT}$$
$$A_y = 0.59 \pm 0.81 \text{ fT}$$

Limits on Lorentz and CPT violating spin coupling

Limits from development run	Existing best limit	
$\|b^n\| < 1.4 \times 10^{-31}$ GeV	$\|b^n\| < 1.1 \times 10^{-31}$ GeV	^{3}He-^{129}Xe co-magnetometer Walsworth, Harvard-Smithonian
$\|b^e\| < 1.0 \times 10^{-28}$ GeV	$\|b^e\| < 0.3 \times 10^{-28}$ GeV	Magnetic torsion pendulum Heckel, Adelberger, U of Washington

Natural size for Lorentz violation ?

$$b \sim \eta \frac{m^2}{M_{pl}}$$

m - light mass scale:
fermion mass
SUSY breaking scale

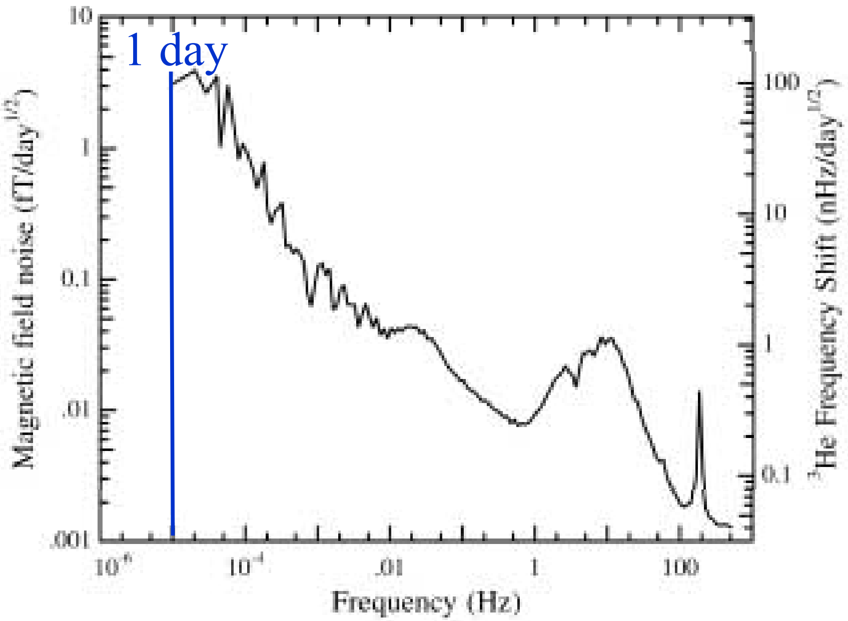
Existing limits: $\eta \sim 10^{-9} - 10^{-12}$

Pospelov, hep-ph/0505029

$1/M_{pl}$ effects are already highly excluded

What’s next?

- Low frequency noise dominates



- Current result 2-3 orders of magnitude below best sensitivity
  - ⇒ Further work on drift reduction and continuous data taking
  - ⇒ Constructing a miniature (30 cm size) system that can be placed on a rotating table to increase modulation frequency

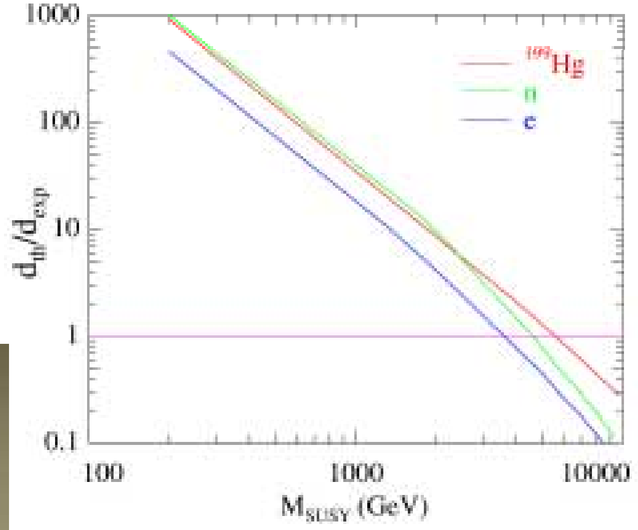
Other applications of co-magnetometer

- Search for a permanent electric dipole moment (EDM)
  - ⇒ EDM violates CP symmetry, but very suppressed in the SM
  - ⇒ Large EDMs generated in SUSY, other extensions
- Need heavy atoms

$$d_a \propto d_e \alpha^2 Z^3$$

- Cs- ^{129}Xe co-magnetometer
  - ⇒Sensitivity 1 fT/Hz$^{1/2}$
  - ⇒E = 10kV/cm, t = 10^7 sec

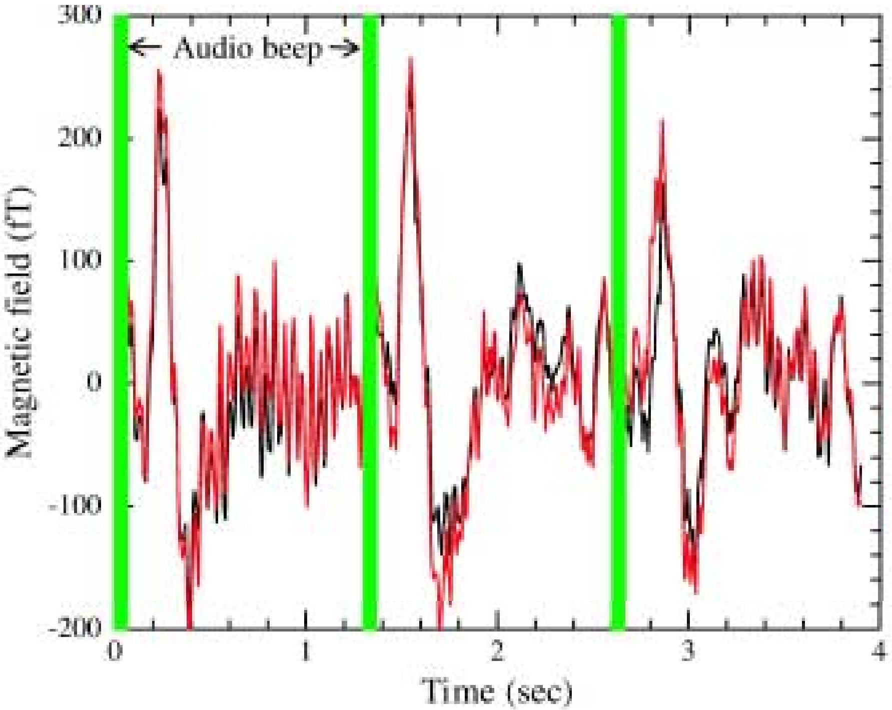
$\delta d_e = 10^{-29}$ e-cm, $\delta d_{Xe} = 10^{-30}$ e-cm
Factor of 100 improvement in both limits



$$d \sim \frac{e\alpha}{24\pi} \frac{m}{M_{SUSY}^2} \sin(\phi_{SUSY})$$

Cs-^{129}Xe cell

Atomic Magnetoencephalography Setup



- DC Shielding Factor ~ 10000
- 256 channel 2D photodiode array
- No conductive materials inside
- 10 measurement positions
- Optimization in progress

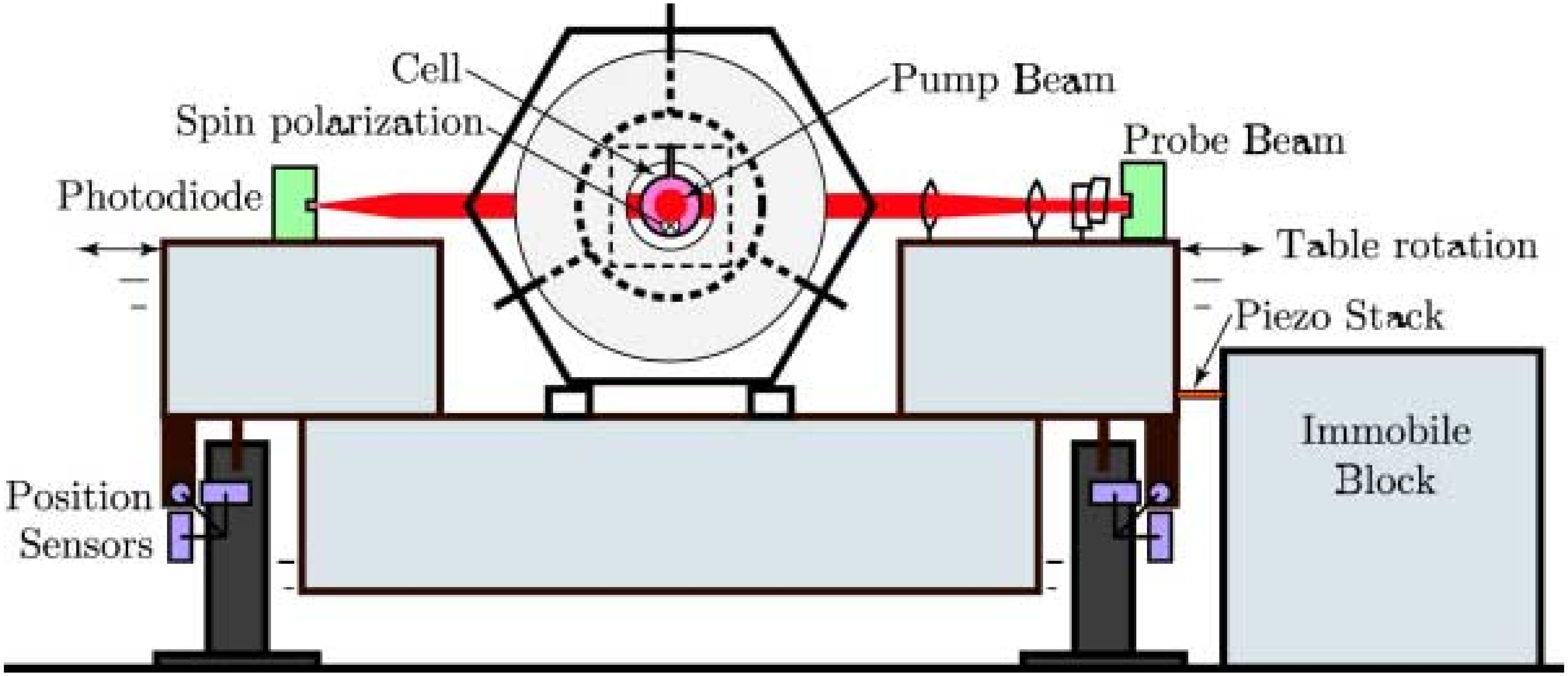
Atomic Gyroscope

- Rotation creates an effective magnetic field $B_{eff} = \Omega/\gamma$

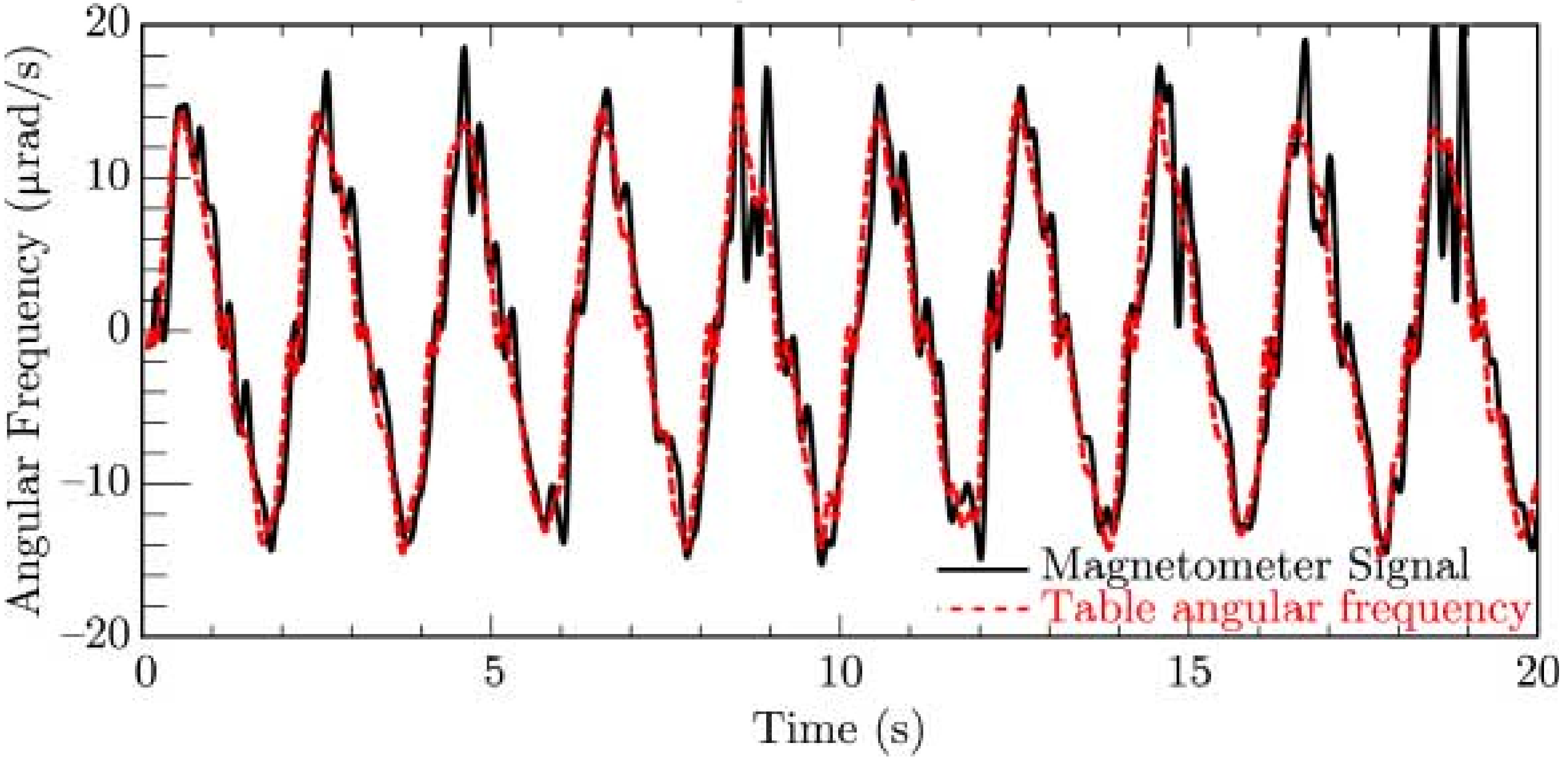
$$S_\Omega = \frac{P_z}{R}\left(\frac{\gamma_e}{\gamma_n} - 1\right)\Omega$$

For ^{3}He 0.001 deg/hour$^{1/2}$ ⇒ 1 fT/Hz$^{1/2}$

For ^{21}Ne 0.001 deg/hour$^{1/2}$ ⇒ 10 fT/Hz$^{1/2}$



Rotation signal



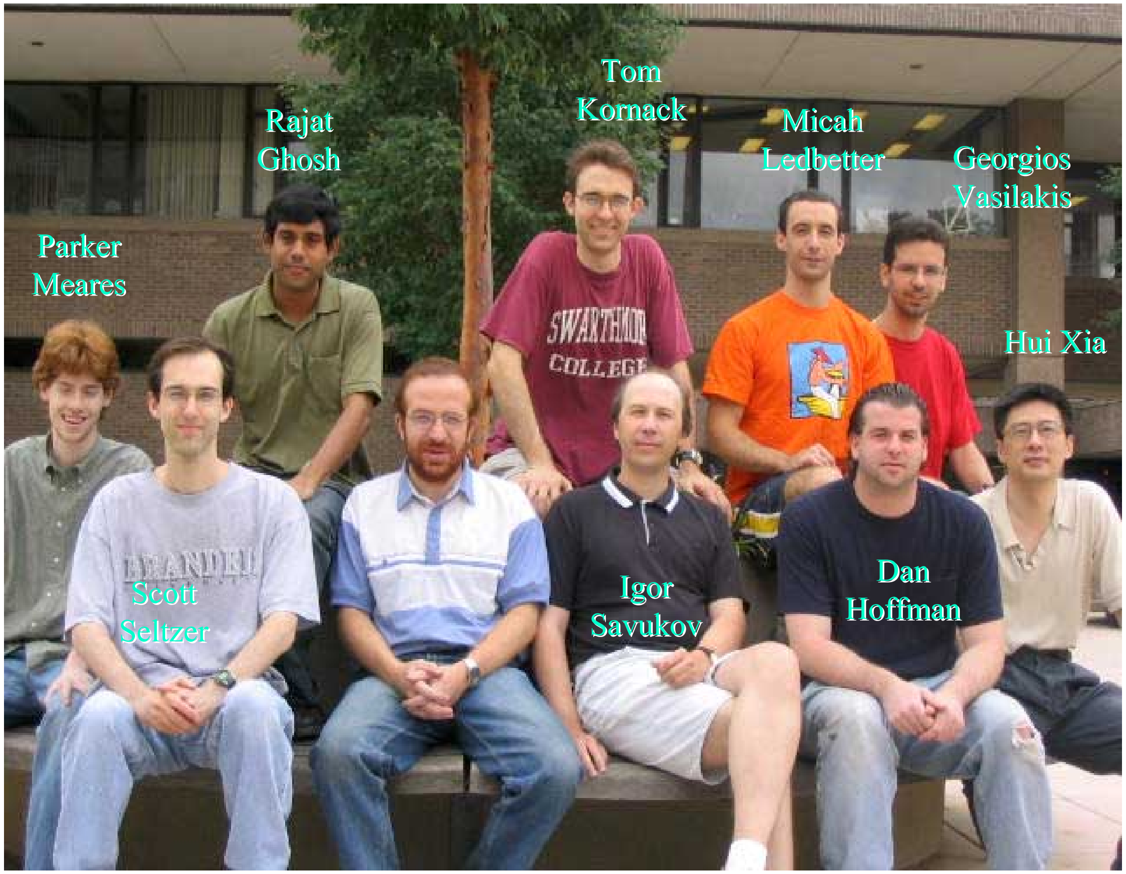
- Motion and rotation agree with no free parameters
- Short term noise is 2.2×10^{-7} rad/s / $\text{Hz}^{1/2}$
- Competitive with compact ring laser and fiber gyros

T. W. Kornack, R. K. Ghosh and MVR, PRL (in press)

Conclusions

- Lorentz and CPT symmetry tests provide one of the few ways to experimentally probe Quantum Gravity
- Noble-gas - alkali-metal co-magnetometers allow sensitive tests of Lorentz violation and other precision measurements.

- Collaborators
  - ⇒ Tom Kornack
  - ⇒ Iannis Kominis
  - ⇒ Scott Seltzer
  - ⇒ Igor Savukov
  - ⇒ Georgios Vasilakis
  - ⇒ Andrei Baranga
  - ⇒ Rajat Ghosh
  - ⇒ Hui Xia
  - ⇒ Dan Hoffman
  - ⇒ Joel Allred
  - ⇒ Robert Lyman



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