

Atomic magnetometers:
new twists to the old story

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Outline

- K magnetometer
 - ⇒ Elimination of spin-exchange relaxation
 - ⇒ Experimental setup
 - ⇒ Magnetometer performance
 - ⇒ Theoretical sensitivity
 - ⇒ Magnetic field mapping and other applications
 - K-³He co-magnetometer
 - ⇒ K-³He spin-exchange
 - ⇒ Self-compensating operation
 - ⇒ Coupled spin resonances
 - ⇒ CPT tests and other fundamental measurements
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Atomic Spin Magnetometers

$$\omega = \gamma B$$

- Optically pumped alkali-metals: K, Rb, Cs
- Hyperpolarized noble gases: ^3He , ^{129}Xe
- DNP-enhanced NMR: H

Fundamental Sensitivity limit: $\delta\omega = \frac{1}{P\sqrt{T_2 N t}}$

- State-of-the-Art magnetometers:

- ⇒ Alkali-metal: K or Rb

- D. Budker (Berkeley)

- ⇒ Large cell: 10 - 15 cm diameter

- E. Aleksandrov (St. Petersburg)

- ⇒ Surface coating to reduce spin relaxation

- ⇒ Alkali-metal density $\sim 10^9 \text{ cm}^{-3}$

- ⇒ Linewidth $\sim 1 \text{ Hz}$

- Fundamental Limitation: Spin-exchange collisions

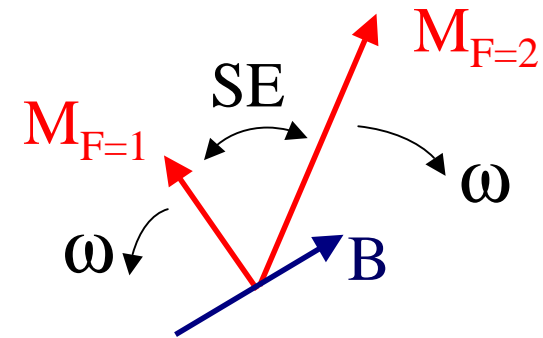
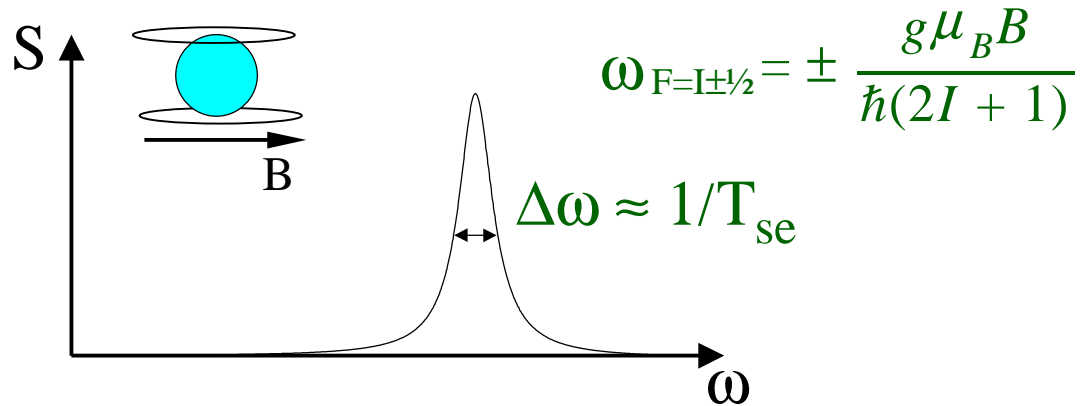
$$T_2^{-1} = \sigma_{se} \bar{v} n$$
$$\sigma_{se} = 2 \times 10^{-14} \text{ cm}^2$$

$$\gamma = \frac{g\mu_B}{\hbar(2I + 1)}$$

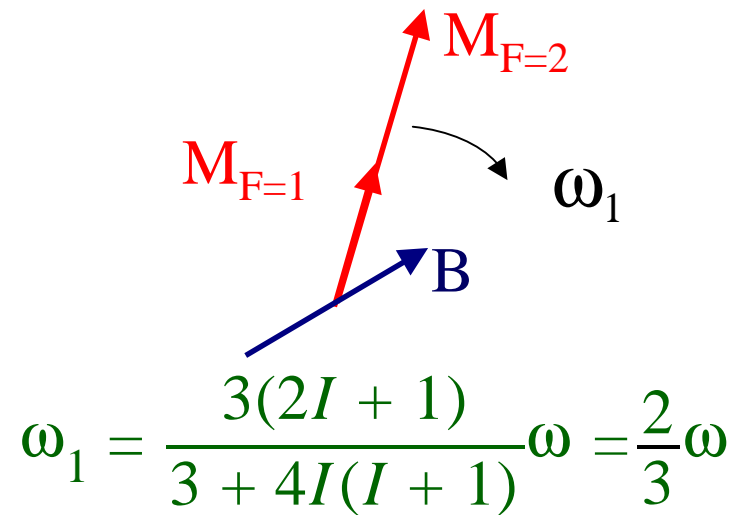
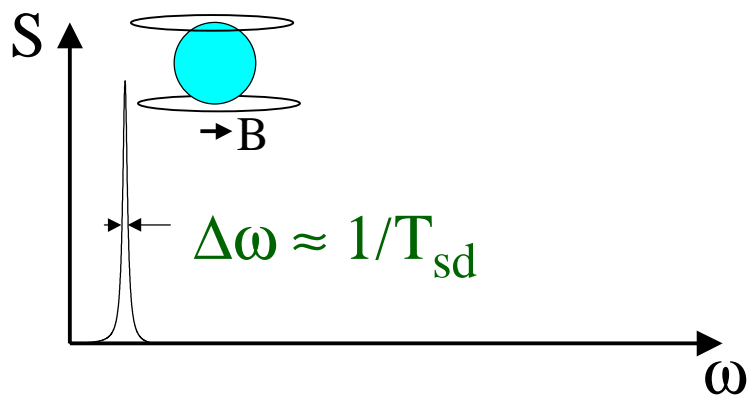
$$\delta B = 1 \text{ fT} \sqrt{\frac{\text{cm}^3}{\text{Hz}}}$$

Eliminating spin-exchange relaxation

- Spin exchange collisions preserve total m_F , but change F



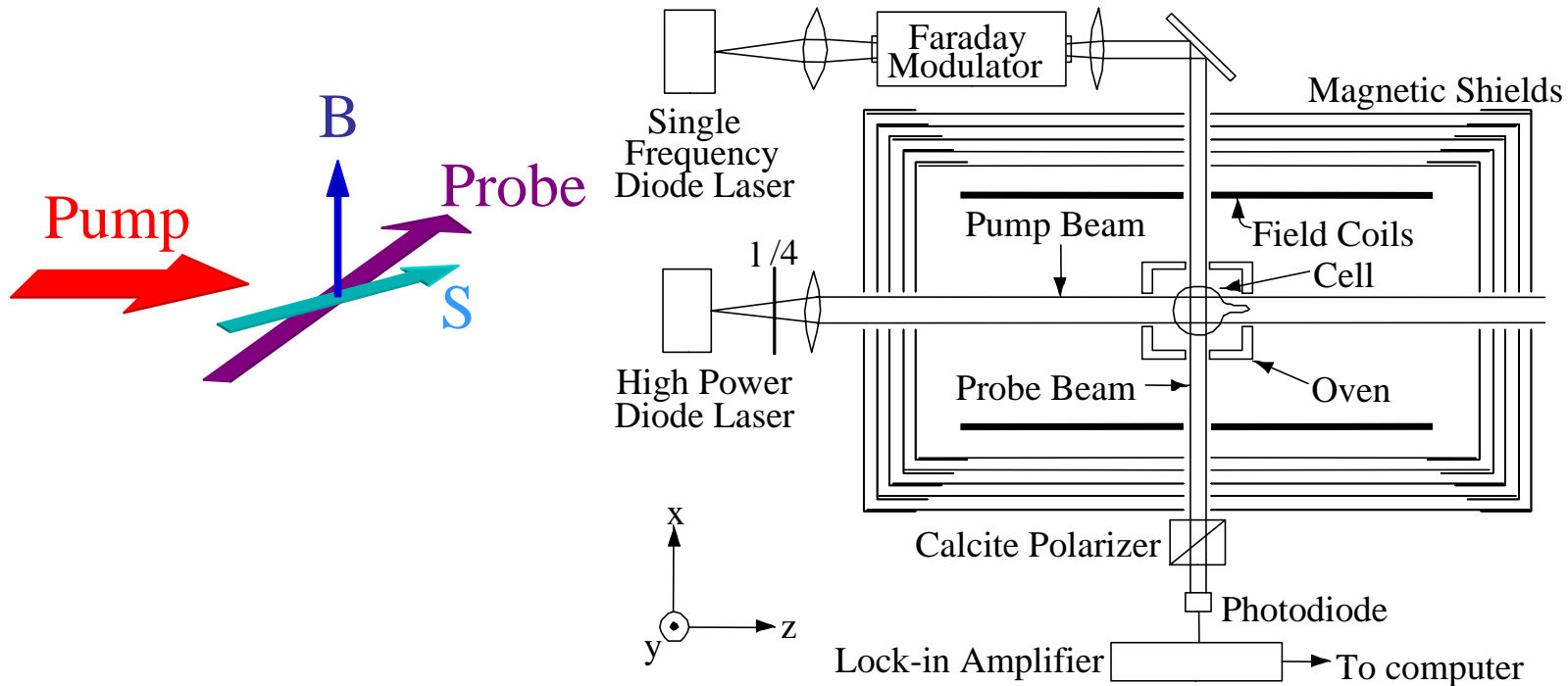
- For $\omega \ll 1/T_{se}$ ($B \ll 0.1\text{G}$)



\Rightarrow No relaxation due to spin exchange

(low P)

Zero-Field Magnetometer

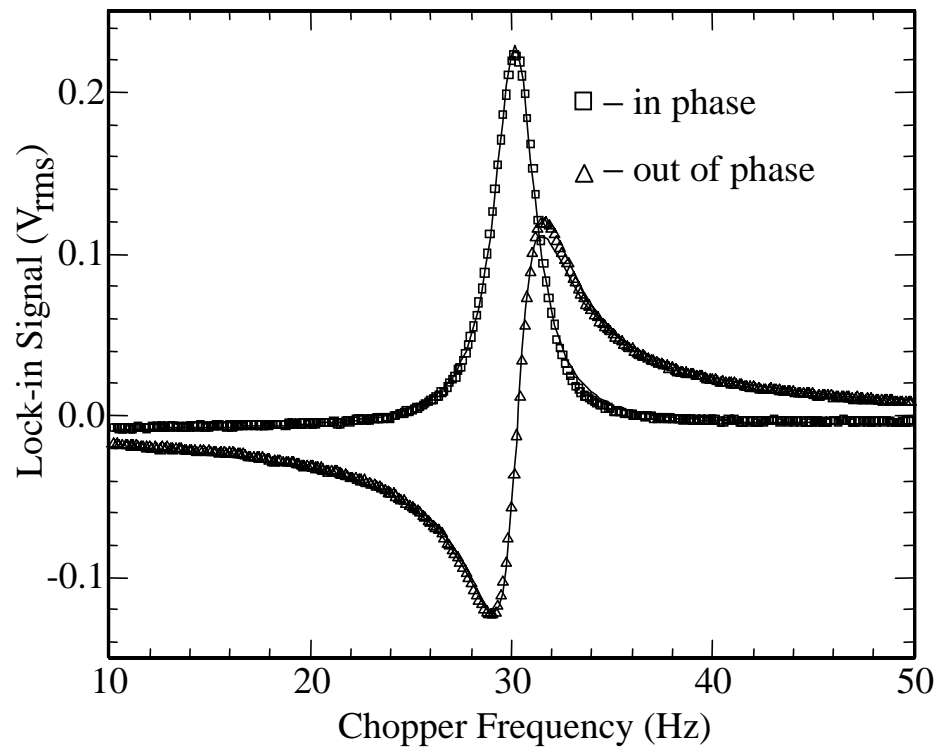
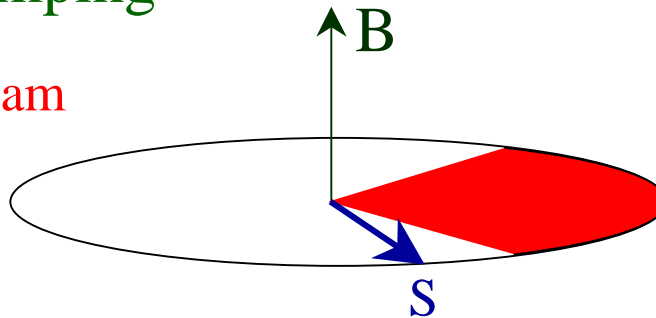


- Residual fields are zeroed out
- Pump laser defines quantization axis
- Detect tilt of K polarization due to a \hat{y} magnetic field
- Optical rotation used for detection

Measurements of T_2

- Synchronous optical pumping

Chopped pump beam

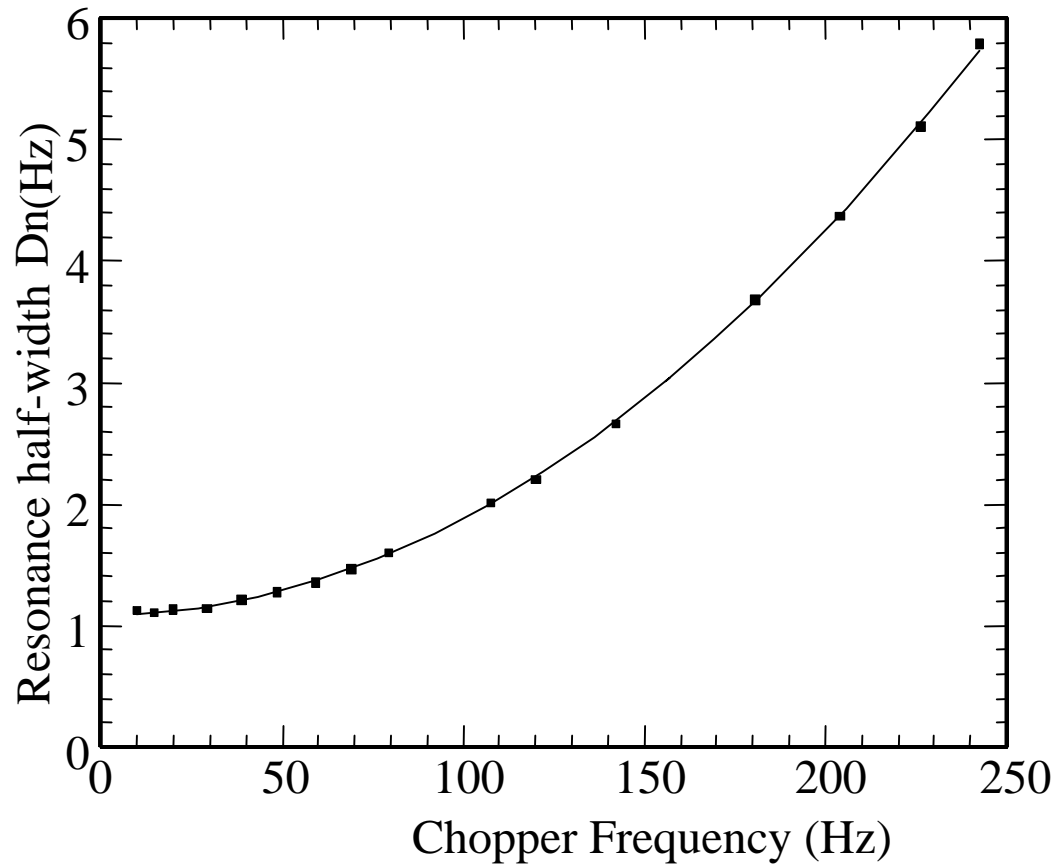


$$n = 10^{14} \text{ cm}^{-3}$$

$$1/T_{se} = 10^5 \text{ sec}^{-1}$$

Lorentzian linewidth = 1.1 Hz

Magnetic Field Dependence



$$T_2^{-1} = \Gamma_{sd} + \frac{5\omega^2}{3\Gamma_{se}}$$

Γ_{sd} due to K-K, K-³He collisions,
diffusion

W. Happer and H. Tang, PRL **31**, 273 (1973),
W. Happer and A. Tam, PRA **16**, 1877 (1977)

Spin-Destruction collisions

$$T_2^{-1} = D \frac{\pi^2}{R^2} + \sigma_{sd}^{\text{K}} \bar{v} n_{\text{K}} + \sigma_{sd}^{\text{He}} \bar{v} n_{\text{He}}$$

	Alkali Metal	He	Ne	N ₂
K	$1 \times 10^{-18} \text{ cm}^2$	$8 \times 10^{-25} \text{ cm}^2$	$1 \times 10^{-23} \text{ cm}^2$	
Rb	$9 \times 10^{-18} \text{ cm}^2$	$9 \times 10^{-24} \text{ cm}^2$		$1 \times 10^{-22} \text{ cm}^2$
Cs	$2 \times 10^{-16} \text{ cm}^2$	$3 \times 10^{-23} \text{ cm}^2$		$6 \times 10^{-22} \text{ cm}^2$

- Calculated linewidth

⇒ T = 190°C

$n_{\text{K}} = 1 \times 10^{14} \text{ cm}^{-3}$

⇒ 3 amg of He

$n_{\text{He}} = 8 \times 10^{19} \text{ cm}^{-3}$

R = 1 cm

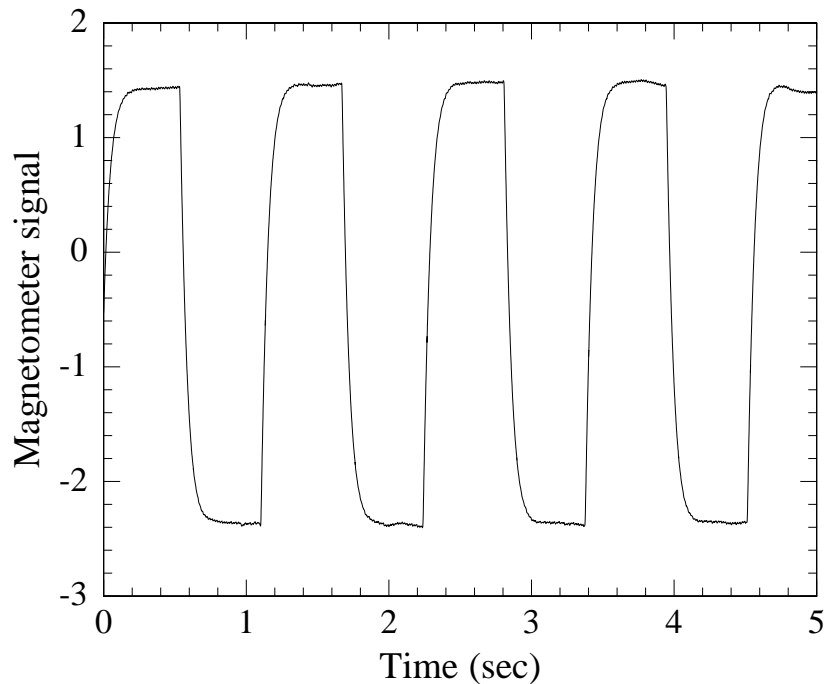
$\Gamma_{sd} = 12 \text{ sec}^{-1}(\text{Diff}) + 7 \text{ sec}^{-1}(\text{K-K}) + 13 \text{ sec}^{-1}(\text{K-He}) + 2 \text{ sec}^{-1}(\text{N}_2) = 34 \text{ sec}^{-1}$

- From measured linewidth $\Gamma_{sd} = 6 \times 2\pi \Delta\nu = 41 \text{ sec}^{-1}$

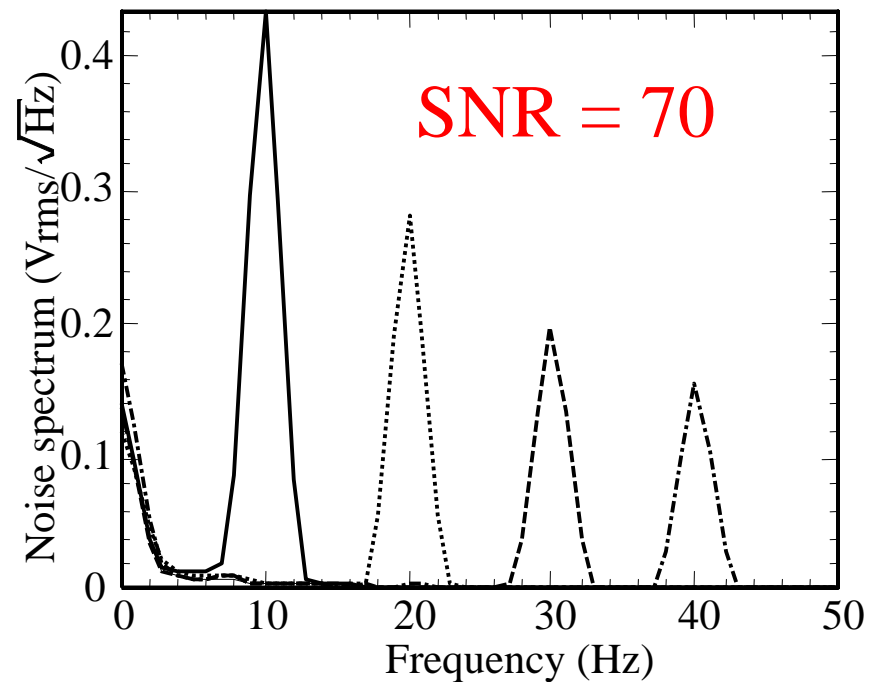
Slowing-down factor

Magnetometer Sensitivity

Response to square modulation of vertical field



700 fT_{rms} modulation at different frequencies

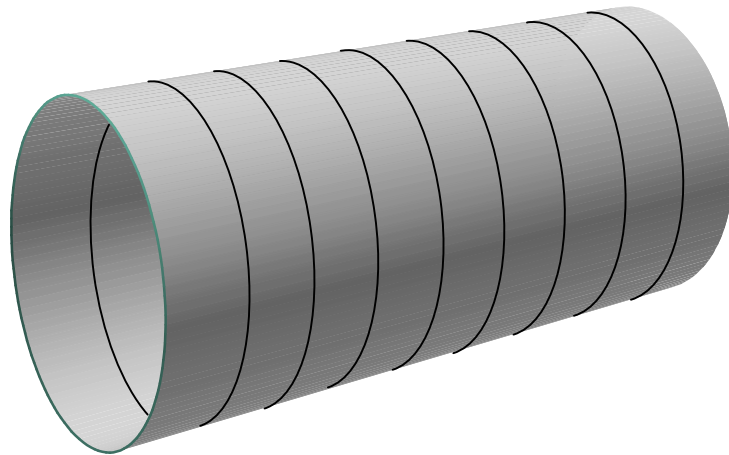


Direct sensitivity measurement gives $10\text{fT}/\sqrt{\text{Hz}}$

Highest demonstrated in an atomic magnetometer

Present Limitation

- Johnson noise currents in magnetic shields



$$I = \sqrt{\frac{4kT\Delta f}{R}}$$

- Removed all conductors from within the 16" inner shield
 - Noise estimates $7 \pm 2 \text{ fT} \sqrt{\text{Hz}}$
 - No Johnson noise in superconducting shields
-

Theoretical Sensitivity Estimates

- Transverse polarization signal

$$P_x = \frac{g\mu_B B_y R}{(T_2^{-1} + R)^2}$$

- Probed using optical rotation

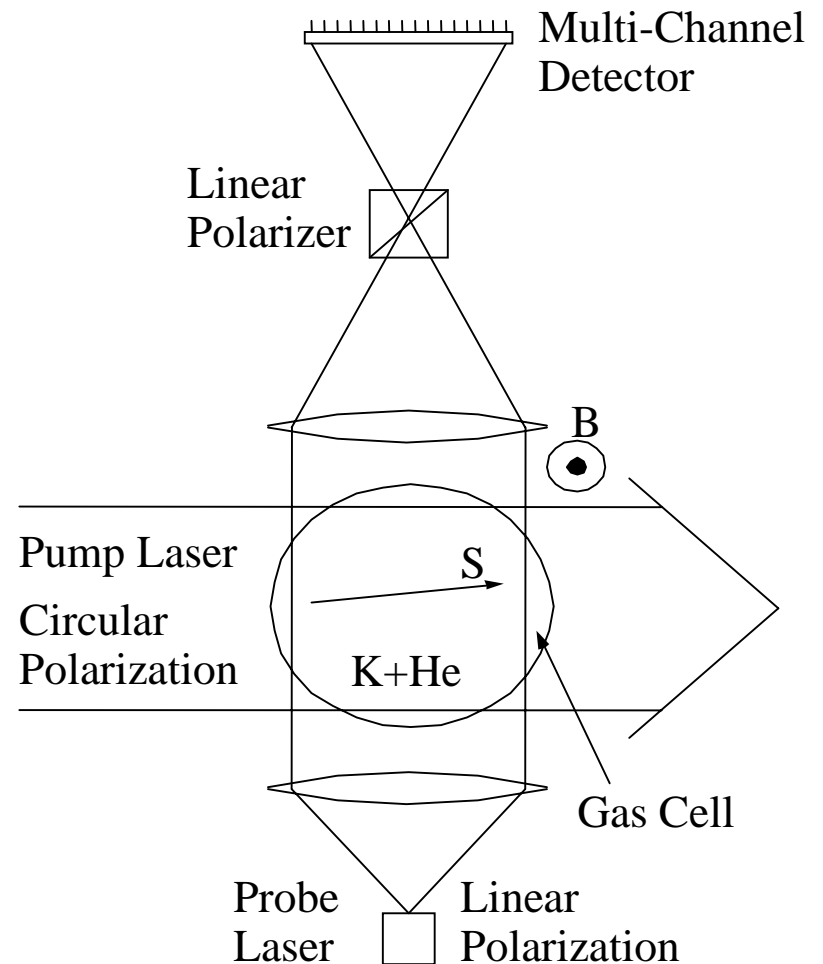
⇒ Shot noise for a 1" dia. cell

$$\delta B = 0.002 \text{fT}/\sqrt{\text{Hz}}$$

- Higher than theoretical estimates for SQUID detectors
-

Magnetic Gradient Imaging

- Higher buffer gas pressure
- Higher K density
- Higher pumping rate
 - ⇒ Reduce diffusion
 - ⇒ Increase bandwidth
 - ⇒ Suppress Johnson noise
- Applications
 - ⇒ Magnetic fields produced by brain, heart, etc
 - ⇒ Replacement for arrays of SQUIDs in liquid helium

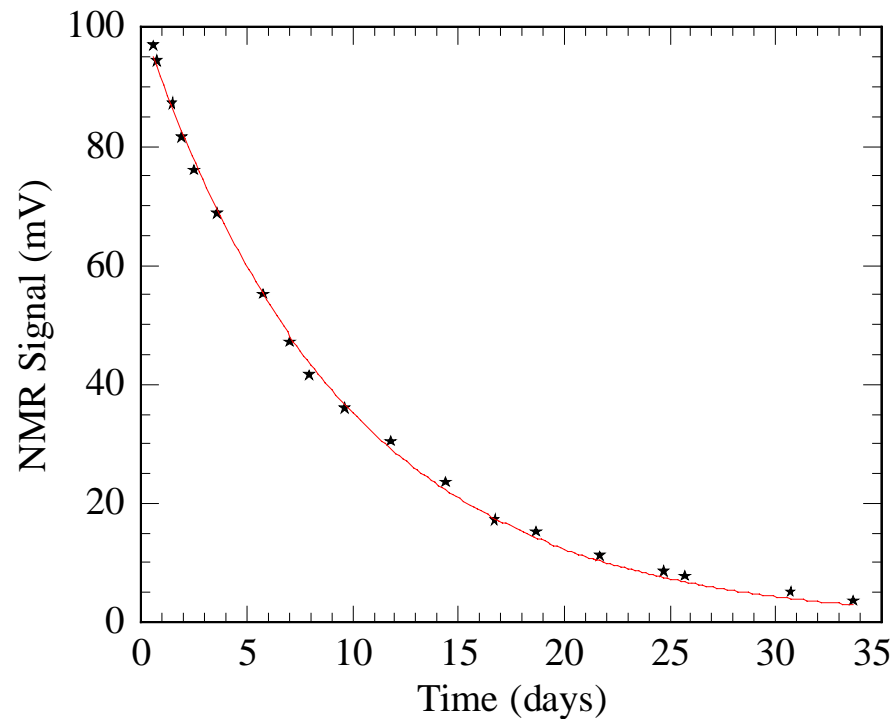


^3He Co-magnetometer

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

$\Rightarrow T_{\text{SE}}^{\text{K-He}} = 40 \text{ hours for } n_{\text{K}} = 10^{14} \text{ cm}^{-3}$

$\Rightarrow T_1^{\text{He}} \sim 300 \text{ hours}$



Spin-exchange shifts

- Polarized ^3He creates a magnetic field seen by K atoms

$$B_{\text{K}} = \frac{8\pi}{3} \kappa_0 M_{\text{He}}$$

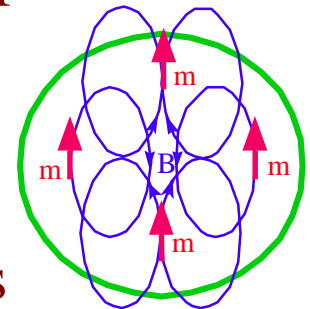
⇒ Enhanced due to contact interaction: $\kappa_0 = 6$

⇒ Typical value: 1-10 mG

- Polarized ^3He does not see its own classical field in a spherical cell

⇒ Long range field average to zero

⇒ No contact interaction



- Polarized K creates a magnetic field seen by ^3He atoms

$$B_{\text{He}} = \frac{8\pi}{3} \kappa_0 M_{\text{K}}$$

⇒ Typical value 10-50 μG

Simultaneous operation

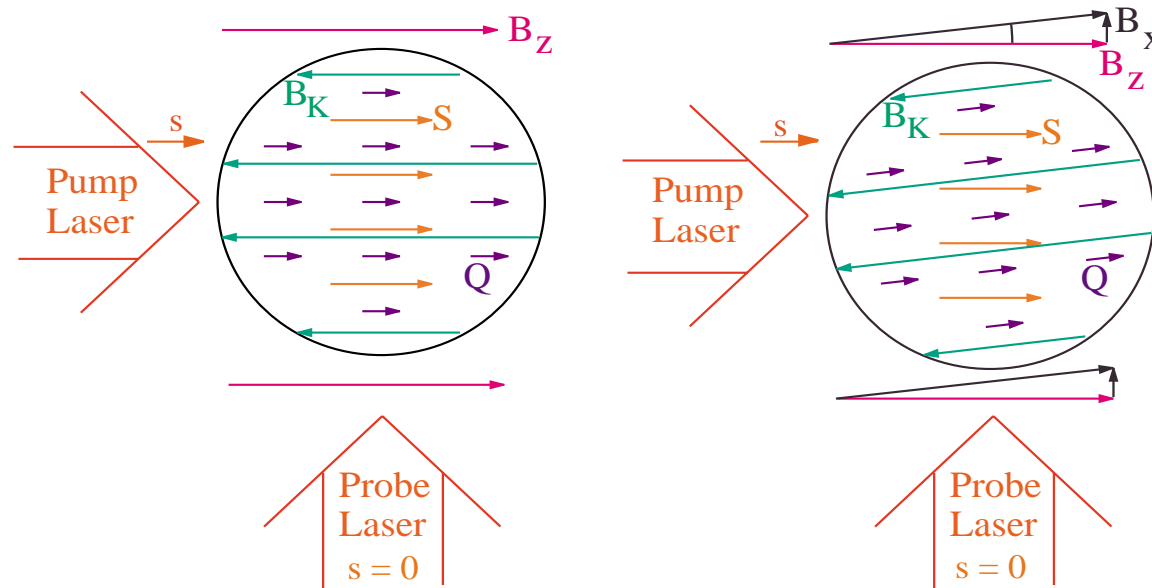
Apply an axial magnetic field that:

- Cancels the field B_K due to ^3He , so K magnetometer operates at zero field
- Provides a holding field for ^3He , so it doesn't relax due to field gradients

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

- Allows self-compensating operation
-

Magnetic field self-compensation



Perfect alignment

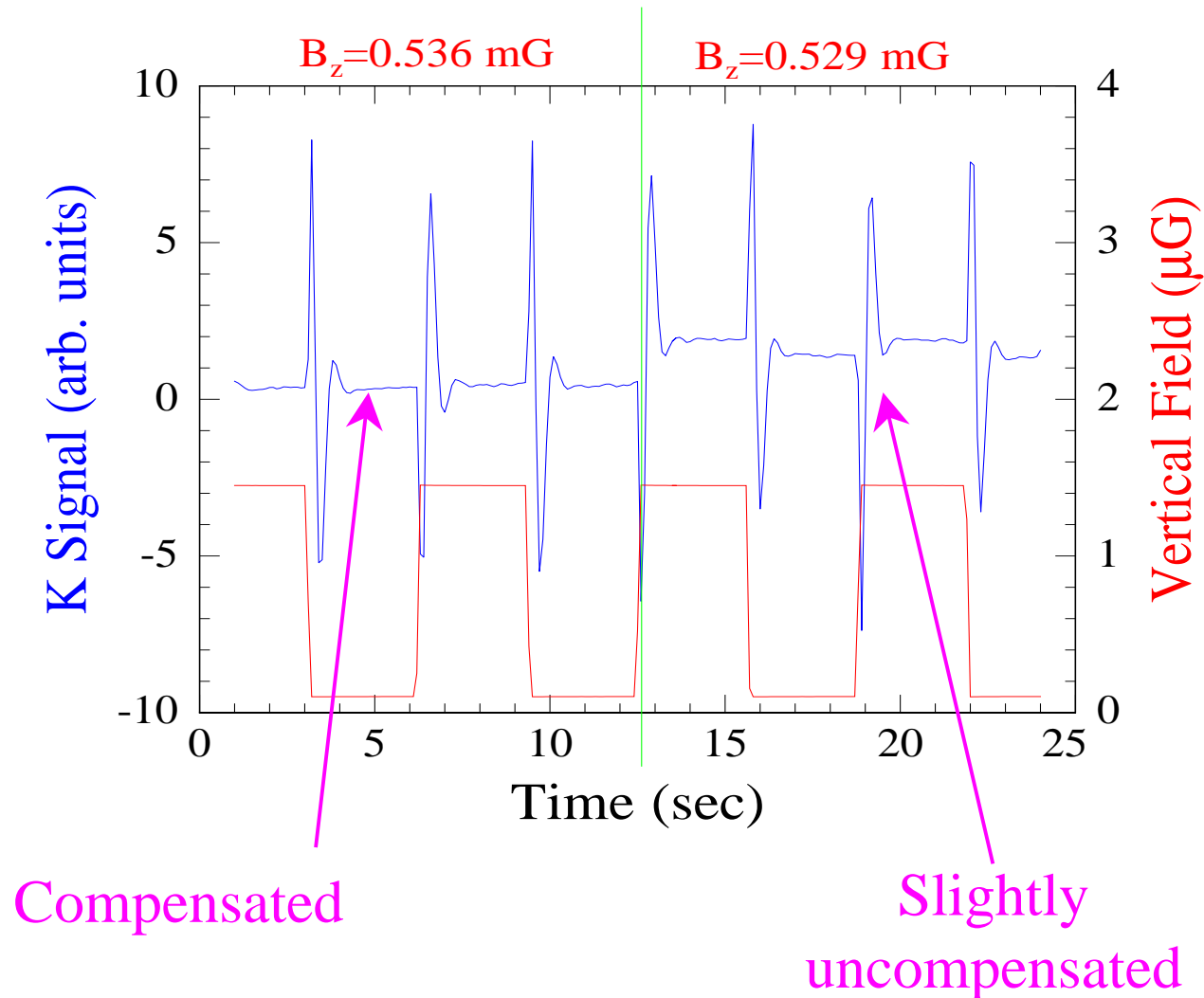
S – electron spin,

Small transverse field

Q – ^3He spin

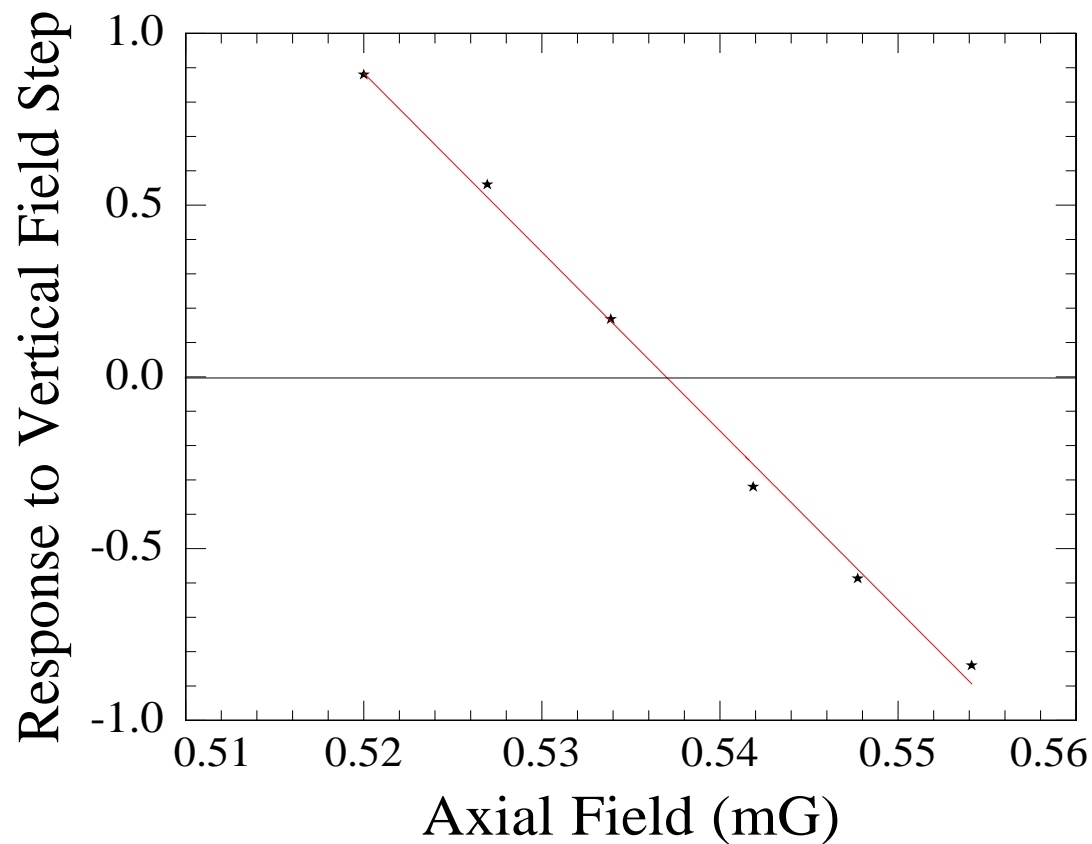
- Perfect compensation for $B_z = -B_K$
- ^3He polarization adiabatically follows total magnetic field
⇒ For changes slow compared with ^3He Larmor frequency
- K spins do not see a magnetic field change
- Also works for magnetic field gradients

Response of the co-magnetometer to a step in vertical magnetic field



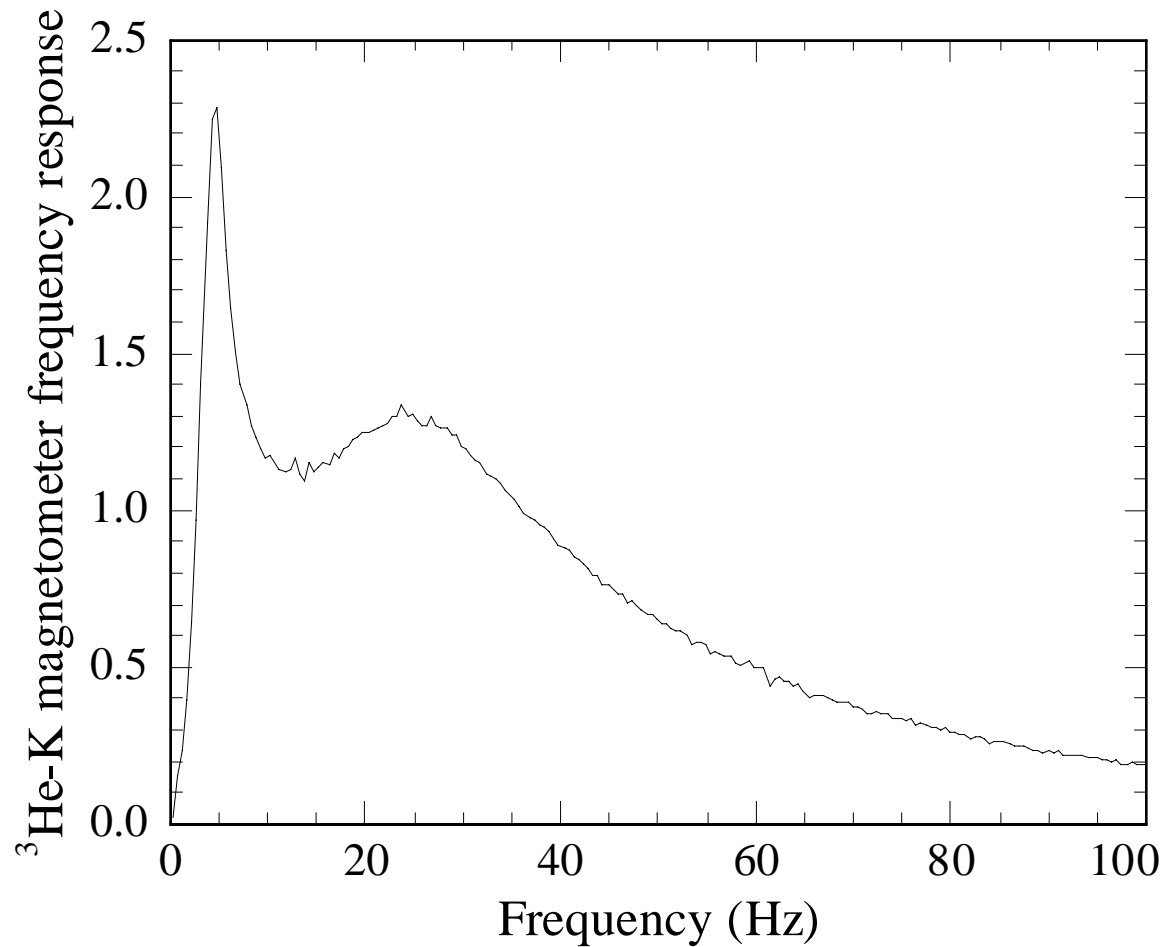
Adjustment of self-compensation

- Response changes sign as axial field is scanned across compensation point

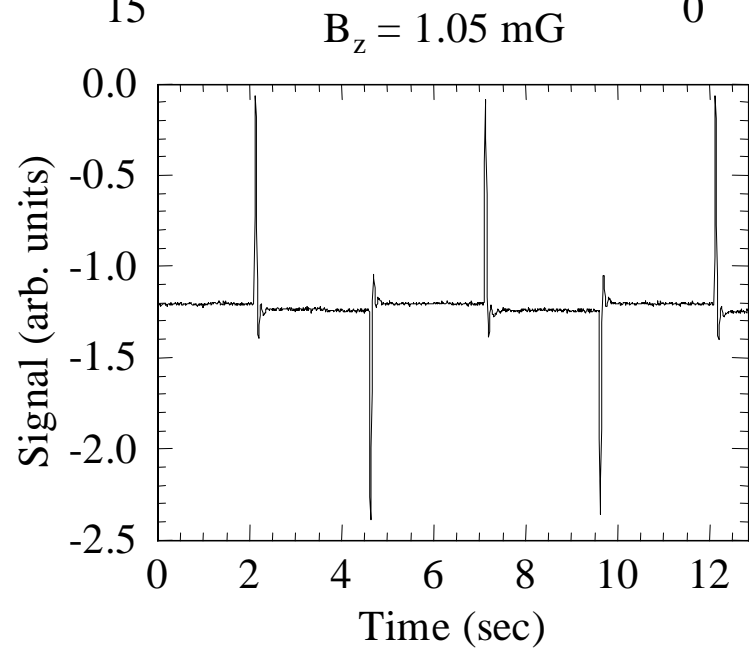
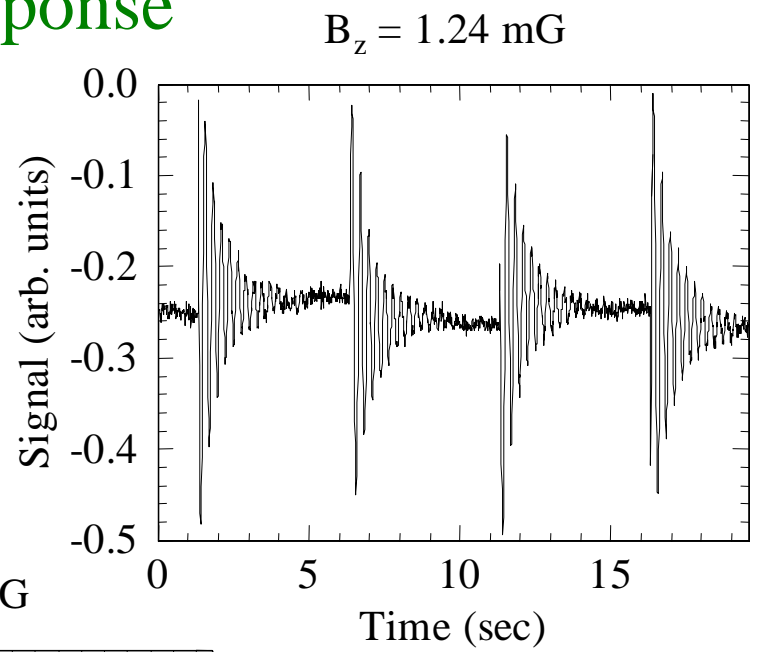
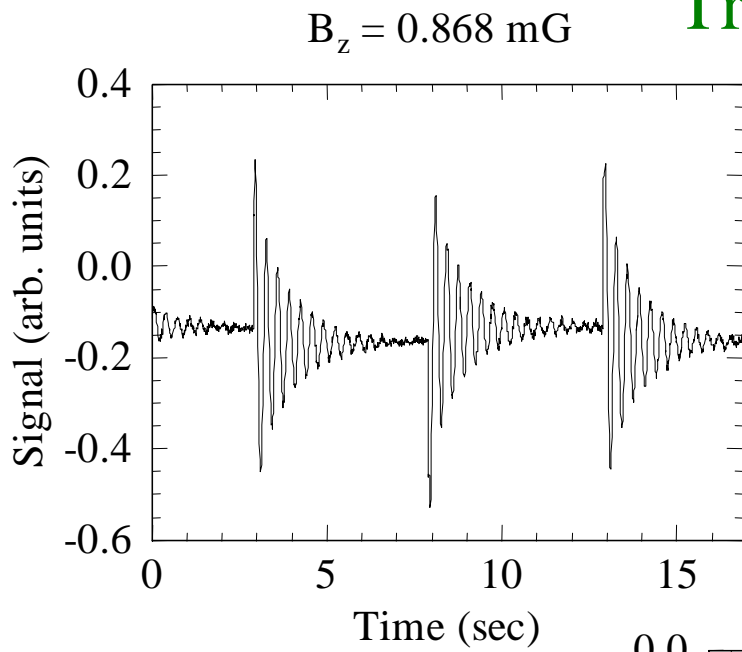


Frequency response of compensated ^3He -K magnetometer

- Apply a sine-wave of varying frequency

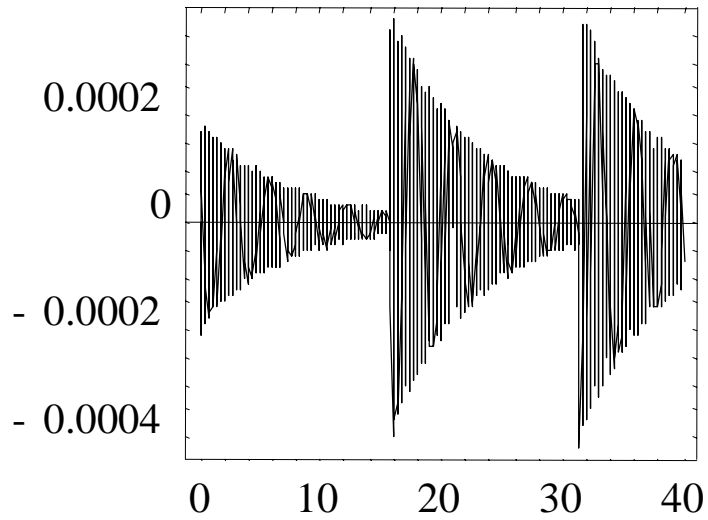


Transient Response

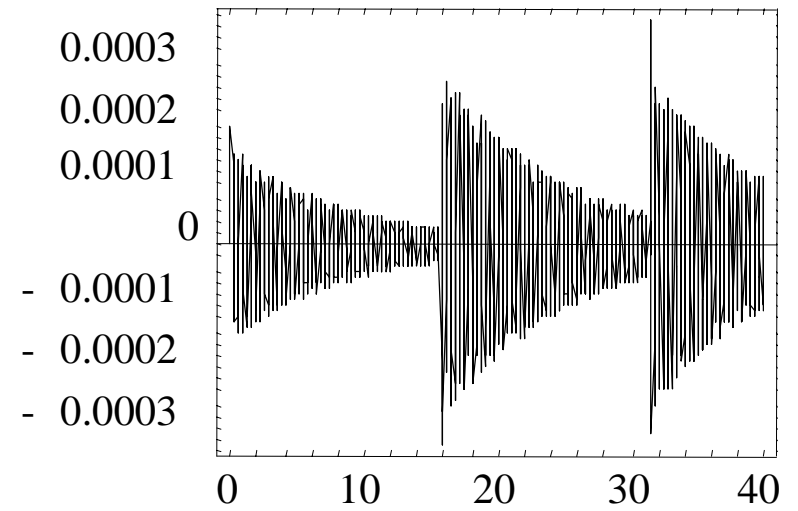


Transient Response - Bloch Model

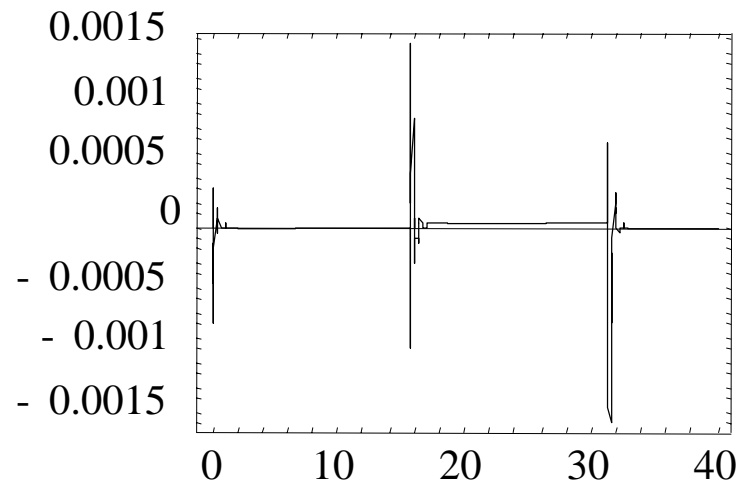
- 60. mG



50. mG

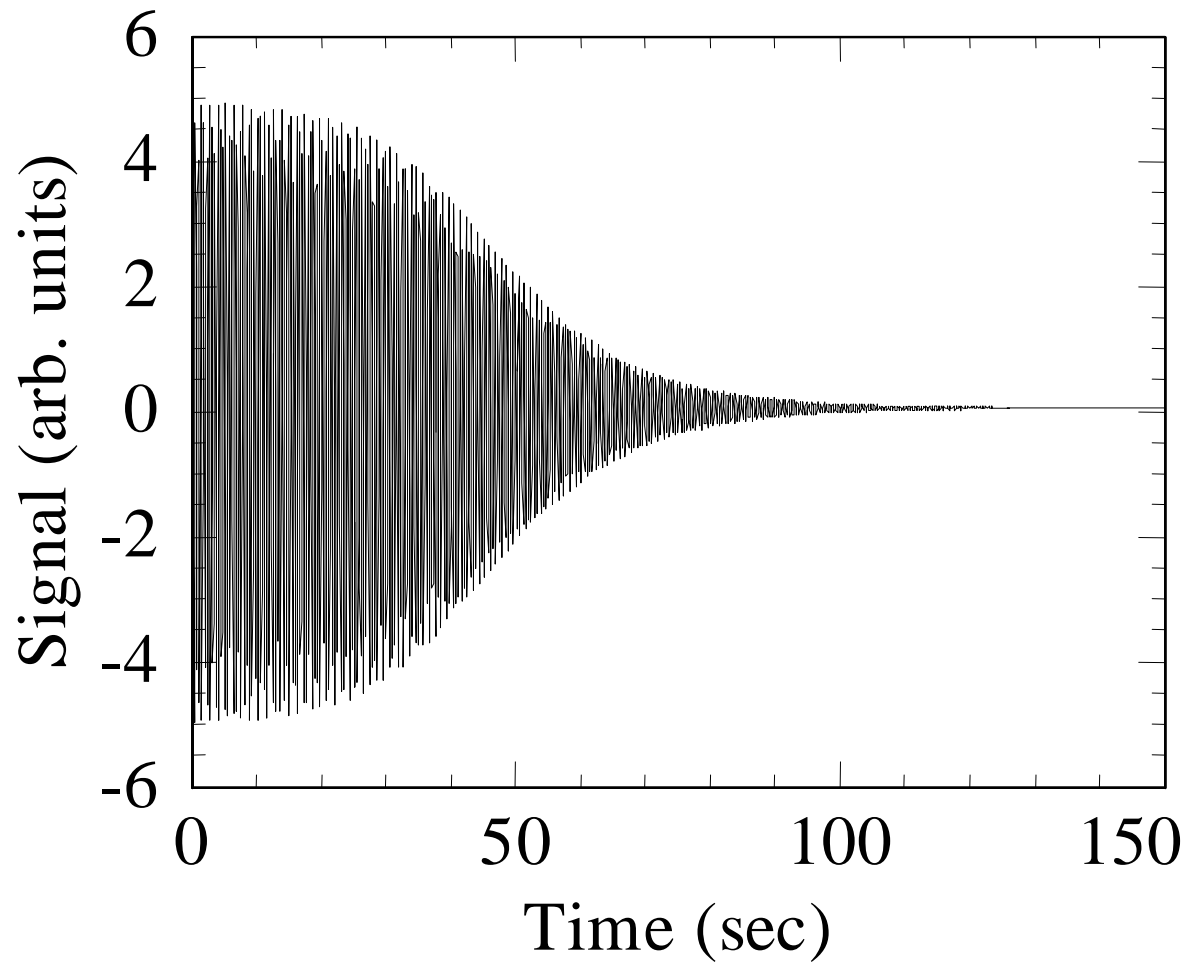


- 10. mG



Large ^3He Perturbation

Non-linear ^3He magnetization relaxation (similar to LXe)



CPT Violation

- CPT is an exact symmetry in a local field theory with point particles, such as the Standard Model or Supersymmetry
 - String Theory or any theory of Quantum Gravity **is not** a local field theory with point particles
 - Symmetry tests is one of very few possible ways to access Quantum Gravity effects experimentally.
 - Lorentz Symmetry can also be broken in String Theory
 - Symmetry violation can be due to Cosmological anisotropy - Was the Universe really created isotropic?
-

How to detect CPT violation ?

- Compare properties of particles and anti-particles
 - ⇒ Masses, magnetic moments, etc
 - ⇒ Anti-particles are difficult to produce and store
- Note that CPT violation is a vector interaction

$$L = -b_\mu \bar{\psi} \gamma_5 \gamma^\mu \psi = -b_i \sigma_i$$

- ⇒ b_μ is a CPT and Lorentz violating vector field in space
 - ⇒ Acts as a magnetic field
 - ⇒ Depends on the orientation of the spin direction in space
 - ⇒ Presumably couples to particles differently from magnetic field
 - ⇒ Can be detected in a co-magnetometer as a diurnal signal
-

Expected Sensitivity

$10\text{fT}/\sqrt{\text{Hz}}$
 Integration time of 10^6 sec \longrightarrow $b_i^e = 10^{-30}$ GeV,
 $b_i^n = 10^{-33}$ GeV

2 orders of magnitude improvement over best existing limits

	$b_i^e, 10^{-3}b_0^e$	$b_i^{n,p}, 10^{-3}b_0^{n,p}$	$c_{ik}^{n,p}, 10^{-3}c_{00}^{n,p}$	$d_{0i}^e, 10^{-3}d_{00}^e$	$d_{0i}^{n,p}, 10^{-3}d_{00}^{n,p}$
electron $g - 2$ [25]	10^{-24} GeV			10^{-21}	
$p - \bar{p}$ [26]			10^{-26}		
$^{201}\text{Hg}-^{199}\text{Hg}$ [27]		10^{-29} GeV	10^{-27}		10^{-26}
$^{21}\text{Ne}-^3\text{He}$ [28]			10^{-27}		
Cs- ^{199}Hg [24]	10^{-27} GeV	10^{-30} GeV		10^{-25}	10^{-28}
$^3\text{He}-^{129}\text{Xe}$ [29]		10^{-31} GeV			10^{-28}
Polarized Solid [30]	10^{-28} GeV				
K- ^3He (This proposal)	10^{-31} GeV	10^{-34} GeV		10^{-29}	10^{-32}

Non-magnetic shifts

- Light shift suppression
 - ⇒ Pump laser
 - Perpendicular to probe direction
 - Tuned exactly on resonance
 - ⇒ Probe Laser
 - Linearly polarized
 - Detuned far off-resonance
 - Perpendicular to field measurement direction
 - Polarization Shift Suppression
 - Spherical cell
 - Polarization perpendicular to the measurement direction
 - Balanced magnetic fields
 - Beam Pointing Stability
 - μrad stability using active steering $\sim 1/\sqrt{N}$
 - Pump power modulation
-

Other Applications

- EDM search ?
 - ⇒ Cs
 - Higher density at lower temperature
 - Larger relaxation cross-sections
 - ⇒ ^{129}Xe
 - Higher enhancement factor κ_0
 - Larger relaxation cross-sections
 - ⇒ Application of electric field?
 - Axion, exotic forces
-

Conclusions

- Sensitive K magnetometer
 - ⇒ Spin-exchange relaxation eliminated

 - ^3He -K co-magnetometer
 - ⇒ Effective compensation of magnetic fields by ^3He
 - ⇒ Noise reduction at low frequency
-

- Collaborators

- ⇒ Tom Kornack

- ⇒ Iannis Kominis

- ⇒ Joel Allred

- ⇒ Rob Lyman

- ⇒ Marty Boyd



Princeton



U. of Washington

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- ⇒ NIH

- ⇒ Packard Foundation

- ⇒ U. of Washington, Princeton U.
