Measurements with dense alkali vapors

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Spin Interactions

\[ H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - \hbar \mathbf{\Omega} \cdot \mathbf{S} \]

Magnetic Field  
Rotation

Beyond Standard Model:

\[ -d \mathbf{E} \cdot \frac{\mathbf{S}}{S} \]

Electric Dipole Moment  
CP, T violation

\[ -b \cdot \frac{\mathbf{S}}{S} \]

Background Vector Field  
Lorentz, CPT violation

\[ g^2 \mathbf{S}_1 \cdot \mathbf{S}_2 \]

Spin Dependent Forces  
Pseudoscalar Exchange
Spin Precession

\[ \omega = \frac{2\mu B}{\hbar} \]

Quantum noise limit for \( N \) atoms:

\[ \delta \omega = \frac{1}{\sqrt{T_2 N t}} \]

Prefer small measurement volume:
- Compact
- High spatial resolution
- Electric field application
- Insensitivity to gradients

Need large number of atoms long coherence time

High-density spin ensembles
- Strong interactions
1. **High density alkali-metal magnetometer**
   - Elimination of alkali-metal spin-exchange broadening
   - High sensitivity multi-channel magnetic field measurements
   - Application: Detection of brain magnetic field
   - Application: Detection of nuclear quadrupole resonance

2. **Noble gas-alkali – alkali-metal co-magnetometer**
   - Automatic cancellation of magnetic fields
   - Application: Nuclear spin gyroscope
   - Application: Search for a Lorentz-violating background field

3. **Resonance narrowing in optically dense vapor**
Alkali-metal spin-exchange collisions

Increasing density of atoms decreases spin relaxation time:

\[ T^{-1}_2 = \sigma_{se} \bar{v} n \]

\[ \sigma_{se} = 2 \times 10^{-14} \text{cm}^2 \]

Other \( \sigma \sim 10^{-18} \text{cm}^2 \)

⇒ Increasing density of atoms decreases spin relaxation time: \( T_2N = \sigma_{se} \bar{v}V \)

⇒ Under ideal conditions: \( \delta B \approx 1 \text{fT} \sqrt{\frac{\text{cm}^3}{\text{Hz}}} \)

⇒ One solution: use large cells with low density (Budker, Alexandrov)
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

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

Ground state Zeeman and hyperfine levels

Zeeman transitions \( +\omega \)

Zeeman transitions \( -\omega \)

\[
m_F = -2, -1, 0, 1, 2
\]
Eliminating spin-exchange relaxation

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

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

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

• No relaxation due to spin exchange

W. Happer and H. Tang, PRL 31, 273 (1973)
Complete elimination of spin-exchange broadening

Chopped pump beam

K density: $10^{14}$ cm$^{-3}$
Temperature: 185°C

Linewidth at finite field: 3kHz
Linewidth at zero field: 1 Hz

Magnetometer Performance

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

Best SQUID
Gradiometer Sensitivity
0.5 fT/Hz$^{1/2}$ - limited by magnetic shield gradient noise

- Fundamental sensitive limit

$$\delta B = \frac{1}{\gamma \sqrt{T_2 N t}}$$

- $T_2 = 0.16$ sec
- $n = 10^{14}$ cm$^{-3}$
- $V_{cell} = 10$ cm$^3$
- $N \sim 10^{15}$ atoms

$$\delta B = 2 \times 10^{-18} \text{ T Hz}^{-1/2}$$

Magnetoencephalography

- Low-temperature SQUIDs in LHe
- 100 – 300 channels, $5 \text{fT/Hz}^{1/2}$, 2 – 3 cm channel spacing
- Cost $\sim$ $2-3m$
- Clinical and functional studies

Auditory response

H. Weinberg, Simon Fraser University
Atomic magnetometer advantages

• Potentially higher sensitivity than SQUID (fundamental noise limitation below 0.01 fT/Hz\(^{1/2}\))

• Does not require cryogenic cooling:
  
  ⇒ Smaller magnetic shields with better shielding
  ⇒ No magnetic dewar noise
  ⇒ Accommodates variations in head size
  ⇒ Lower construction cost
  ⇒ No cryogenic maintenance

• Multi-channel photodetector technology well developed and inexpensive

• Higher detector density

• Allows independent and simultaneous measurement of all 3 components of the magnetic field
• Pyrex cell 75X75X75 mm @ 1 atm
• Hot air oven @ 160-180 deg. C

The Dream Capsule

• 3-layer μ-metal shields with transverse shielding factor of 7000 and longitudinal factor of 1000 at low frequency.

• 18 computer-controlled coils to compensate residual fields
Auditory stimuli delivered to opposite ear with pneumatic earphone; each stimulus is a train of clicks lasting $16\text{ms}$; stimuli interval varying randomly between $0.9$~$1.7\text{sec}$

- Averaged over 600 stimuli

- N100m peak clearly seen; P300m also observed
N100m peak recorded by 16x16 image array

Photodetector
Detection of Explosives with Nuclear Quadruple Resonance

- Most explosives contain $^{14}$N which has a large quadrupole moment
- NQR frequency is determined by interaction with electric field gradient in a crystal
- Each material has a very specific resonance frequency, linewidth $\sim 1$ kHz
- Very low rate of false alarms.
- Main problem – low signal/noise

100 g of TNT located 10 cm away gives a 4 fT signal with a bandwidth of $\sim 1$ kHz.

Under best conditions, SNR~ 0.5 with conventional RF detection

Tunable RF atomic magnetometer

• Tune $B_0$ field to the resonance condition $\omega_{rf} = \gamma B_0$

• Measure transverse spin precession induced by rf field $S_\perp = \gamma B_{rf} T_2$

Double-layer magnetic shield
  Aluminum RF shield
  $B_0$ coil

RF excitation coil with shield

Sample at room temperature
  Hot air oven (180ºC)
  K vapor cell

Probe laser beam

Pump laser beam

$B_{detuning}$ coil

$B_0$ coil

Polarimeter

NQR signal
Reduction of spin-exchange broadening in finite magnetic field

\[ \Delta \nu = \left( \frac{R_{\text{ex}} R_{\text{sd}}}{5} \right)^{1/2}/2\pi \]

RF detection limitations

• RF coil - Thermal Johnson Noise

\[ B_{\text{rms}} = \frac{4}{\omega a} \sqrt{\frac{kT \rho}{V_{\text{wire}}}} \]

⇒ \( V_{\text{wire}} \) limited by skin depth = 0.06 mm
⇒ For typical coils \( B = 0.8 \text{ fT/Hz}^{1/2} \)

• Atomic magnetometer - Quantum Spin Fluctuations

\[ B_{\text{rms}} = \frac{2}{\gamma} \sqrt{\frac{\nu[\sigma_{se} \sigma_{sd}/5]^{1/2}}{V_{\text{cell}}}} \]

⇒ \( V_{\text{cell}} \) limited by distance to the target = 0.1-0.5 m
⇒ For typical magnetometer cells \( B = 0.01 \text{ fT/Hz}^{1/2} \)
RF magnetometer setup

Simple balanced polarimeter
Rotation sensitivity: 4 nrad/Hz$^{1/2}$

Optical detection of liquid-state NMR,
RF magnetometer sensitivity

Note:
At high frequencies conductive materials generate much less thermal magnetic noise

0.2 fT/Hz$^{1/2}$
First detection of NQR signals with atomic magnetometer

- Spin-echo sequence

22 g of Ammonium Nitrate
4 minutes/point
(2048 echoes, 8 repetitions)

Averaged echo signal

Signal/noise 12 times higher than for RF coil located equal distance away from the sample!
Resonance narrowing in optically dense samples

- Use large number of atoms \( N = 10^{15}-10^{17} \)
- Requires very low noise readout, e.g. \( \delta \phi \sim 10^{-8}-10^{-9} \) rad
- Affected by technical noise

*Would be nice to use atoms themselves to amplify detected signal*

- Use laser absorption to arrange interaction between atoms
- Same laser acts as both pump and probe beam
Phase amplification

Chopped pump beam

Pump

Cell

Probe

$\omega = \gamma B$

$\omega < \gamma B$

$\phi$

$z$

$I, S_z$

$I, S_z$

$I, S_z$
Further Details

• Use convergent pump beam and a conical cell to compensate for pump absorption

• He buffer gas to limit diffusion

• N₂ buffer gas for quenching of spontaneous emission

• Numerical light propagation model indicates phase gain ≅ OD under optimized conditions
First experimental demonstration

- Compare resonance linewidth when pumping from the front and the back of the cell:
  - Observed resonance narrowing below intrinsic linewidth
  - Need to optimize parameters to get a larger effect
• Collaborators

⇒ Tom Kornack
⇒ Iannis Kominis
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⇒ Andrei Baranga
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⇒ SeungKuyn Lee
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