B160-303: Optimizing Readout for Nuclear Magnetic Resonance Axion Searches

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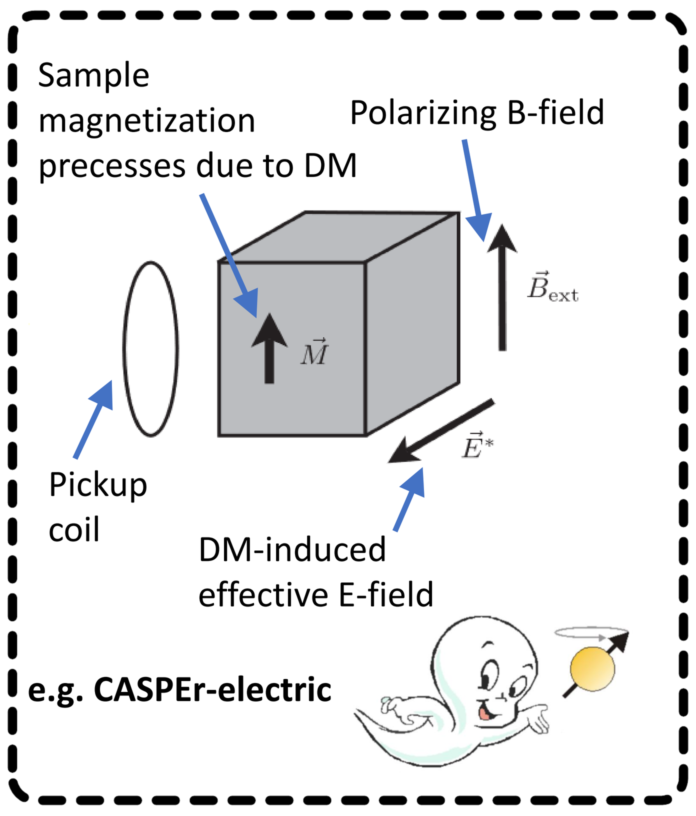
Nuclear Magnetic Resonance Axion Searches

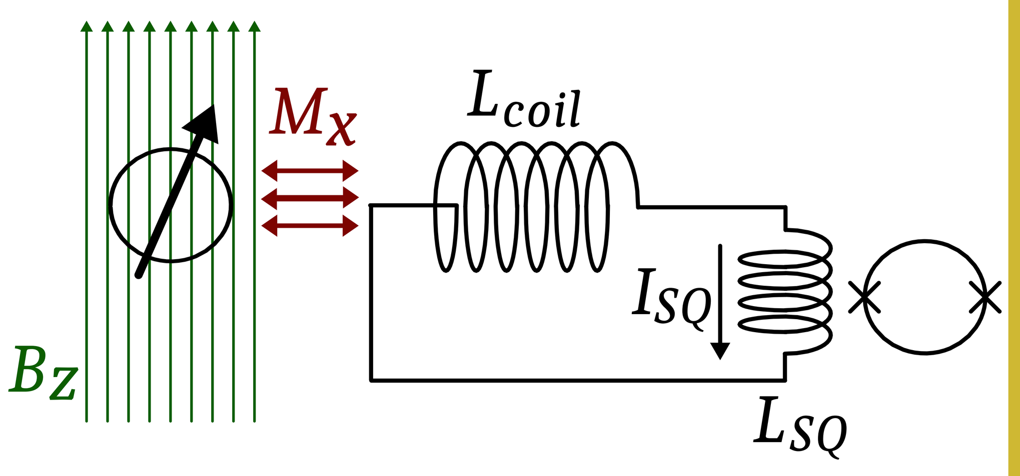
- The QCD axion is a well motivated dark matter candidate, which solves the longstanding Strong CP Problem in QCD.
- Axions produce oscillating signals at $f_{ax} = mc^2/h$, with long coherence times of ~10^6 periods.
- Axions couple to gluons, causing an effective oscillating nuclear electric dipole moment, which can be detected with a sensitive NMR spectrometer.[1]



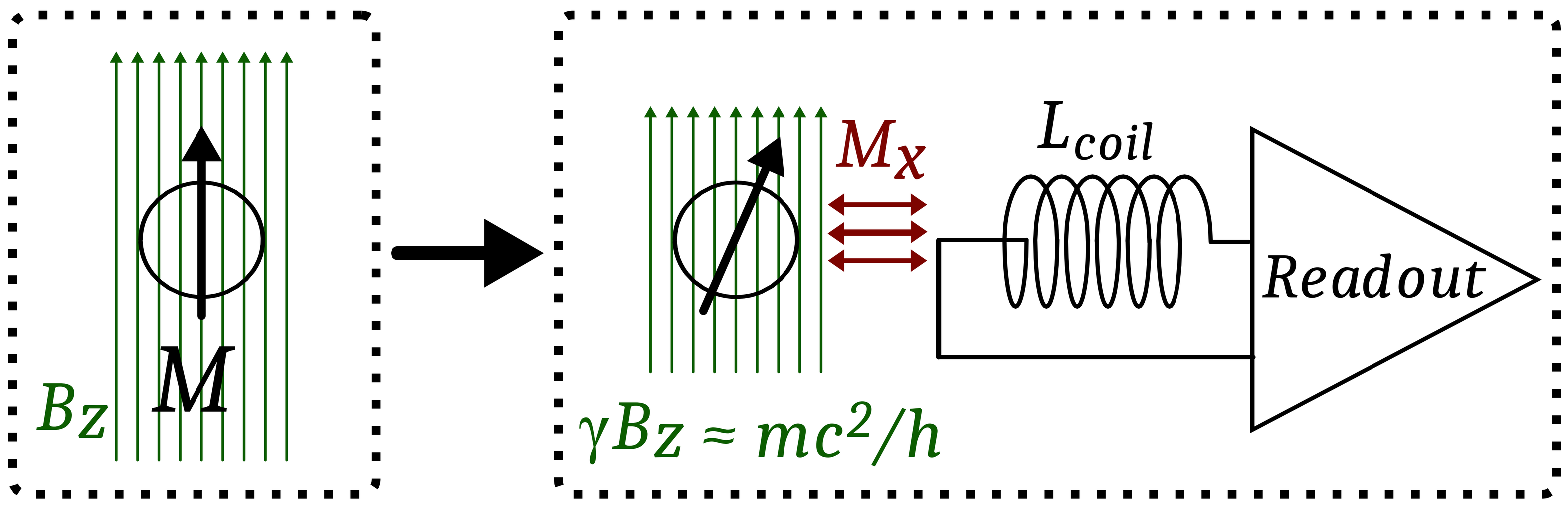
Current State of the Art

- dc SQUIDs are extremely sensitive magnetometers.
- Optimal readout noise is achieved when $L_{coil} \approx L_{SQ}$.[3]
- However, the energy sensitivity of dc SQUIDs is limited by their loop inductance:

$$\frac{S_\Phi}{2L_{SQ}} \geq n\hbar$$



NMR Measurement Cycle



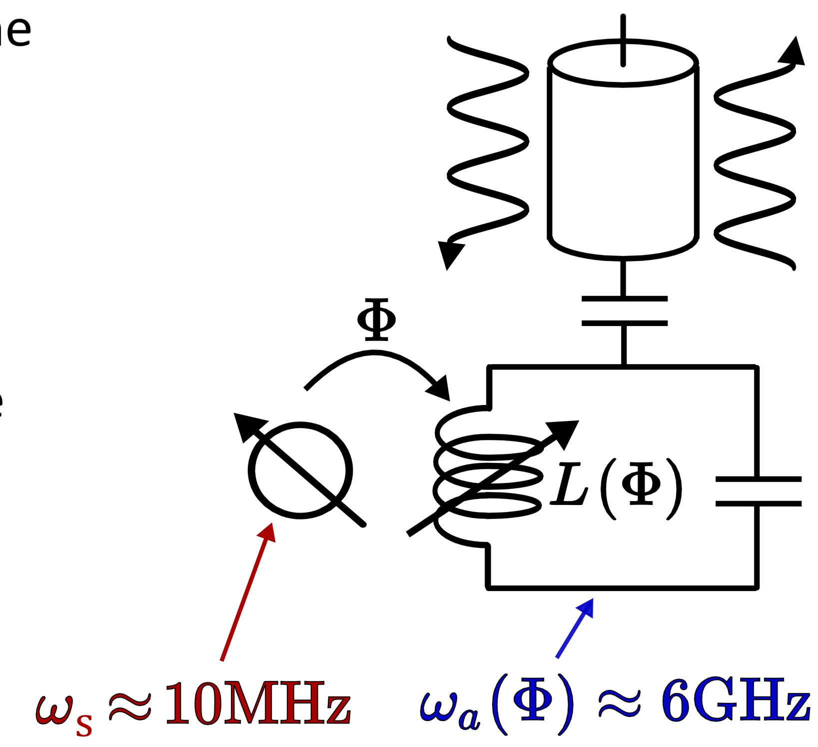
Polarize spins in a strong magnetic field

Detect axion-induced torques on spins by transverse magnetization

- Spins are aligned in an external magnetic field.
- The magnetic field is tuned such that the sample's Larmor frequency matches the axion search frequency.
- The axion-induced transverse magnetization is monitored with a pickup coil and amplifier.
- The magnetization signal is extremely weak, requiring a low noise amplifier.

Improved Readout with RF Quantum Upconverter (RQU)

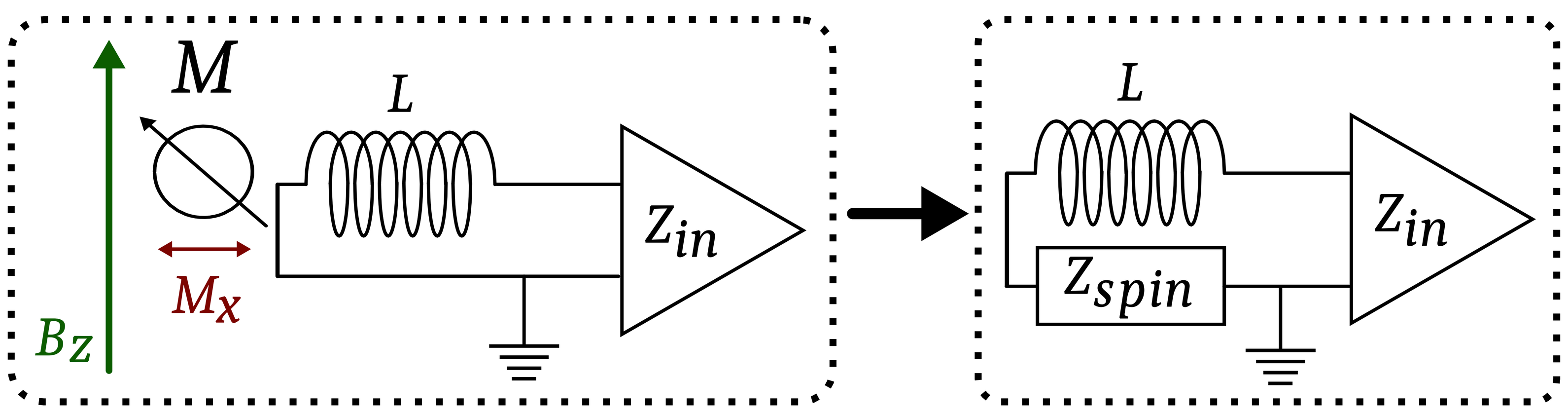
- Dispersive readout, where the RF flux signal is upconverted to microwave frequencies offers the possibility of improved flux resolution.
- See poster **A22-305** for more details.
- The flux sensitivity can be improved by increasing the number of microwave photons, $n_{\mu w}$.
- The quantity $\gamma n_{\mu w}$ can be made larger than 1, yielding an energy sensitivity better than $\hbar$, better than any dissipative SQUID.



RQU energy sensitivity:

$$\frac{S_\Phi}{2L_{SQ}} = \frac{n\hbar}{\gamma n_{\mu w}}$$

Pickup Coil Impedance



- The spins can be modelled as presenting an effective impedance Z_{spin} to the readout amplifier, and the goal is to minimize the overall magnetization-referred noise.
- For most NMR samples with modest polarization, this spin impedance is small compared to the pickup coil impedance: $|Z_{spin}| << \omega_L L$.
- Initial experiments will use untuned pickup coils, so readout must be optimized for an inductive source impedance.

Non-Classical Techniques

- Further improvements are possible using quantum readout and state preparation techniques:
  - Using squeezed microwave states with reduced phase noise to detect the RQU state allows for even larger enhancements in energy sensitivity.
  - Hyperpolarization of NMR sample leads to enhancement of axion signal.

References

1. Budker, Dmitry, et al. "Proposal for a cosmic axion spin precession experiment (CASPEr)." *PRX* (2014).
2. Clarke, John, Claudia D. Tesche, and R. P. Giffard. "Optimization of dc SQUID voltmeter and magnetometer circuits." *Journal of Low Temperature Physics* (1979).
3. Aspelmeyer, Markus, et al. "Cavity optomechanics." *Reviews of Modern Physics* (2014).

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