Probing fundamental physics with highly-coherent nuclear spins

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1. Abstract

Experiments using large numbers of highly-coherent, spin-polarized nuclei are some of the most sensitive probes of physics beyond the standard model, including:

- probes of CP-violation, in measurements of the ^{199}Hg and ^{129}Xe EDMs [1, 2],
- Tests of Lorentz (and CPT) symmetry, in studying nuclear Zeeman splittings as a function of orientation. These measurements also provide the most stringent constraints on a preferred rest frame for photons [3]
- Searches for low-mass axionic dark matter [4]
- Searches for long-range spin-dependent forces [5, 6],

several of which are poised to improve significantly over the next decade as our understanding and control of these systems improve.

Schematically these experiments involve measuring the spin-up/spin-down energy splitting of the nuclei as well as possible, while configuring the system such that the energy levels depend on the physics of interest. For instance, to measure an EDM, an electric field is applied along the quantization axis. The sensitivity of these techniques comes down to the fact that 1) the nuclear spins are well isolated from the environment and can remain in a given eigenstate for many hours, allowing highly time-coherent measurements of the energy levels, and 2) large numbers ($10^{15} - 10^{18}$) of nuclei can be prepared and manipulated in the same state, using optical and magnetic fields.

A common feature of all such experiments is the need to separate magnetic energy shifts from the shifts of interest. This can be accomplished in a number of ways, whether it be comparing different nuclear spin species, or the same spin species in different volumes, or nuclei with electrons. One implementation which is already very sensitive and seems poised for significant improvements in the near-term utilizes a pair of noble-gases polarized via spin-exchange optical pumping and coupled into a SQUID magnetometer. Table 1 shows that realistic improvements to the measurements can yield 3+ order of magnitude reduction in statistical uncertainty in the near term.

System	Xe pol [%]	He pol [%]	Signal [pT]	Noise [$\frac{\text{fT}}{\sqrt{\text{Hz}}}$]	Drift [pHz/s]	Decay [s]	T (meas) [s]	CRLB σ_f [nHz]
2019 Xe-EDM	2.5	0.05	60	6	10	10000	500	2
Realistic Upgrades	2.5	0.05	230	0.2	10^{-4}	10000	10000	10^{-3}

Table 1. Comparison of the 2019 Xe-EDM experiment [2], and the experiment I am planning. The SQUID parameters are commercially available as of 2017 [7]. The reduction in noise comes from lower-noise thermal shielding and a larger pick-up loop. The increase in signal comes from better geometric coupling between the SQUID pick-up and the cell. The scientific challenge will be in understanding and controlling all frequency drifts, many of which come from self-interactions. CRLB is the Cramer-Rao lower bound on the statistical uncertainty of the measurement.

2. Motivations and considerations for specific experiments

- *Dark matter axion search*: Axions are predicted to have spin-dependent couplings to nucleons, which modify the energy levels and whose strength oscillates over the sidereal and at the axions Compton frequency. The anticipated energy resolution would make possible direct searches for axionic dark matter far beyond astrophysical constraints across 7-10 decades of mass range, out of a possible mass range of 21 decades [4], and is likely the only way to perform direct detection experiments in much of that mass range. Searching for very low dark matter masses requires experimental stability over multiple days. The challenge will therefore be to maintain sufficient stability and repeatability in all relevant aspects of the system.

- *Fifth-force axion search*: Developing high-density spin sources and improved magnetic shielding would be necessary. Put together, these advances could make possible fifth-force searches for pseudo-Goldstone bosons that probe symmetry breaking scales of $\sim 10^7$ GeV, at or beyond current stellar-cooling constraints [8,9]. If successful, this would be one of the most important low-energy probes for new physics of any type.
- *Xenon Electric Dipole Moment:* The latest Xenon EDM limit was $1.4{\cdot}10^{-27}$e-cm [2], and was limited by statistical sensitivity. The most recent Mercury EDM experiment reached $7.4{\cdot}10^{-30}$e-cm [1]. Once the targeted 1000x improvement in energy resolution is reached undertaking another Xenon EDM measurement would be worthwhile, if there have not been comparable advances in Mercury and Thallium experiments.
- *Lorentz and CPT Symmetry*: Many of the experimental challenges are similar to those of the dark matter axion search, however it is especially interesting to perform tests of Lorentz symmetry on quadrupolar nuclei (such as noble gas ^{21}Ne) as it is sensitive to Lorentz-symmetry in the photon sector as well. This requires understanding the four-state spin-3/2 system as well.

With more extensive investment and taken to a larger scale this technique could be potentially be pushed quite a lot further:

- *Optimized spin-exchange pumping:* Spin-exchange-optical pumping of high pressure gases and multiple species at the same time is an active area of research. Improved understanding and optimization of the pumping could yield ~5-10 times larger signals.
- *Increased nuclear spin coherence:* The intrinsic limit from spin-spin interactions caps the coherence time at around ~ 2 times those given in Table 1. Suppressing spin-exchange relaxation beyond that is an interesting problem in noble-gas-spin physics with possible solutions being to reduce the formation of the Xenon-dimers and using dynamic decoupling techniques to suppress the spin-exchange-relaxation.
- *Reducing the SQUID sensor noise:* a custom system that optimally couples the nuclear spins to the Josephson junction could provide $\sim$ 20-fold reduction in the read-out noise. This would require collaboration with a group specialized in SQUIDs to develop.
- *Scaling to large size:* A large cell and SQUID system would require a fairly significant investment to ensure sufficient magnetic field uniformity and stability, and that thermal magnetic noise does not limit the readout noise, but a priori it could be made 10x larger for a 30x increase in signal-to-noise.

References

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