# Searching for CP-Violating Hadronic Physics via Precision Measurements of Nuclear Magnetic Quadrupole Moments

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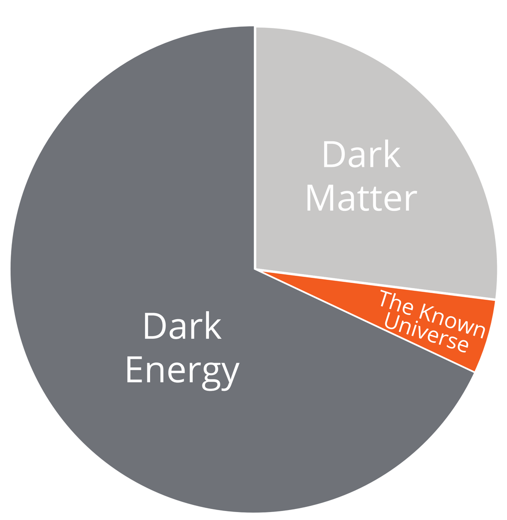
## Overview

One of the major unsolved problems in modern physics is the source of the matter/anti-matter imbalance, or Baryon Asymmetry, of the Universe. For this imbalance to exist, there must be new sources of Charge Parity (CP) violation beyond the Standard Model of particle physics. New CP-violating physics can manifest itself as exotic electromagnetic moments such as nuclear magnetic quadrupole moments (MQMs). Precision measurements in atomic/molecular/optical (AMO) systems are sensitive to these exotic electromagnetic moments and can therefore reveal new particles and forces. Searching for a nuclear MQM in AMO systems allows new hadronic physics to be explored in a low energy, table-top setting.

## Motivation

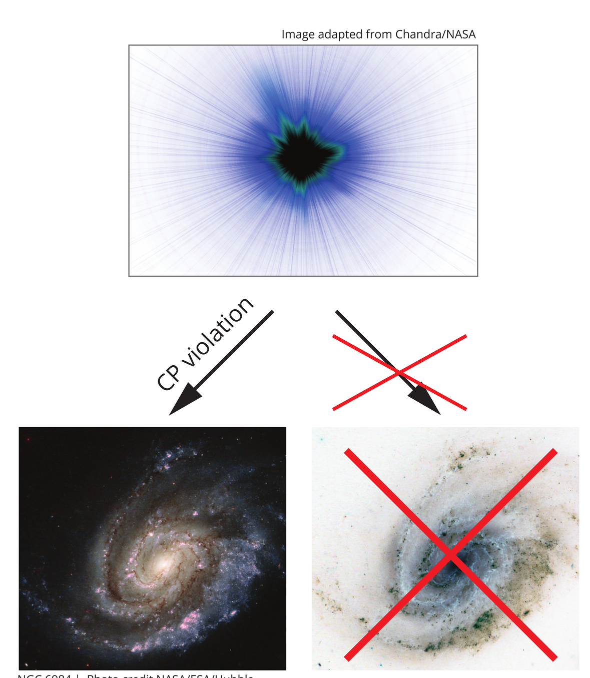



95% of the Universe is dark, and we don't know what it is. The other 5% of the universe is "normal" matter, such as atoms, molecules, stars, galaxies, and everything else that we know about.

However, the origin of this matter is a total mystery. No known physical processes can create a universe full of matter and no anti-matter. This problem is known as the, **Baryon Asymmetry of the Universe (BAU)**, and is one of the biggest problems facing physics.

One requirement for the BAU is the existence of undiscovered **CP-violating interactions** that exist beyond the Standard Model of particle physics.

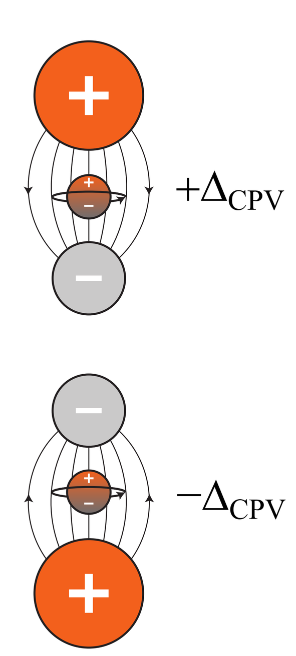
CP-Violating physics also gives rise to low energy effects in the spectra of atoms and molecules, which can be sensitively probed using modern spectroscopic techniques. New CP-violating physics in the hadronic sector can result in low-energy observables, such as **nuclear magnetic quadrupole moments (MQMs) and electric dipole moments (EDMs)**, which can be probed through precision measurements in polar molecules.




## Precision Measurements with Polar Molecules

The extremely large electromagnetic fields inside polar molecules make them extremely sensitive to CP-violating electromagnetic moments of molecular constituents , in particular electrons and nuclei. These moments cause symmetry-violating energy shifts that can be detected through precision measurements.

Certain molecules contain closely spaced states of opposite parity that allow the molecule to be fully polarized in modest laboratory fields (**<1 kV/cm**) and act as **internal co-magnetometers.** These states allow the reversal of CP-violating interactions, such as the orientation of nuclear spin relative to the internal molecular field, without reversing laboratory fields. This provides **powerful systematic error rejection, including motional fields, geometric phases, and leakage currents**.




Precision measurements in atoms and molecules are already probing the TeV scale for leptonic and hadronic CP-violation. By expanding existing techniques to probe polar molecules, we can explore the complex hadronic parameter space and continue improving sensitivity.

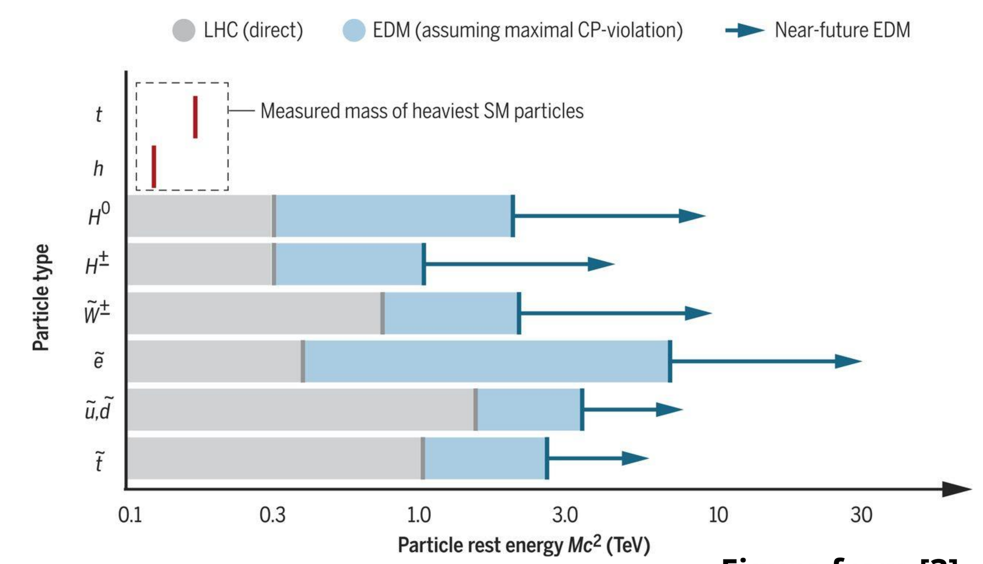


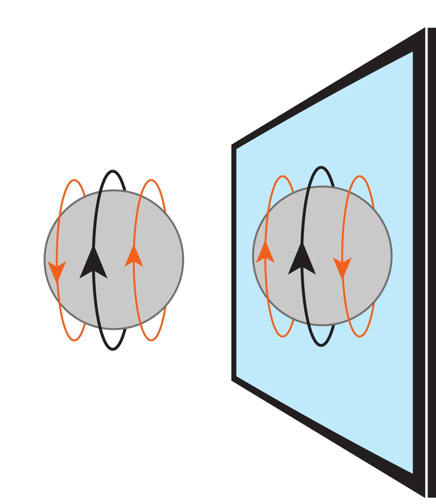

**Figure from [3]**

***Precision measurements in molecules can investigate PeV-scale CP violation***

## MQMs and Symmetry Violation

A particle with a permanent magnetic quadrupole moment (MQM) would be distinguishable from its mirror image, therefore only one of the versions can exist. The existence of such a moment would mean that parity is not a good symmetry of the universe.

An analogous argument demonstrates that any **permanent nuclear MQM violates CP symmetry**. Additionally, the converse is true: CP-violating physics generically gives rise to CP-violating moments such as nuclear MQMs. Therefore, measurements of nuclear MQMs can place limits on new particles and forces, such as supersymmetry, at the **TeV scale, and beyond**.



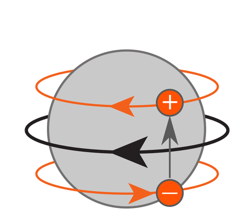
Permanent MQMs violate fundamental symmetries

| Molecule | $I_t$ | State | $\lvert W_M\rvert$ $10^{33}$ Hz/$e\cdot\mathrm{cm}^2$ | $\lvert W_M MS\rvert$ ($\mu$Hz) $10^{25} d_p/e\cdot\mathrm{cm}$ | $10^{10}\tilde{\theta}$ | $10^{27}(\tilde{d}_u-\tilde{d}_d)/\mathrm{cm}$ |
|---|---|---|---|---|---|---|
| $^{135,137}$BaF | $\frac{3}{2}$ | $^2\Sigma_{1/2}$ | 0.83$^a$ | ~0.1 | 1 | 0.6 |
| $^{173}$YbF | $\frac{5}{2}$ | $^2\Sigma_{1/2}$ | 2.1$^b$ | 22 | 42 | 25 |
| $^{201}$HgF | $\frac{3}{2}$ | $^2\Sigma_{1/2}$ | 4.8$^a$ | ~1 | 10 | 6 |
| $^{177}$HfF$^+$ | $\frac{7}{2}$ | $^3\Delta_1$ | 0.5 | 20 | 33 | 20 |
| $^{179}$HfF$^+$ | $\frac{9}{2}$ | $^3\Delta_1$ | 0.5 | 14 | 26 | 16 |
| $^{181}$TaN | $\frac{7}{2}$ | $^3\Delta_1$ | ~1 | 30 | 50 | 30 |
| $^{229}$ThO | $\frac{5}{2}$ | $^3\Delta_1$ | 1.9 | ~10 | 72 | 44 |
| $^{229}$ThF$^+$ | $\frac{5}{2}$ | $^3\Delta_1$ | 1.7 | ~10 | 65 | 39 |

**Table from [3]**

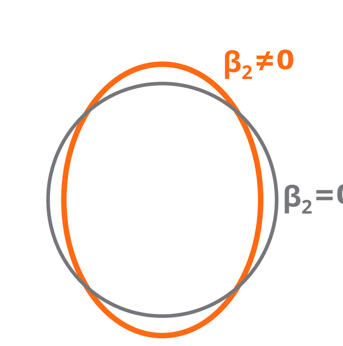
Nuclear MQM measurements are sensitive to a variety of new hadronic physics including the QCD θ term and the resulting effects of new massive particles, such as: proton, neutron, and quark EDMs, quark chromo EDMs, and CP-violating pion mediated or quark-quark interactions.

## Enhancement in Deformed Nuclei



Consider a nucleus with a single valence nucleon. If the valence nucleon has a permanent EDM, then the nucleus will have an MQM. Notice that only nuclei with $I \geq 1$ can support a quadrupole moment.

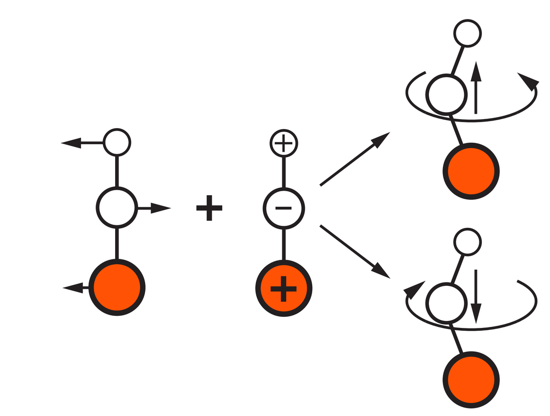
Nuclear MQMs are enhanced relative to the above single nucleon in nuclei with large quadrupole ($\beta_2$) deformations, as nucleons in nominally filled shells can contribute collectively. Therefore, **MQMs in nuclei with large quadrupole deformations are especially sensitive to collective effects such as CP-violating nucleon interactions**. Nuclei with large $\beta_2$ paramaters include isotopes of Yb, Ta, and Th as well as others.



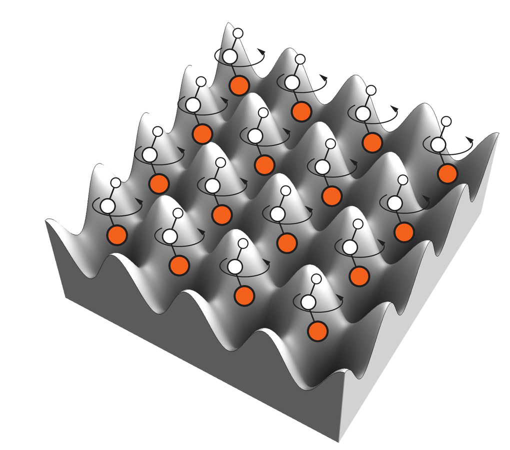

## Advantages of Polyatomic Molecules

Neither atoms nor diatomic molecules offer the ability to laser cool and trap while maintaining robust error rejection through internal co-magnetometer states. On the other hand, polyatomic molecules generically offer internal co-magnetometer states via degenerate mechanical motions.

Since laser cooling and robust error rejection will both be necessary for significant sensitivity improvements, **polyatomic molecules are a promising route to exploring CP-violation at the PeV scale [1].**



Parity doublet arising from bending modes in linear triatomic molecule.



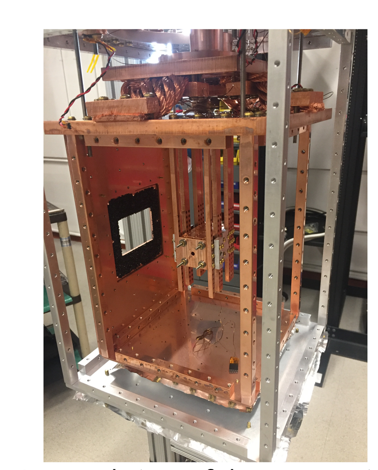
Precision measurement of the future:
ultracold molecules trapped in an optical lattice

$10^6$ trapped molecules
10 second coherence time
Robust error rejection
1 week integration time

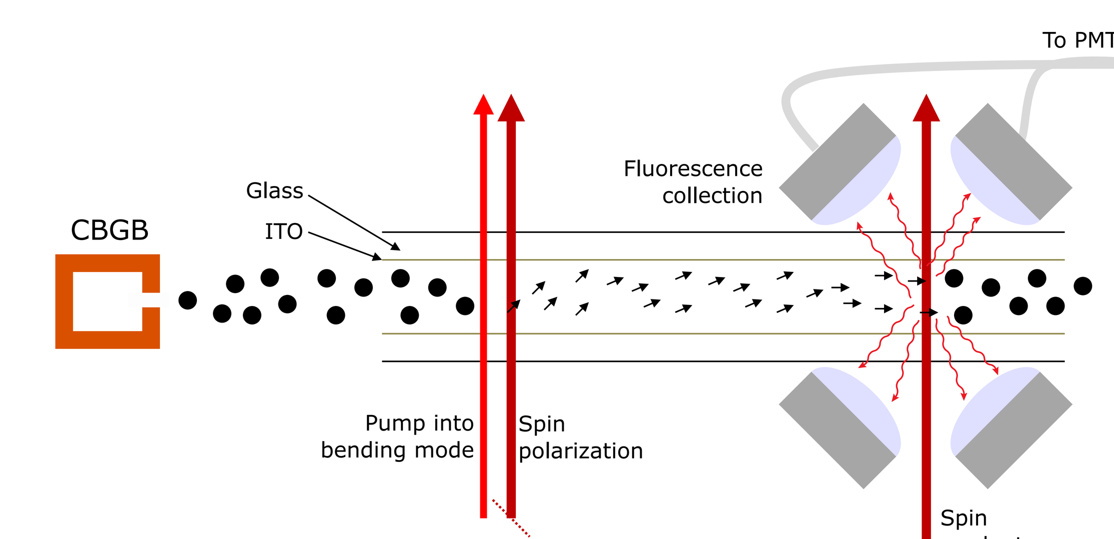
**PeV Scale Sensitivity**

## Nuclear MQM Search in $^{173}$YbOH

We will search for the nuclear MQM of $^{173}$Yb (I=5/2) by preforming spin procession measurements on a cryogenic buffer gas cooled beam of ytterbium-173 hydroxide, $^{173}$YbOH. The MQM will induce an EDM in the molecule, resulting in CP-violating energy shifts. By measuring the procession angle in different E-fields, B-fields, and hyperfine states we will disentangle the MQM signal from other spin procession sources.

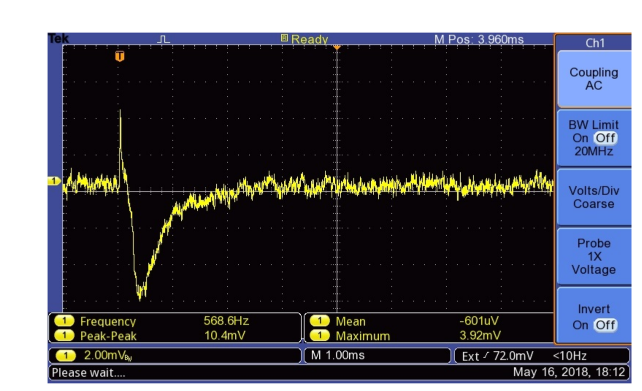


Internal view of the cryogenic buffer gas beam source




**Current Progress**:

We have created a cryogenic buffer gas beam of YbOH. The absorption signal for the $X^2\Sigma^+ \rightarrow A^2\Pi_{1/2}$ Q(0) transition of YbOH is shown to the right. We are continuing to optimize and characterize the beam. Now that we have a beam, we can begin construction of the precision measurement apparatus.



First YbOH signal

**References**:

[1] I. Kozyryev and N. R. Hutzler, "Precision Measurement of Time-Reversal Symmetry Violation with Laser-Cooled Polyatomic Molecules," PRL 119, 133002 (2017)

[2] V. V. Flambaum, D. Demille, and M. G. Kozlov, "Time-Reversal Symmetry Violation in Molecules Induced by Nuclear Magnetic Quadrupole Moments," PRL 113, 103003 (2014)

[3] D. DeMille, J. M. Doyle, and A. O. Sushkov, "Probing the frontiers of particle physics with tabletop-scale experiments," Science 357, 990-994 (2017)