Fundamental Symmetries with Atoms, Molecules, and Optics (AMO)

Nick Hutzler

Caltech
State of the field

- Molecules have been used to search for the electron electric dipole moment with high precision
  - Already probing the ~50 TeV (~2 TeV) scale for CPV physics at 1 (2) loops
  - ~100x EDM sensitivity improvement since last Snowmass
  - Leverages combination of intrinsic amplification of CPV moments, coherent quantum control, and robustness against systematics

- Next-generation searches are starting
- Upgrades to existing experiments
- New methods with enhanced sensitivity
- Access to new parameter spaces (leptonic and hadronic)
- Major advances will take place in the next decade
- Implementation of advanced quantum control
- New measurement approaches
- Access to exotic nuclei
- These are getting started!
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100 s coherence time
Heavy, deformed nucleus
Quantum control
Robust error rejection
Two weeks integration
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$\sim$PeV-scale CP-violating physics @ 1 loop
$\sim$100 TeV-scale CP-violating physics @ 2 loops
Both leptonic and hadronic sectors
Extreme precision, $\theta_{QCD} \lesssim 10^{-14}$
$\sim$10 year time scales
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+ ~5-10 year time scale?
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- This is just one specific approach as a motivating example
- There are many complementary approaches which can leverage these advances
- How can we realize this experiment?
Progress in the last ~year

**Precision spectroscopy in trapped, ultracold, engineered molecules**

![Graph showing microwave frequency vs. fraction remaining]

**Creation, trapping, cooling, control of radioactive molecular ions**

![Graph showing frequency vs. normalized Fourier amplitude]

**Quantum-controlled ultracold molecules**

**Precision spectroscopy of radioactive molecules**

![Graph showing wavenumber vs. counts (a.u.)]

**Long spin coherence times in optical traps**

PolyEDM Collaboration
Fan et al., PRL 126, 023002 (2021)
Doyle Group @ Harvard

Udrescu et al., PRL 127, 033001 (2021)
Zheng et al., arXiv:2207.08140 (2022)
What will it take to access CPV?

Again, this is just a *particular* example, but many of the challenges are shared.
Looking Ahead

Orders-of-magnitude gains in energy reach are possible in next 10 years, and beyond

Long-term roadmap includes quantum-enhanced metrology, extremely exotic nuclei, and more
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  - *Not* the case at last Snowmass

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  - *Not* the case at last Snowmass
- Need sustained support and coordination
  - Theory and experiment
  - AMO, HEP, NP, QIS, chemistry, beam facilities, ...
- Complementary approaches are required
- Broad parameter space!
- Multiple AMO systems
- srEDM for nucleons/nuclei
- Most new AMO CPV experiments are multi-PI, multi-institution, multi-year
- Necessitated by both scale and complexity
- This is not the "traditional" AMO operating condition
- Challenges most existing AMO support and coordination models

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