Identifying ideal nuclei in which to search for CP violating moments: *Necessity to populate nuclear levels and characterize their nuclear deformation*

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New sources of CP violation, beyond the known sources in the standard model (SM) via the CKM matrix, are required to explain the baryon asymmetry of the universe. Measurement of P,T violating moments, such as the electric dipole moment (EDM) or the magnetic quadrupole moment (MQM), of sub-atomic particles like the neutron or the electron as well as of atoms, serves as powerful tools with which to probe sources of CP violation. Besides the EDM and MQM of sub-atomic constituents of the nucleus, various other CP violating hadronic interactions, like long range πNN interactions, contribute to the generation of nuclear EDM and MQM. In addition to nuclear EDM and MQM, CP violating semi-leponic interactions between the electrons and nuclei also contributes to atomic EDM and MQM.

While nuclear EDM is Schiff screened by the electron cloud of the atom [1], nuclear MQM is not. The residual of the improper screening of the nucleus is usually referred to as the Schiff moment. Such improper screening can lead to large atomic EDMs [1], and arise from: (i) relativistic electrons, as is the case with paramagnetic atoms with unpaired valence electron, such as ^{85}Rb [2], ^{133}Cs [3], ^{205}Tl [4], (ii) the nucleus having quadrupole and octupole deformations, as is the case with diamagnetic atom of ^{225}Ra [5], or if (iii) there exists dominant CP violating interactions between the constituents of the atom, as is the case with the diamagnetic atoms of ^{129}Xe [6] and ^{199}Hg [7]. The combination of CP violating nuclear moments are usually referred to as the nuclear Schiff moment. Measurement of atomic EDM [8] and MQM [9], using molecular systems, has gained traction in recent days, due to the enhancement of the sensitivity to atomic EDM in such system coming from very large effective intra-molecular electric fields. The motivation to use molecular systems is further bolstered by the ability to employ various powerful atomic physics techniques such as spin squeezing [10].

Quadrupole and octupole deformation of nuclei can significantly enhance the atomic EDM by many orders of magnitude compared to that with a spherical nucleus [13]. Nuclear quadrupole and octupole deformation has been well characterized in theory by various models for all isotopes, like *eg.* in Refs. [12–14]. Using the theoretical deformation parameters, the isotopes of ^{221,223,225}Rn, ^{221,223,225,227}Fr, ^{221,223,225}Ra, ^{223,225,226,227,231}Ac, ^{227,229}Th, and ^{226,229}Pa were identified as ideal systems, in which to attempt a nuclear Schiff moment measurement in [15]. In addition to these, the isotopes of ^{153}Eu, ^{161}Dy, ^{167,173}Yb, ^{169,177,179}Hf, ^{177,181}Ta, ^{223}Rn, ^{221,223}Fr, ^{223}Ra, ^{225,227}Ac, ^{229}Th, ^{229}Pa, and ^{231,233,235}U were also identified as ideal systems, in which to attempt a nuclear MQM measurement in [9, 16].

Nuclear deformation parameters of $\{\beta_2, \beta_3\}$ can be accessed through the measurement of $E2$ and $E3$ transitions via nuclear spectroscopy [17], respectively, as well as through atomic-spectroscopy [18]. Particularly, to access the octupole deformation, $E3$ transition energies are necessary. The nuclear level diagram of the states $[\mathcal{E}(J^\pi)]$ for the above isotopes, from which they $E2$ transition to their respective ground state, are well characterized. However, the states from which they $E3$ transition to their respective ground state are not available for the isotopes of ^{221,223,225}Rn, ^{221}Ra, ^{226}Ac, and ^{226}Pa. Since it is hard to populate the states involved in a $E3$ transition, atomic-spectroscopy of these isotopes to ascertain their nuclear octupole deformation parameter, β_3, looks particularly attractive.

On the other hand, it is also vital to establish non-degeneracy of the parity doublet in the ground state for their nuclear EDM or MQM to be CP-violating. The energy difference between the ground state parity doublet has not yet been measured for the isotopes of ^{173}Yb, ^{177}Hf, ^{181}Ta, ^{223,225}Rn, ^{226}Ac, and ^{231}U. This is due to the states which are a parity conjugate of the ground states not yet being characterized. Given that the lifetime of the relevant state [which are a parity conjugate of the ground state] are of the order ~ 10 ns, atomic-spectroscopy is not a viable technique here. In these cases, we may have to rely on further precision nuclear γ-spectroscopy or infer the energies of the relevant states from $\{\beta, \alpha\}$-decay or e^--capture.

[1] L. I. Schiff, *Measurability of Nuclear Electric Dipole Moments*, Phys. Rev. **132**, 2194 (1963). DOI: 10.1103/Phys-

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[1] Only atomic EDM experiments that have produced a result are used as examples here, but similar examples can made using EDM experiments that use molecules

Rev.132.2194.
[2] E. S. Ensberg, *Experimental Upper Limit for the Permanent Electric Dipole Moment of Rb85 by Optical-Pumping Techniques*, Phys. Rev. **153**, 36 (1967). DOI: 10.1103/PhysRev.153.36.
[3] S. A. Murthy, D. Krause Jr, Z. L. Li, and L. R. Hunter, *New Limits on the Electron Electric Dipole Moment from Cesium*, Phys. Rev. Lett. **63**, 965 (1989). DOI: 10.1103/PhysRevLett.63.965.
[4] E. D. Commins et al., *Improved Experimental Limit on the Electric Dipole Moment of the Electron*, Phys. Rev. A **50**, 2960 (1994). DOI: 10.1103/PhysRevA.50.2960.
[5] M. Bishof et al., *Improved Limit on the 225Ra Electric Dipole Moment*, Phys. Rev. C **94**, 025501 (2016). DOI: 10.1103/PhysRevC.94.025501.
[6] F. Allmendinger et al., *Measurement of the Permanent Electric Dipole Moment of the 129Xe Atom*, Phys. Rev. A **100**, 022505 (2019). DOI: 10.1103/PhysRevA.100.022505.
[7] B. Graner, Y. Chen, E. G. Lindahl, and B. R. Heckel, *Reduced Limit on the Permanent Electric Dipole Moment of 199Hg*, Phys. Rev. Lett. **116**, 161601 (2016). DOI: 10.1103/PhysRevLett.116.161601.
[8] V. V. Flambaum and V. A. Dzuba, *Electric Dipole Moments of Atoms and Molecules Produced by Enhanced Nuclear Schiff Moments*, Phys. Rev. A **101**, 042504 (2020). DOI: 10.1103/PhysRevA.101.042504.
[9] V. V. Flambaum and A. J. Mansour, *Enhanced Magnetic Quadrupole Moments in Nuclei with Octupole Deformation and Their CP-Violating Effects in Molecules*, Phys. Rev. C **105**, 065503 (2022). DOI: 10.1103/PhysRevC.105.065503.
[10] T. Bilitewski et al., *Dynamical Generation of Spin Squeezing in Ultracold Dipolar Molecules*, Phys. Rev. Lett. **126**, 113401 (2021). DOI: 10.1103/PhysRevLett.126.113401.
[11] V. Spevak, N. Auerbach, and V. V. Flambaum, *Enhanced T-Odd, P-Odd Electromagnetic Moments in Reflection Asymmetric Nuclei*, Phys. Rev. C **56**, 1357 (1997). DOI: 10.1103/PhysRevC.56.1357.
[12] P. Moller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, *Nuclear Ground-State Masses and Deformations*, At. Data Nucl. Data Tables **59**, 185 (1995). DOI: 10.1006/adnd.1995.1002.
[13] V. Spevak, N. Auerbach, and V. V. Flambaum, *Enhanced T-Odd, P-Odd Electromagnetic Moments in Reflection Asymmetric Nuclei*, Phys. Rev. C **56**, 1357 (1997). DOI: 10.1103/PhysRevC.56.1357.
[14] S. E. Agbemava, A. V. Afanasjev, and P. Ring, *Octupole Deformation in the Ground States of Even-Even Nuclei: A Global Analysis within the Covariant Density Functional Theory*, Phys. Rev. C **93**, 044304 (2016). DOI: 10.1103/PhysRevC.93.044304.
[15] P. Mohanmurthy, U. Silwal, D. P. Siwakoti, and J. A. Winger, *Survey of Deformation in Nuclei in Order to Estimate the Enhancement of Sensitivity to Atomic EDM*, AIP Conf. Proc. **2249**, 030046 (2020). DOI: 10.1063/5.0008560.
[16] B. G. C. Lackenby and V. V. Flambaum, *Time Reversal Violating Magnetic Quadrupole Moment in Heavy Deformed Nuclei*, Phys. Rev. D **98**, 115019 (2018). DOI: 10.1103/PhysRevD.98.115019.
[17] ENSDF database, URL: nndc.bnl.gov/ensarchivals/.
[18] X. F. Yang, S. J. Wang, S. G. Wilkins, and R. F. G. Ruiz, *Laser Spectroscopy for the Study of Exotic Nuclei*, Prog. Part. Nucl. Phys. **104005** (2022). DOI: 10.1016/j.ppnp.2022.104005.