The observed matter-antimatter asymmetry in the universe is an important open question in modern physics. Three necessary conditions were postulated by Sakharov[1] including the requirement that combined charge and parity (CP) symmetry is violated. While the current standard model (SM) includes a CP-violating mechanism through a CP-violating phase in the CKM matrix [2] this alone is insufficient to account for the observed matter-antimatter asymmetry by several orders of magnitude (see e.g. Refs. [1, 3–7]). Therefore, other sources and mechanisms of CP-violation beyond the current SM must exist and investigating these will give insight into new physics.

The violation of CP symmetry was first detected in the decay modes of the kaon system [3] and more recently in the B meson sector [4,10], however detection of CP-violation in other systems has not been confirmed. By the CPT theorem a mechanism which violates combined CP symmetry must also violate time-reversal (T) symmetry. Therefore, the existence of permanent electromagnetic moments which violate T symmetry is a promising avenue for constraining theories which incorporate a higher degree of CP-violation than the SM such as supersymmetric theories which has been postulated to exist due to the nuclear polarization effects [22].

In the expression for the Schiff moment there is a partial cancellation between the first term and the second (screening) term. There is also a screening correction to the octupole moment [17, 22, 23].

In the Hg and Xe atoms where the most accurate measurements of atomic EDM have been performed, the valence nucleon is a neutron. Therefore, the electrostatic moments (EDM, Schiff and octupole) moments do not appear directly, they exist due to the nuclear polarization effects [22]. Due to the screening effect and the indirect polarization origin of the Schiff moment the nuclear calculations are rather unstable. In the case of the MQM moment both valence protons and neutrons contribute directly and the result is expected to be more accurate [24]. A promising method of measuring CP-violating moments is in diatomic molecular experiments where the effective electric field is significantly larger than those directly accessible in laboratory experiments. There is a considerable body of work for calculating the effective electric field in diatomic molecular systems which may be experimentally viable. Both theoretical

$T,P$-violating moments (EDM, Schiff and octupole moments) may have the following advantages:

- The nuclear EDM in neutral atoms and molecules are completely screened [10]. The Schiff and octupole moments have an additional second power of a very small nuclear radius. The magnetic interaction is not screened. The MQM contribution to atomic EDM typically is an order of magnitude larger than the contribution of the Schiff moment and several orders of magnitude larger than the octupole contribution [15, 20].

- In quadrupole deformed nuclei MQM is enhanced by an order of magnitude [21], therefore, the MQM contribution to atomic EDM may be two orders of magnitude larger than the Schiff moment contribution.

- In the Hg and Xe atoms where the most accurate measurements of atomic EDM have been performed, the valence nucleon is a neutron. Therefore, the electrostatic moments (EDM, Schiff and octupole) moments do not appear directly, they exist due to the nuclear polarization effects [22]. Due to the screening effect and the indirect polarization origin of the Schiff moment the nuclear calculations are rather unstable. In the case of the MQM moment both valence protons and neutrons contribute directly and the result is expected to be more accurate [24]. A promising method of measuring CP-violating moments is in diatomic molecular experiments where the effective electric field is significantly larger than those directly accessible in laboratory experiments. There is a considerable body of work for calculating the effective electric field in diatomic molecular systems which may be experimentally viable. Both theoretical
and experimental progress has been made in measuring the $T,P$-odd effects in YbF $^{172,173}$, HfF $^{174,175}$, ThO $^{176,177}$, ThF$^+$$^{178,179}$, TaN $^{180,181}$, TaO$^+$ $^{182}$ and TaO$^{183}$ particularly in relation to the nuclear Schiff moment and electron EDM. In section III we present the molecular energy shift due to the nuclear MQM for these molecules.

The collective enhancement of MQM for some heavy deformed nuclei were estimated in $^{[21,24]}$ where they considered the contribution using a spherical wave function basis. In this work we will use the Nilsson model of the the nucleus which is an empirically successful single particle model which accounts for the quadrupole deformation of a nucleus by using an anisotropic oscillator potential $^{[55-57]}$. In the Nilsson model the deformation breaks the degeneracy of the isotropic shell model which results in several overlapping partially filled nuclear shells containing a large number of nucleons. Each nucleon in the Nilsson model is defined in the Nilsson basis $^{[55,57]}$ where $N$ is the principle shell number $(N = n_x + n_y + n_z)$, $\Lambda$ is the projection of the orbital angular momentum on the deformation axis (chosen to be the $z$-axis) and $\Omega = \Lambda + \Sigma$ is the projection of the total angular momentum of the nucleon on the deformation axis.

To illustrate why the MQM tensor should be enhanced in quadrupole deformed nuclei let us compare it with the EDM vector property of nuclei. The direction of the EDM of a nucleon is characterised by its angular momentum projection on the deformed nucleus axis $\Omega$. In the case of the vector properties such as EDM and magnetic moment the contributions of $\Omega$ and $-\Omega$ cancel each other and there is no enhancement in the quadrupole deformed nuclei. For the second rank tensors such as MQM and nuclear electric quadrupole moment the contributions of $\Omega$ and $-\Omega$ double the effect. There are many nucleons in the open shells of deformed nuclei and this leads to a collective enhancement of second rank tensor properties.

In the Nilsson model we consider the nucleus in the intrinsic frame which rotates with the nucleus. However the nucleus itself rotates with respect to the fixed laboratory frame $^{[57]}$. Due to this rotation the tensor properties transform between the intrinsic and laboratory frame. The relationship between these two frames is $^{[57]}$

$$A_{\text{Lab}} = \frac{I(I+1)}{2I+1} A_{\text{Intrinsic}},$$  

where $I = I_z = |\Omega|$ is the projection of total nuclear angular momentum (nuclear spin) on the symmetry axis. This expression shows that only in nuclei with spin $I > 1/2$ can we detect these second order tensor properties.

\section*{I. MQM CALCULATION}

The magnetic quadrupole moment of a nucleus due to the electromagnetic current of a single nucleon with mass $m$ is defined by the second order tensor operator $^{[15]}$

$$\mathcal{M}^\nu_m = \frac{e}{2m} \left[ 3\mu_\nu \left( r_k \sigma^i_n + \sigma^i k r_n \right) - \frac{2}{3} \delta^{kn} \sigma \cdot \mathbf{r} \right] + 2q_\nu \left( r_k l_n + l_k r_n \right)$$  

where $\nu = p, n$ for protons and neutrons respectively and, $\mu_\nu$ and $q_\nu$ are the magnetic moment and charge of the nucleon respectively. The nuclear MQM is $T,\ P$- odd and therefore it is forbidden in the absence of nucleon EDMs and $T,\ P$- odd nuclear forces. It is understood the shell nucleons interact with the core of the nucleus through a $P-$ and $T-$ potential $^{[14,15,21]}$. This results in a perturbed “spin hedgehog” wavefunction of a nucleon given by $^{[13,21]}$

$$|\psi'\rangle = \left( 1 + \xi_\nu \frac{e}{m} \sigma \cdot \nabla \right) |\psi_0\rangle$$  

$$\xi_\nu \approx -2 \times 10^{-21} \eta_\nu \ e \cdot \text{cm}$$

where $\nu = p,n$ for protons and neutrons respectively. Here $\eta_\nu$ represent $T,\ P$- odd nuclear strength constants from the $T,\ P$- violating nuclear potential $H_{T,P} = \eta_\nu G_F/(2^{3/2} m_\nu) (\sigma \cdot \nabla \rho)$ and $|\psi_0\rangle$ is the unperturbed nuclear wavefunction. Here $\rho$ is the total nucleon number density and $G_F$ is the Fermi weak constant. It should be noted that we used $T,\ P$- odd interaction in the contact limit while the actual interaction has a finite range due to the pion exchange contribution. Another approximation used in the derivation of the Eq. (3) is that the strong potential and nuclear density have similar profiles (not necessarily the spherical one). These approximations introduce a sizeable theoretical uncertainty. Using $^{[24]}$ and $^{[43]}$ the MQM for a single nucleon due to the $P-$, $T-$ odd valence-core interaction is given by,

$$M^{TP} = M^{TP}_{zz} = \xi \left( \frac{2}{m} \left( \mu \langle \hat{l} \cdot \hat{l} \rangle - q \langle \hat{z} \hat{l}_z \rangle \right) \right).$$

In the Nilsson basis $^{[55]}$ the nucleon’s total angular momentum projection onto the symmetry axis is given by $\Omega_N = \Lambda_N + \Sigma_N$, where $\Sigma_N = \pm 1/2$ is the spin projection and $\Lambda$ is the orbital angular momentum projection of the nucleon. In this basis the MQM generated by the spin-hedgehog Eq. (3) is given by,

$$M^{TP}_{\nu} = 4 \Sigma_N \Lambda_N \xi (\mu_\nu - q_\nu) \frac{\hbar}{m_\nu c}.$$  

The orbit of a permanent electric dipole moment (EDM) also generates a contribution to the nuclear MQM, $M^{\nu}_{\text{EDM}} \propto d_\nu$ $^{[58]}$. As both the proton and neutron are expected to have an EDM both will contribute to the MQM. From $^{[24]}$ using a valence nucleon approach the
we see that the use of the deformed Nilsson orbitals enhanced by a factor of 3. Similarly, for $^{179}$Yb the neutron contribution has doubled. Note also that MQMs in these heavy quadrupole deformed nuclei are an order of magnitude larger than MQM due to a valence proton ($\sim M_0^p$) or neutron ($\sim M_0^n$) in spherical nuclei.

The $T-,P$-odd nuclear potential which generated the MQM is dominated primarily by the neutral $\pi_0$ exchange. We can express the strength constants $\eta_\nu$ in the $T-,P$- violating nuclear potential $H_{T,P}$ in terms of the strong $\pi NN$ coupling constant $g$ and three $T-,P$- odd coupling constants, corresponding to the different isotopic channels, $g_i$ where $i = 0, 1, 2$. For heavy nuclei the results are the following [17, 63]:

$$\eta_n = -\eta_p \approx 5 \times 10^6 g (\bar{g}_1 + 0.4\bar{g}_2 - 0.2\bar{g}_0). \quad (8)$$

We can rewrite the contribution of both the proton and nucleon MQMs in terms of these coupling constants [21, 64],

$$\begin{align*}
M_p^0(g) &= \left[ g (\bar{g}_1 + 0.4\bar{g}_2 - 0.2\bar{g}_0) \\
&\quad + \frac{d_p}{1.2 \times 10^{-14} \text{ e cm}} \right] 3.0 \times 10^{-28} \text{ e cm}^2 \\
M_n^0(g) &= \left[ g (\bar{g}_1 + 0.4\bar{g}_2 - 0.2\bar{g}_0) \\
&\quad + \frac{d_n}{1.3 \times 10^{-14} \text{ e cm}} \right] 3.2 \times 10^{-28} \text{ e cm}^2.
\end{align*} \quad (9)$$

We can write the contributions of the $T-,P$-odd $\pi NN$ interaction and nuclear EDMs in terms of more fundamental $T-,P$- violating parameters such as the QCD CP-violating parameter $\bar{\theta}$ which is the heart of the strong $CP$ problem, or in terms of the EDMs $d$ and chromo-EDMs $d$ of $u$ and $d$ quarks. They are [3, 63, 64]:

$$\begin{align*}
g\bar{g}_0(\bar{\theta}) &= -0.37\bar{\theta} \\
g\bar{g}_0(d_u, d_d) &= 0.8 \times 10^{15} (\bar{d}_u - \bar{d}_d) \text{ cm}^{-1} \\
g\bar{g}_1(d_u, d_d) &= 4 \times 10^{15} (\bar{d}_u + \bar{d}_d) \text{ cm}^{-1} \\
d_p(d_u, d_d, \bar{d}_u, \bar{d}_d) &= 1.1e (\bar{d}_u + 0.5\bar{d}_d) + 0.8d_u - 0.2d_d \\
d_n(d_u, d_d, \bar{d}_u, \bar{d}_d) &= 1.1e (\bar{d}_d + 0.5\bar{d}_u) - 0.8d_d + 0.2d_u
\end{align*} \quad (10)$$

where the chromo-EDM contributions in eqs. (11) and (12) arise from the Peccci-Quinn mechanism [3, 70]. The corresponding substitutions give the following results for the dependence on $\bar{\theta}$ of proton and neutron MQM contributions:

$$\begin{align*}
M_p^0(\bar{\theta}) &= 1.9 \times 10^{-29} \bar{\theta} \text{ e cm}^2 \\
M_n^0(\bar{\theta}) &= 2.5 \times 10^{-29} \bar{\theta} \text{ e cm}^2.
\end{align*} \quad (14)$$

| Nuclei | $I^+_t$ | $M$ | Nuclei | $I^+_t$ | $M$ |
|--------|---------|-----|--------|---------|-----|
| $^9$Be  | $\frac{3}{2}^+$ | $0M_0^p + 0.4M_0^n$ | $^{167}$Er | $\frac{5}{2}^-$ | $21M_0^p + 36M_0^n$ |
| $^{21}$Ne | $\frac{3}{2}^+$ | $0M_0^p + 0.4M_0^n$ | $^{173}$Yb | $\frac{5}{2}^-$ | $14M_0^p + 26M_0^n$ |
| $^{27}$Al | $\frac{5}{2}^+$ | $3M_0^p + 4.5M_0^n$ | $^{177}$Hf | $\frac{7}{2}^-$ | $17M_0^p + 42M_0^n$ |
| $^{151}$Eu | $\frac{5}{2}^+$ | $12M_0^p + 23M_0^n$ | $^{179}$Hf | $\frac{7}{2}^+$ | $20M_0^p + 50M_0^n$ |
| $^{153}$Eu | $\frac{5}{2}^+$ | $12M_0^p + 20M_0^n$ | $^{181}$Ta | $\frac{7}{2}^+$ | $19M_0^p + 45M_0^n$ |
| $^{163}$Dy | $\frac{5}{2}^-$ | $11M_0^p + 21M_0^n$ | $^{229}$Th | $\frac{7}{2}^+$ | $13M_0^p + 27M_0^n$ |

Table I. Total nuclear MQM for each quadrupole deformed nucleus calculated using the Nilsson model. This table presents both the proton and neutron contributions to the total nuclear MQM in the laboratory frame.
The dependence on the up and down quark EDMs is
\[
M^0_\theta(d_u - d_d) = 1.2 \times 10^{-12}(d_u - d_d) \, e \cdot cm \\
M^n_\theta(d_u - d_d) = 1.3 \times 10^{-12}(d_u - d_d) \, e \cdot cm.
\]
(15)

While there have been more sophisticated treatments of the \( \pi NN \) interaction with respect to \( \theta \) and the quark chromo-EDMs [24], the values used above are within the accuracy of our model.

II. MQM ENERGY SHIFT IN DIATOMIC MOLECULES

Direct measurement of the nuclear MQM is unfeasible and a more indirect method is required. As mentioned above the use of neutral molecular systems is promising as the nuclear MQM will interact with the internal electromagnetic field. Molecules in particular present a lucrative option due to existence of very close paired levels of opposite parity, the \( \Omega \)-doublet - see e.g. [24]. For highly polar molecules consisting of a heavy and light nucleus (for example, Th and O) the effect of MQM is \( \sim Z^2 \), therefore it is calculated for the heavier nucleus. The Hamiltonian of diatomic paramagnetic molecule including the \( T, P \)- odd nuclear moment effects is given by [13, 73]:
\[
H = W_M d_s S \cdot n + W_Q \frac{Q}{T} I \cdot n - \frac{W_M M}{2I(2I-1)} S T n,
\]
(16)

where \( d_s \) is the electron EDM, \( Q \) is the nuclear Schiff moment, \( M \) is the nuclear MQM, \( S \) is the electron spin, \( n \) is the symmetry axis of the molecule, \( T \) is the second rank tensor operator characterised by the nuclear spins \( T_{ij} = I_I I_j + I_j I_i - \frac{4}{9} \delta_{ij} I(I+1) \) and \( W_d, W_Q \) and \( W_M \) are fundamental parameters for each interaction which are dependent on the particular molecule. We have omitted the \( P,-T \)- odd electron-nucleon interaction terms which are presented e.g. in reviews [11, 13]. These parameters \( W_d, W_Q \) and \( W_M \) are related to the electronic molecular structure of the state. For each molecule there is an effective field for each fundamental parameter, these effective fields are calculated using many-body methods for electrons close to the heavy nucleus [24]. For the nuclear MQM we are interested only in \( W_M \) which has been calculated for molecules Ybf [75], HfF [76], TaN [52, 53], TaO [54] and ThO [43]. Using these values we present the results for the energy shifts in molecules induced by MQM in terms of \( CP \)- violating parameters \( \theta, d_p \) and \( (d_u - d_d) \) in Table II.

The MQM molecular energy shifts for HfF\( ^+ \), TaN, TaO\( ^+ \) and ThO were calculated in Refs. [40], [52], [54] and [43] respectively. They used the MQM calculated in the spherical basis method outlined in [24] and represent the shifts in fundamental \( T,-P \)- odd parameters as in Table II. Using the Nilsson model, the MQM energy shifts are larger for TaN, TaO\( ^+ \) and ThO molecules by a factor of 2 however for \( ^{177} \)HfF\( ^+ \) the values of the two models are similar. Using the currents limits on the \( CP \)- violating parameters [77] \( |d_p| < 8.6 \times 10^{-25}\) e-cm, \( \theta < 2.4 \times 10^{10} \) and \( d_u - d_d < 6 \times 10^{-27} \) cm the respective MQM energy shifts \( (|W_M M|) \) in \( ^{229} \)ThO are \( < 300 \) \( \mu \)Hz, \( < 250 \) \( \mu \)Hz and \( 340 \) \( \mu \)Hz. The \( ^{232} \)ThO molecule has recently been used to set new limits on the electron EDM with a factor of 12 improvement in accuracy of 80 \( \mu \)Hz [78, 79]. As \( ^{232} \)Th has an even number of nucleons there is no spectroscopic nuclear MQM. Therefore in principle, if a similar experiment is possible with \( ^{229} \)ThO future measurements should improve constraints on nuclear \( CP \)- violating interactions. It is interesting to find the minimal SM prediction for the energy shifts which comes solely from the CKM matrix. Using eqs. (9) and (10), the lower limit on the CKM nucleon EDM \( d_n^{\text{CKM}} = -d_n^{\text{CKM}} \approx 1 \times 10^{-32}\) e-cm [80] and the strengths of the \( CP \)- odd pion nucleon couplings in the CKM model \( g_{00} \approx -1.6 \times 10^{-16}, g_{03} \approx -1.8 \times 10^{-16} \) and \( g_{04} \approx 4.7 \times 10^{-20} \) [81] we find \( |M_p^{\text{CKM}}| \approx |M_n^{0,\text{CKM}}| \approx 4.5 \times 10^{-44}\) e-cm\(^2\). This corresponds to an energy shift of \( |W_M M| \approx 1 \) nHz in \( ^{229} \)ThO due to the MQM which is 4 orders of magnitude lower than the current accuracy. Results for other molecules in Table II are similar.

### Table II. Frequency shifts due to the MQM interaction with the electron magnetic field of the molecules. We present the energy shifts in terms of the \( CP \)- violating parameters of interest. These are the strong \( CP \)- term in QCD \( \theta \), the permanent EDM of the proton \( d_p \) and the difference of quark chromo-EDMs \( (d_u - d_d) \).

| Molecule | \( I \) | State | \( |W_M| \) (\( \mu \)Hz/ e-cm\(^2\)) | \( |W_M M| \) (\( \mu \)Hz) |
|----------|------|------|-------------------------------|------------------|
| \(^{177} \)Ybf \( ^+ \) | \( \frac{3}{2}\) | \( ^2 \)\( \Sigma_{1/2} \) | 2.1 \( \times 10^5 \) | 37 |
| \(^{177} \)HfF \( ^+ \) | \( \frac{3}{2}\) | \( ^3 \)\( \Delta \) | 0.494 \( \times 10^5 \) | 21 |
| \(^{179} \)HfF \( ^+ \) | \( \frac{3}{2}\) | \( ^3 \)\( \Delta \) | 0.494 \( \times 10^5 \) | 25 |
| \(^{181} \)TaN \( ^+ \) | \( \frac{3}{2}\) | \( ^3 \)\( \Delta \) | 1.08 \( \times 10^5 \) | 51 |
| \(^{181} \)TaO \( ^+ \) | \( \frac{3}{2}\) | \( ^3 \)\( \Delta \) | 0.45 \( \times 10^5 \) | 21 |
| \(^{229} \)ThO \( ^+ \) | \( \frac{3}{2}\) | \( ^3 \)\( \Delta \) | 1.10 \( \times 10^5 \) | 35 |
| \(^{229} \)ThF \( ^+ \) | \( \frac{3}{2}\) | \( ^3 \)\( \Delta \) | 0.88 \( \times 10^5 \) | 28 |

III. CONCLUSION

In this work we present a novel method for calculating the nuclear MQM for any nuclei that satisfy the angular momentum condition \( I_I \geq 3/2 \). In heavy nuclei with large quadrupole deformations there is an enhancement of the nuclear MQM due to the collective effect of partially filled nucleon shells and therefore these nuclei present an opportunity for detecting and measuring \( T,-P \)- violating effects in the hadronic sector. The molecular systems which have been used to study the electron EDM with promising results are also
excellent candidates for measuring the nuclear MQM and chromo-EDMs ($\delta_n - \delta_d$).

This work is supported in part by the Australian Research Council, the Gutenberg Fellowship and by the National Science Foundation under grant No. NSF PHY11-25915. V.F. is grateful to Kavli Institute for Theoretical Physics at Santa Barbara for hospitality.

[1] A. D. Sakharov, JETP 5, 24 (1967).
[2] M. Kobayashi and T. Maskawa, Prog. Theo. Phys. 49, 2 (1973).
[3] G. R. Farrar and M. E. Shaposhnikov, Phys. Rev. Lett. 70, 2833 (1993).
[4] P. Huet and E. Sather, Phys. Rev. D 51, 379 (1995).
[5] M. Pospelov and A. Ritz, Ann. Phys. 318, 119 (2005).
[6] L. Canetti, M. Drewes, and M. E. Shaposhnikov, New J. Phys. 14, 095012 (2012).
[7] V. V. Flambaum and E. Shuryak, Phys. Rev. D 82, 073019 (2010).
[8] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. 13, 138 (1964).
[9] Abe, K. and et. al. Belle Collab., Phys. Rev. Lett 87, 091802 (2001).
[10] LHCB Collab., Phys. Rev. Lett. 110, 221601 (2013).
[11] M. S. Safronova, D. Budker, D. DeMille, D. F. J. Kimball, A. Derevianko, and C. W. Clark, Rev. Mod. Phys. 90, 25008 (2017).
[12] T. Chupp, P. Fierlinger, M. Ramsey-Musolf, and J. Singh, (2018), arXiv:1710.02504 [hep-ph].
[13] J. S. M. Ginges and V. V. Flambaum, Phys. Rep. 397, 63 (2004).
[14] I. B. Khriplovich, Parity NonConservation In Atomic Phenomena, 1st ed. (Gordon and Breach Science Publishers, 1981).
[15] O. P. Sushkov, V. V. Flambaum, and I. B. Khriplovich, JETP 60, 873 (1984).
[16] B. M. Roberts, V. A. Dzuba, and V. V. Flambaum, Ann. Rev. Nucl. Part. Sci. 65, 63 (2015).
[17] I. B. Khriplovich and S. K. Lamoreaux, CP Violation Without Strangeness, 1st ed. (Berlin: Springer, 1997).
[18] C.-P. Liu, J. de Vries, E. Mereghetti, R. G. E. Timmermans, and U. van Klock, Phys. Lett. B 713, 447 (2012).
[19] L. I. Schiff, Phys. Rev. 132, 2195 (1963).
[20] V. V. Flambaum, D. W. Murray, and S. R. Orton, Phys. Rev. C 56, 2820 (1997).
[21] V. V. Flambaum, Phys. Lett. B 320, 211 (1994).
[22] V. V. Flambaum, I. B. Khriplovich, and O. P. Sushkov, Nucl. Phys. A 449, 750 (1986).
[23] V. V. Flambaum and A. Kozlov, Phys. Rev. C 85, 068502 (2012).
[24] V. V. Flambaum, D. DeMille, and M. G. Kozlov, Phys. Rev. Lett. 113, 103003 (2014).
[25] J. J. Hudson, D. M. Kara, I. J. Smallman, B. E. Sauer, M. R. Tarbutt, and E. A. Hinds, Nature 473, 493 (2011).
[26] N. S. Mosyagin, M. G. Kozlov, and A. V. Titov, J. Phys. B 31, L763 (1998).
[27] H. M. Quiney, H. Skaane, and I. P. Grant, J. Phys. B 31, L85 (1998).
[28] F. A. Parpia, J. Phys. B 31, 1409 (1998).
[29] M. G. Kozlov and V. F. Ezhev, Phys. Rev. A 49, 4502 (1994).
[30] M. K. Nayak and R. K. Chaudhuri, Pramana J. Phys. 73, 581 (2009).
[31] T. C. Steimle, T. Ma, and C. Linton, J. Chem. Phys. 127, 234316 (2007).
[32] M. Abe, G. Gopakumar, M. Hada, B. P. Das, H. Tatemaki, and D. Mukherjee, Phys. Rev. A 90, 022501 (2014).
[33] K. C. Cossel, D. N. Gresh, L. C. Sinclair, T. Coffey, L. V. Skripnikov, A. N. Petrov, N. S. Mosyagin, A. V. Titov, R. W. Field, E. R. Meyer, E. A. Cornell, and J. Ye, Chem. Phys. Lett. 546, 1 (2012).
[34] H. Loh, K. C. Cossel, M. C. Grau, K. K. Ni, E. R. Meyer, J. L. Bohn, J. Ye, and E. A. Cornell, Science 342 (2013).
[35] A. N. Petrov, N. S. Mosyagin, T. A. Issaev, and A. V. Titov, Phys. Rev. A 76, 030501(R) (2007).
[36] T. Fleig and M. K. Nayak, Phys. Rev. A 88, 032514 (2013).
[37] E. R. Meyer, J. L. Bohn, and M. P. Deskevich, Phys. Rev. A 73, 062108 (2006).
[38] L. V. Skripnikov, N. S. Mosyagin, A. N. Petrov, and A. V. Titov, JETP Lett. 88, 578 (2008).
[39] A. Le, T. C. Steimle, L. Skripnikov, and A. V. Titov, J. Chem. Phys. 138, 124313 (2013).
[40] L. V. Skripnikov, J. Chem. Phys. 147, 021101 (2017).
[41] W. B. Cairncross, D. N. Gresh, M. Grau, K. C. Cossel, T. S. Roussy, Y. Ni, Y. Zhou, J. Ye, and E. A. Cornell, Phys. Rev. Lett. 119, 153001 (2017).
[42] A. N. Petrov, L. V. Skripnikov, A. V. Titov, N. R. Hutzler, P. W. Hess, B. R. O’Leary, B. Spaun, D. DeMille, G. Gabrielse, and J. M. Doyle, Phys. Rev. A 89, 062505 (2014).
[43] E. R. Meyer and J. L. Bohn, Phys. Rev. A 78, 010502(R) (2008).
[44] L. V. Skripnikov, A. N. Petrov, and A. V. Titov, J. Chem. Phys. 139, 221103 (2013).
[45] L. V. Skripnikov, A. N. Petrov, A. V. Titov, and V. V. Flambaum, Phys. Rev. Lett. 113, 263006 (2014).
[46] L. V. Skripnikov and A. V. Titov, J. Chem. Phys. 142, 024301 (2015).
[47] T. Fleig and M. K. Nayak, J. Mol. Spectrosc. 300, 16 (2014).
[48] M. Denis and T. Fleig, J. Chem. Phys. 145, 214307 (2016).
[49] J. Baron et al., New J. Phys. 19, 073029 (2017).
[50] L. V. Skripnikov and A. V. Titov, Phys. Rev. A 91, 042504 (2015).
[51] M. Denis, M. S. Norby, H. J. A. Jensen, A. S. P. Gomes, M. K. Nayak, S. Knecht, and T. Fleig, New J. Phys.
[52] L. V. Skripnikov, A. N. Petrov, N. S. Mosyagin, A. V. Titov, and V. V. Flambaum, Phys. Rev. A 92, 012521 (2015).
[53] T. Fleig, M. K. Nayak, and M. G. Kozlov, Phys. Rev. A 93, 012505 (2016).
[54] T. Fleig, Phys. Rev. A 95, 022504 (2017).
[55] S. G. Nilsson, Math.-Fys. Medd. Kgl. Danske Vid. Selsk. 29 (1955).
[56] B. R. Mottelson and S. G. Nilsson, Phys. Rev. 99, 1615 (1955).
[57] A. Bohr and B. R. Mottelson, Nuclear Structure: Volume II (W.A. Benjamin Inc., 1975).
[58] I. B. Khriplovich, JETP 44, 25 (1976).
[59] B. G. C. Lackenby and V. V. Flambaum, J. Phys. G: Nucl. Part. Phys. 45, 075105 (2018).
[60] N. Yoshinaga, K. Higashiyama, and R. Arai, Prog. Theor. Phys. 124, 1115 (2010).
[61] N. Yoshinaga, K. Higashiyama, R. Arai, and E. Teruya, Phys. Rev. C 89, 045501 (2014).
[62] N. Yamanaka, B. K. Sahoo, N. Yoshinaga, T. Sato, K. Asahi, and B. P. Das, Eur. Phys. J. A 53, 54 (2017).
[63] V. F. Dmitriev, I. B. Khriplovich, and V. B. Telitsin, Phys. Rev. C 50, 2358 (1994).
[64] V. V. Flambaum and O. K. Vorov, Phys. Rev. C 51, 1521 (1995).
[65] R. J. Crewther, P. Di Vecchia, G. Veneziano, and E. Witten, Phys. Lett. B 88, 123 (1979).
[66] M. Pospelov and A. Ritz, Phys. Rev. Lett. 83, 2526 (1999).
[67] C. Alexandrou, M. Constantinou, P. Dimopoulos, R. Frezzotti, K. Hadjijianakou, K. Jansen, C. Kalidonis, B. Kostrewa, G. Koutsou, M. Mangin-Brinet, A. Vaquero Avilés-Casco, and U. Wenger, Phys. Rev. D 95, 114514 (2017).
[68] JLQCD Collab., Phys. Rev. D 98, 054516 (2018).
[69] PNDME Collab., (2018), arXiv:1808.07597 [hep-lat].
[70] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977).
[71] J. de Vries, E. Mereghetti, and A. Walker-Loud, Phys. Rev. C 92, 045201 (2015).
[72] J. Engel, M. J. Ramsey-Musolf, and U. van Kolck, Prog. Part. Nucl. Phys. 71, 21 (2013).
[73] K. Fuyuto, J. Hisano, and N. Nagata, Phys. Rev. D 87, 054018 (2013).
[74] C. Y. Seng, (2018), arXiv:1809.00307 [hep-ph].
[75] M. G. Kozlov and L. N. Labzovskii, J. Phys. B 28, 1933 (1995).
[76] L. V. Skripnikov, A. V. Titov, and V. V. Flambaum, Phys. Rev. A 95, 022512 (2017).
[77] M. D. Swallows, T. H. Loftus, W. C. Griffith, B. R. Heckel, E. N. Fortson, and M. V. Romalis, Phys. Rev. A 87, 012102 (2013).
[78] ACME Collab., Science 343, 269 (2014).
[79] ACME Collab., Nature 562, 355 (2018).
[80] C.-Y. Seng, Phys. Rev. C 91, 025502 (2015).
[81] N. Yamanaka and E. Hiyama, JHEP 2016, 67 (2016).