Predicting outcomes of electric dipole and magnetic moment experiments

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744. WE-Heraeus-Seminar “Towards Storage Ring Electric Dipole Moment Measurements”

Agenda

- EDM and AMM
  - P/T-odd quantities and model requirements
  - Spin equation for Dirac electrons (fermions)
- Dirac electrons versus QED electrons
  - Main hypothesis
- Spin equations with pseudoscalar correction
  - What does it give us?
- Final comments (prediction)

It is the derivations-free summary of our recent papers

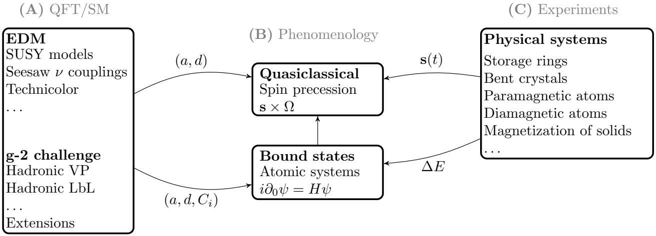
arXiv: 2010.14218

arXiv: 2012.11751

arXiv: 2101.05064 (*Phys.Scr.*)

EDM and AMM ecosystem

(How are QFT predictions connected with measurements?)



- Parts A and C are very active - new extensions, verification, new tests, ...
- Part B is rigidly set - solidly supported by available data so far (except muon g-2)

$$i\frac{\partial \mathbf{s}}{\partial t} = \mathbf{s} \times \Omega_{T-BMT} \qquad H = -\frac{eg}{2m}\hat{s}\mathbf{B} + \frac{e(g-1)}{2m}\hat{s}(\mathbf{v} \times \mathbf{E})$$

- Successful matching of precise AMM data supports A-C, g-2 discrepancy questions them

Is the phenomenological part a potentially "blind spot"?

- Until and if g-2/EDM challenge is resolved, every Part A-C must be checked thoroughly

Quantities originated by symmetry violation

(Are we capturing all potential P/T-odd effects?)

CKM matrix SUSY models Higgs models ... $-C_i(\bar{\psi}\gamma^5\psi)\,(\bar{N}N)$ $-C_i(\bar{\psi}\gamma^5\psi)\,(\bar{\phi}\phi)$ ...	$\longrightarrow$	EDM d P/T-odd polarizabilities ... $-C_i(\bar{\psi}\gamma^5\psi)\,(\bar{N}N)$

- Discrete symmetry-violating effects are typically described
  - For "simpler" particles (electron, muon, ...), with $d \neq 0$
  - For composite systems, with $d \neq 0$ and P/T-odd polarizabilities
- P/T-odd polarizabilities mix magnetic and electric contributions
  - Applied electric field generates magnetic and vice versa
- Suggestion that all types (atom, neutron, electron, ...) have nonzero P/T-odd polarizabilities was made in Baryshevsky1999-2004 (Phys.Rev.Lett.)

How this idea can be implemented in consistent way?

- What can be polarizability-like for particles (leveraging analogy)
- How to incorporate it into the existing and very constrained models

Requirements for phenomenological model

(What do we expect from a good model?)

- Self-consistent motion and spin equations
  - BMT-like equation is gauge-invariant and Lorentz-covariant

$$\frac{\mathrm{d}s^\mu}{\mathrm{d}\tau} = \frac{ge}{2m} F^{\mu\nu} s_\nu + \frac{ae}{m} s^\rho F_{\rho\nu} u^\nu u^\mu - 2d\left(\tilde{F}^{\mu\nu} s_\nu + s^\rho \tilde{F}_{\rho\nu} u^\nu u^\mu\right)$$

  - For the laboratory system, Thomas-BMT precession follows as

$$\Omega = \frac{e}{m}\left[\left(a + \frac{1}{\gamma}\right)\mathbf{B} - \frac{a\gamma}{\gamma+1}(\mathbf{v}\cdot\mathbf{B})\,\mathbf{v} - \left(a + \frac{1}{\gamma+1}\right)\mathbf{v}\times\mathbf{E}\right] + 2d\left[\mathbf{E} - \frac{\gamma}{\gamma+1}(\mathbf{v}\cdot\mathbf{E})\,\mathbf{v} + \mathbf{v}\times\mathbf{B}\right]$$

- Applicability conditions (quasiclassical) are in Mane2005
- Tested down to $\Delta a_e < 10^{-12}$, $\Delta a_\mu < 10^{-9}$, and $d_i < d_i^{\text{upper limit}}$

Acceptable model must satisfy strict requirements

- Equations must be gauge-invariant, Lorenz-covariant, free of artifacts
- Corrections to AMM must not exceed the existing uncertainty limits

Spin equation for Dirac particles

(How do we arrive at spin motion equations?)

There exist three ways to derive BMT-like equation (with a and d terms)

	Heuristic	Foldy–Wouthuysen	WKB
Starting point		Dirac Hamiltonian	Dirac Equation
		$i\frac{\partial\psi}{\partial t} = H_D\psi$	$(i\partial\!\!\!/ - eA\!\!\!/ - \dots)\psi = 0$
Assumptions	Linear in s_μ and $F_{\mu\nu}$	$\psi = U_{FW}\psi'$	$q_0 = i\bar{\psi}\gamma^5\psi = 0$
	$\mathbf{s}\times\mathbf{B}$ at rest	$\begin{pmatrix}\phi\\ \chi\end{pmatrix} \to \begin{pmatrix}\phi'\\ 0\end{pmatrix}$	$\begin{pmatrix}\phi\\ \chi\end{pmatrix} \to \begin{pmatrix}\phi'\\ 0\end{pmatrix}_{\text{rest}}$
Result	Same BMT or Thomas-BMT like equation in weak-field limit		

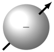
Derivations lead to the same results based on

- Single first-order Dirac equation, simplified representation $\beta = \frac{q_0}{\bar{\psi}\psi} = 0$
- T(CP)-symmetry violating effects are in d-term

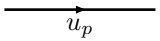
Dirac electrons versus QED electrons

(How can we extend the existing model non-controversially?)

Dirac electron (bare)

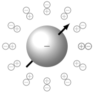


$u = \binom{\phi}{0}$

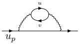


no. Dirac equations $= 1$

QFT electron (dressed)



$M_2(\ldots, v) \quad v = \binom{0}{\chi}$



no. Dirac equations $\to \infty$

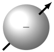
- The idea to take account of polarization cloud in phenomenological models is not new (Baryshevsky2000-2012, Baym2016)
- Specific realization and motivation were missing - now we have g-2 challenge
- g-2 challenge might or might not require new phenomenological model (open question)

Assuming that an extension to existing phenomenology is required, how can it be done in non-controversial way?

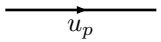
Main Hypothesis

(How to take account of polarization cloud non-controversially?)

Dirac electron (bare)



$u_p = \binom{\phi}{0}$



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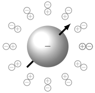
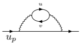
QFT electron (dressed)



$M_2(\ldots, v) \quad v = \binom{0}{\chi}$



no. Dirac equations $\to \infty$

- Main difference - bare fermion is missing antifermion component
- A fermion is described by 16 bilinears (densities, current, spin, spin tensor), free fermion by 15 since $(i\bar{\psi}\gamma^5\psi)_{\text{free}} = 0$ (there is only one remaining unused parameter!)
- Allowing nonzero $\beta \neq 0$ adds antifermion component to free fermions
- Hypothesis - free fermion has a tiny nonzero pseudoscalar density $(i\bar{\psi}\gamma^5\psi)_{\text{free}} \neq 0$

Extended model captures additional potential T/CP-violating effects

- β is P- and T-odd, gauge-invariant and experimentally observable
- Effectively, a fermion is described with two Dirac equations (squared Dirac with $\beta \neq 0$)

$T(CP)$-symmetry violation and spin equations

(Can we extend well proven model in noncontroversial way?)

Step-by-step derivations for $\beta \neq 0$ are in arXiv: 2012.11751 and 2101.05064

- BMT-like equation now includes effective moments ($2a' = g' - 2$)

$$\frac{\mathrm{d}s^\mu}{\mathrm{d}\tau} = \frac{g' e}{2m} F^{\mu\nu} s_\nu + \frac{a' e}{m} s^\rho F_{\rho\nu} u^\nu u^\mu - 2d' \left(\tilde{F}^{\mu\nu} s_\nu + s^\rho \tilde{F}_{\rho\nu} u^\nu u^\mu \right)$$

- where they are approximately given by ($|\beta| \ll 1$ and $|d| m/e \ll |a|$)

$$a' = a + d\,\frac{2m}{e}\,\beta\,, \qquad\qquad d' = d - a\,\frac{e}{2m}\,\beta$$

- For the laboratory system, modified Thomas-BMT precession is

$$\Omega = \frac{e}{m}\left[\left(a' + \frac{1}{\gamma}\right)\mathbf{B} - \frac{a'\gamma}{\gamma+1}(\mathbf{v}\cdot\mathbf{B})\,\mathbf{v} - \left(a' + \frac{1}{\gamma+1}\right)\mathbf{v}\times\mathbf{E}\right] + 2d'\left[\mathbf{E} - \frac{\gamma}{\gamma+1}(\mathbf{v}\cdot\mathbf{E})\,\mathbf{v} + \mathbf{v}\times\mathbf{B}\right]$$

New model retains functional form of original T-BMT equation where

- Nonzero pseudoscalar density mixes moments; could be guessed heuristically
- Corrections to $g-2$ are of second degree of smallness
- $T(CP)$-symmetry violation effects are given by means of d and β

Predictions

(What does it give us?)

The model predicts that these moments are measured

$$a^{\text{exp}} = a + d\,\frac{2m}{e}\,\beta\,, \qquad d^{\text{exp}} = d - a\,\frac{e}{2m}\,\beta$$

Several scenarios are possible

	d^{exp}	$\Delta a = a^{\text{exp}} - a$	β	Comment
1	0	0	0	No NP
2	d^{exp}	0	0	NP, conventional model
3	d^{exp}	$\neq 0$	$\neq 0$	NP, mixed case, new model
4	0	$\lvert a^{\text{exp}}\rvert > \lvert a\rvert$	$\neq 0$	NP, screened EDM, new model

New model extends number of experimental outcomes positive for NP

- Case 4 is most restrictive, $|a^{\text{exp}}| > |a|$ independently of signs of β, a, or d
- Inability to bring Δa to zero signals nonzero β
- Case 3 potentially favors heaviest fermions since screening scales $\sim m^{-2}$

Final comments I

(What might be the most probable scenario?)

Factoring in the observed trends and overall view of combined EDM/AMM tests

- No EDM observed across the board while significantly reducing upper bounds (neutron EDM by 5 orders of magnitude, electron by 9 orders, and so on)
- Unresolved muon $g-2$ discrepancy (since 2005), might be same for electron (2021). Similar $g-2$ disconnects might exist for other fermions (but lacking theoretical accuracy)
- Hence EDM no observability and $g-2$ discrepancy might be universal phenomenon and two sides of the same coin

Cannot reject any positive case (2-4) yet

- However EDMs are getting quite small in case 2

Final comments II

(What might be the most probable scenario?)

Our prediction (taken to extreme) sees this trend emerging

- Increasing accuracy of EDM/AMM tests will continue yielding null EDMs, while AMM tests will continue confirming the gap against corresponding theoretical evaluations
- The physical reason is the conversion of nonspherical electric moment into the additional magnetic anomaly by means of β (P/T-odd polarizability)

$$d^{\mathrm{exp}} = d - a\,\frac{e}{2m}\,\beta \approx 0 \qquad \rightarrow \qquad a^{\mathrm{exp}} = a(1+\beta^2)$$

- Storage rings are great opportunity for combined EDM/AMM tests
- Higher order corrections might partially un-screen EDM (work in progress)

Finally: must continue with combined EDM and AMM experiments - three scenarios (cases 2-4) are positive for NP