Electric Dipole Moments of Fundamental Particles

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Electric dipole moment (EDM) experiments are at the forefront of search for physics beyond the standard model. The next generation searches promise to improve by several orders of magnitude the current EDM sensitivity levels.

1. Theoretical Motivation

The search for electric dipole moments (EDM) of fundamental particles started approximately fifty years with Ramsey’s search for a neutron EDM. Even though the techniques have been improved and the sensitivities has reached an unprecedented small level no EDM of a fundamental particle has been observed so far. Non-the-less EDM experiments have put strict limits and constrained the parameter space of models beyond the standard model.

The permanent EDM of fundamental particles would violate both time (T) and parity (P) symmetries: an EDM vector would have to be along the spin vector since there is no other defining vector. Phenomenologically any component in any other direction would average out to zero due to the particle’s spin rotation. The interaction Hamiltonian is given by

$$H_E = -d_E \vec{S} \cdot \vec{E}$$  \hspace{1cm} (1)

where $\vec{S}$, $\vec{E}$ denote the spin vector and the electric field vector respectively. The symbol $d_E$ denotes the electric dipole moment strength. Under parity the axial vector $\vec{S}$ does not change sign whereas $\vec{E}$ does. The opposite happens when the time operator is applied, i.e. the vector $\vec{S}$ does change sign whereas $\vec{E}$ does not. In both cases the interaction Hamiltonian changes sign meaning that if $d_E$ is not zero the Hamiltonian would violate both parity and time reversal symmetries.

This is not the case for the magnetic dipole moments since the interaction Hamiltonian in that case is

$$H_M = -d_M \vec{S} \cdot \vec{B}$$  \hspace{1cm} (2)

Under parity both axial vectors $\vec{S}$ and $\vec{B}$ do not change sign whereas under time reversal they both do. Therefore the interaction Hamiltonian does not suffer a sign change and the parity and time reversal symmetries are respected by the magnetic dipole moments.

If EDMs are not allowed by the above symmetry considerations how then there can be induced EDMs, permanent EDMs of polar molecules, etc? The cases of the induced electric dipole moments are allowed since the EDM vector in those cases is proportional to the electric field vector $d_E = \alpha \vec{E}$ and not the spin vector. The interaction Hamiltonian becomes proportional to the square of the E-field and both symmetries, parity and time reversal, are respected. As far as the polar molecules that exhibit “permanent” electric dipole moments they also respect the above symmetries with their quantum mechanical treatment described by Penny [1].

Through the fundamental CPT conservation theorem, T-violation also means CP-violation. A general overview of the importance of CP-violation is written by J. Ellis in the CERN Courier [2] in October of 1999. Sakharov [3] in his 1967 paper pointed out that CP-violation is one of three requirements needed to explain the matter antimatter asymmetry of our universe.

The first requirement was that the proton should be unstable. The second was that there
would be interactions violating C and CP and the third condition was that the universe would undergo a phase of extremely rapid expansion.

1.1. EDMs are Excellent Probes of Physics Beyond the SM

In the standard model (SM) there is only one CP-violating phase (KM) which results to an EDM only after third order loops with virtual $W^±$s and quarks are considered. This results to a natural suppression of the SM EDMs by several orders of magnitude. In contrary, physics models beyond the SM allow for much higher values of EDM, see Figure 1 (from ref. [4]), many times in the experimentally accessible region. For example super-symmetry (SUSY) has more than 40 CP-violating phases and the first order EDM calculation does not cancel as it does in the SM. Other models with similar EDM predictions include models with left-right symmetry, multi Higgs scenarios, etc.

2. Experimental Approach

The spin of a particle with an electric dipole moment $d$ precesses in the presence of an electric field. Since the $d$ value is presumably very small (non observed so far) the spin precession signal would be of very small frequency. A magnetic field is used to serve as a carrier signal by pressing the spin due to its magnetic dipole moment. The spin precession rate is given by

$$\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \quad (3)$$

For a spin 1/2 particle $\frac{d\vec{S}}{dt} = \frac{1}{2} \hbar \omega$, where $\omega$ is called the Larmor frequency. In case of an atomic or molecular electron the magnetic field causes a spectral split in the line and the transitional frequency is called Zeeman splitting. One then compares the Larmor/Zeeman frequencies with the E-field vector flipped back and forth: $\hbar(\omega_1 - \omega_2) = 4dE$. In order to reduce the effects of a drifting magnetic field another particle with an expected small EDM sensitivity value is used as a B-field sensor, also known as co-magnetometer.

Supersymmetry generates EDM naturally; Standard Model does not.

Figure 1. In many models, like SUSY, EDMs are non-zero at the one loop level but the SM EDMs are zero at that level. This is so because there is only one CP-violating phase in the SM, and the $W$ boson only couples to left handed particles. In contrast SUSY has more than 40 CP-violating phases, plus sfermions couple to both left and right-handed particles making unnatural the first order cancellation of EDMs. The figure is copied from reference [4].

2.1. Schiff theorem

The experimental approach was influenced by the Ramsey-Purcell-Schiff theorem [5] which states that for point like, charged particles in equilibrium the net electric field they feel averages to zero. In an external electric field the electronic and nuclear charge of an atom would be re-arranged so that the net (average) electric field on all charged particles would be zero, known as “Schiff’s theorem”. Otherwise they would be continuously accelerated. However as was pointed out by Schiff himself and others [6] not all the forces need to be electrical. The electric field can thus be compensated by magnetic, nuclear, etc. forces and even though the total force is zero there is a net electrical force. This results to a non-zero EDM value for the atom or molecule, called “Schiff’s moment”. Sandars further pointed out that in paramagnetic atoms, there is even an en-
hancement of the average electric field the unpaired electron feels in the presence of an external electric field when relativistic effects are taken into account. The reason for the enhancement is due to the very strong electric fields present near the nucleus. The enhancement factor calculated by Sandars [7] is given by

\[ R = \frac{d_a}{d_e} \approx 10^Z \alpha^2 \]

which for large size atoms can be quite a big factor. \( d_a \), is the atomic electric dipole moment and \( d_e \) that of the electron, \( Z \) is the atomic number and \( \alpha \) the fine structure constant. As an example \( R = 115 \) for the Cs atom and \( R = -585 \) for the Tl atom. Sandars work is the basis so far of all the searches for the electron EDM with atoms or molecules.

2.2. Electron EDM

The current experimental electron EDM limit comes from the Berkeley atomic thallium experiment [8]. It is a small scale, “table top”, experiment where Tl atomic beams are led to go through high electric field regions where there is also a magnetic field present. The Larmor frequency is probed with the standard technique of Ramsey separated fields. Motional magnetic fields of the form \( \mathbf{u} \times \mathbf{B} \), with \( \mathbf{u} \) the atomic beam velocity can be a problem in the presence of small misalignments between the \( \mathbf{E} \) and \( \mathbf{B} \) fields. Another potential systematic error is Berry’s phase and some 8 atomic beams with fluxes over \( 10^{18} \) atoms/sec are used to study the systematic effects using many different correlations. The final result of this experiment is \( |d_e| < 1.6 \times 10^{-27} \text{e} \cdot \text{cm} \) (90% C.L.) [8].

2.3. \(^{199}\text{Hg} \) EDM

The mercury EDM experiment is a “table top” effort at Washington state. [10] They look for a shift in the Zeeman frequency in \(^{199}\text{Hg} \) vapor when the E-field is flipped. The mercury vapor is contained in two adjacent vapor cells where the B and E-fields are parallel. The mercury atoms are polarized by circularly polarized laser light of 254 nm modulated (chopped) at the Larmor frequency. A plane (linearly) polarized laser goes through the cell with the mercury vapor where its plane of polarization rotates according to \( \alpha \approx \mathbf{k} \cdot \mathbf{S} \), with \( \mathbf{k} \) the laser propagation vector and \( \mathbf{S} \) the mercury spin, precessing in the horizontal plane at the Larmor frequency, Figure 2. The statistical accuracy of the method is given by

\[ \delta d = \frac{\hbar}{2E\sqrt{N\tau T}} \]

with \( N \) the number of observed photons, \( E \) the electric field strength, \( \tau \) the spin coherence time and \( T \) the total running time of the experiment. The result is \( |d(\text{^{199}Hg})| < 2.1 \times 10^{-27} \text{e} \cdot \text{cm}, (90\% \text{ C.L.}) [10,4] \).
2.5. Prospects

The next generation experiments, are very promising. On the electron a Yale group under D. DeMille made great progress towards using the metastable molecule of PbO* [9]. The group promises an order of magnitude improvement over the current electron limits within a year and another two orders within the next couple of years. S. Lamoreaux has described [13] a solid state technique where the alignment of the atoms in an electric field would align the spins of the atoms and hence it will lead to the magnetization of the sample. This work is well underway at Los Alamos and it promises to reach $10^{-31}$ e·cm or so within a year or two.

![Figure 3. A schematic diagram of the new neutron EDM experiment experiment of Los Alamos. From reference [13].](image)

On the $^{199}$Hg EDM experiment the Washington group has upgraded the experiment, using four cells, the middle two with opposite electric field and the outer two without any electric field present, in order to monitor the magnetic field fluctuations. An improvement of the order of a factor of four is expected by the group when the experiment is done [4].

The Los Alamos neutron EDM effort uses a very high flux of UCN in superfluid $^4$He. Polarized $^3$He is used to probe the neutron spin precession and as a co-magnetometer. The neutron spin precession is probed by the reaction $^3$He + n → t + p the cross section of which is $< 10^2$ b when their spins are parallel and $\approx 10^4$ b when the spins are opposite. Since the gyromagnetic ratio of $^3$He is within 10% the same as the neutron’s the beat signal frequency is 10 times smaller making it 10 times less sensitive to the magnetic field fluctuations. One of the challenges of the experiment is to avoid even a single spark of the 50 kV/cm electric field since that would surely destroy the SQUID system that is needed to monitor the magnetic field.

![Figure 4. A schematic diagram of the new neutron EDM experiment experiment of Los Alamos. From reference [13].](image)

Clearly the competition between the different EDM experiments is intense (it’s a horse race!) and their prospects of finding a non-zero EDM value are very good.

3. EDM in Storage Rings

Other than using either atoms, molecules or neutrons in the search of EDM it is possible to look for EDM of charged particles in storage rings. The Schiff theorem does not hold here since the particles are in an accelerated frame. One, in principle, does not need an electric field present in the lab frame to probe the EDM of the particle. Even in a purely magnetic field storage ring there is an electric field in the particle’s rest frame due
to Lorentz transformation: \( \vec{E} = \gamma (\vec{u} \times \vec{B}) \), with \( \vec{u} \) the particle’s velocity. Since the average \( \vec{B} \) vector is vertical the induced electric field is radial and the spin, due to an EDM, will precess in the vertical direction.

Comparing to the traditional methods of searching for EDM one notices that the electric and magnetic fields that the particle feels in its own rest frame are strongly coupled and one cannot significantly change their values independently. Furthermore there is no way of flipping the sign of the electric field while keeping the magnetic field sign the same. More over, since the electric and magnetic fields in the particle’s rest frame are not parallel but orthogonal to each other, the EDM effect on the particle is to precess its spin in a plane orthogonal to the g-2 precession plane.[14] As a result the EDM effect is a small disturbance on the regular g-2 precession.

Non-the-less this method of searching for EDM was used by the CERN as well as the BNL g-2 experiments.[14,15] A new, dedicated method of searching for “EDM in Storage Rings” has been developed [16,17] in which the g-2 precession vector is cancelled by a radial electric field. A major development in this method was the realization that the EDM signal changes between clockwise (CW) and counter-clockwise (CCW) storage.[16] This method has regained the advantages of a traditional EDM search and works best for charged particles with small anomalous magnetic moment values like the muon and deuteron promising several orders of magnitude sensitivity improvement over current methods.

3.1. Muon EDM
It also happens that the same particles provide new opportunities: The muon is the only second generation particle that can be probed at a very sensitive level. Furthermore it is the only system that can be probed in its elementary form and not as part of another system. Therefore its interpretation would be more straightforward than any other system.

The muon anomalous magnetic moment, \( a_\mu \), and electric dipole moment, \( d_\mu \), can be related to each other [18–20] as the real and imaginary parts of a more general dipole moment, D.

\[
a_\mu \frac{e}{2m_\mu} = \Re D \\
d_\mu = \Im D, \tag{5,6}
\]

where \( \Re D \) and \( \Im D \) are correspondingly the real and imaginary parts of D. Writing \( D^{NP} = |D^{NP}|e^{i\phi_{CP}} \) as the contribution of “New Physics” to D provides a measure of the relative probing power of \( a_\mu \) and \( d_\mu \) experiments. If “New Physics” gives rise to a discrepancy between experiment and Standard Model expectations, \( a^{NP}_\mu = a^{exp}_\mu - a^{SM}_\mu \), then one expects that same “New Physics” to induce a muon EDM given by

\[
d_\mu \simeq 3 \times 10^{-22} \left( \frac{a^{NP}_\mu}{3 \times 10^{-9}} \right) \tan \phi_{CP} \text{ e} \cdot \text{cm}. \tag{7}
\]

Of course, the values of \( a^{NP}_\mu \) and \( \tan \phi_{CP} \) are model dependent.

For the current situation (assuming the \( e^+e^- \) data for the hadronic contribution) [21–23]

\[
a^{exp}_\mu - a^{SM}_\mu \simeq 3(1) \times 10^{-9} \tag{8}
\]

one expects

\[
d_\mu \simeq 3 \times 10^{-22} \tan \phi_{CP} \text{ e} \cdot \text{cm}. \tag{9}
\]

So, exploring down to \( d_\mu \sim 10^{-24} \text{ e} \cdot \text{cm} \) would probe

\[
\tan \phi_{CP} \geq 3(1) \times 10^{-3}. \tag{10}
\]

Within specific models, predictions for the muon EDM vary widely [24–28]. In particular, the left-right supersymmetric model with the seesaw mechanism of reference [29] predicts \( d_\mu \) as large as \( 5 \times 10^{-23} \text{ e} \cdot \text{cm} \), 50 times larger than the sensitivity of the proposed experiment. The prediction for the EDM of the electron is of order \( 10^{-28} \text{ e} \cdot \text{cm} \), 10 times smaller than the present experimental limit [8].

3.2. Muon EDM Experimental Approach
In the presence of both electric and magnetic fields, oriented orthogonally to the muon velocity and to each other, the angular frequency of muon
spin precession relative to the momentum is given by
\[ \omega = \frac{e}{m} \left\{ a\vec{B} + \left( \frac{1}{\gamma^2 - 1} - a \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left( \frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right) \right\} \]
where \( a = (g - 2)/2 \) and \( \eta \) is the EDM in units of \( \frac{e\hbar}{mc} \).

The magnetic and electric dipole moments are given by \( \mu = \frac{e\hbar}{2m_e} \) and \( d = \frac{\eta e\hbar}{2m_e} \), respectively. \( \eta \) plays a role for the EDM corresponding to the g factor for the magnetic dipole moment. The muon EDM couples to the external fields through the \( \eta(\vec{E} + c\vec{\beta} \times \vec{B}) \) term. The external B-field couples to the EDM because it produces an E-field in the rest frame of the muon. In fact, for the parameters envisioned in the present proposal, the motional E-field from the \( \vec{\beta} \times \vec{B} \) term is far larger than that due to the applied E-field. The EDM value is given in terms of the dimensionless parameter \( \eta \) by
\[ d_\mu = \frac{\eta e\hbar}{2m_e c} \simeq \eta \times 4.7 \times 10^{-14} \text{ e} \cdot \text{cm}. \] (12)
for the muon.

Assuming that the EDM is 0, from Eq. (11), it is clear that at the “magic” \( \gamma \), (\( \gamma = 29.3 \))
\[ \frac{1}{\gamma^2 - 1} - a = 0, \] (13)
and the muon spin precession depends only on g-2 and the average B-field. The anomalous precession frequency, due to the magnetic moment, is measured by observing the time spectrum of muon decay electrons. In the muon rest frame, the highest energy electrons are emitted preferentially along the muon spin vector. As the spin vector precesses relative to the momentum vector, the number of high energy electrons observed in the lab frame is modulated at the precession frequency.

For the dedicated EDM experiment proposed in this document we will follow a new approach: Use muons with much lower energies, and employ a radial electric field which cancels the g-2 precession. The electric field in the lab required to cancel the g-2 precession is
\[ E \simeq a B c \beta \gamma^2, \] (14)
which we will assume here equal to about 2 MV/m. Using Eqs. (11, 14) the spin precession angular frequency is given by:
\[ \omega = \frac{e\eta}{m/2} \left( \frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right), \] (15)
i.e. the g-2 precession is canceled and only the EDM is left to act on the spin. The torque in the center of mass is given by
\[ \vec{d}\tilde{S}/dt' = \vec{d} \times \vec{E}'. \] (16)
which in terms of laboratory quantities is
\[ \vec{d}\tilde{S}/dt = \vec{d} \times (\vec{E} + c\vec{\beta} \times \vec{B}). \] (17)
As previously mentioned, for realizable values for the applied E-field, the “motional” E-field from the \( \vec{\beta} \times \vec{B} \) term is much larger than that from the \( \vec{E} \) term.

Thus the muon spin direction will be “frozen” relative to the muon momentum if the EDM is zero. In the presence of a non-zero EDM, the radial E-field in the muon’s rest frame will cause rotation of the spin in a vertical plane about an axis parallel to the radial direction. As the spin acquires a vertical component, the decay positron
momenta also acquire a vertical component, resulting in an up-down asymmetry in the number, 
\[ R_N = \frac{N_{\text{up}} - N_{\text{down}}}{N_{\text{up}} + N_{\text{down}}} \] of electrons which grows linearly with time, see Figs. (5,6). Together with other improvements, which will significantly reduce many systematic errors, this new experimental approach will improve our sensitivity to a muon EDM by five orders of magnitude.

Figure 6. MC simulation of the muon EDM signal, 
\[ R = \frac{N_{\text{up}} - N_{\text{down}}}{N_{\text{up}} + N_{\text{down}}} \] versus time.

3.3. Deuteron EDM

The situation with the deuteron is similar to the muon with the difference that the deuteron does not decay and can, in principle, be stored for a long time. The limitation to the EDM measurement is the spin coherence time \( \tau_p \), i.e. the time the deuteron beam is stored without losing its polarization. Another difference is that it is much heavier than the muon, its spin is 1, and its anomalous magnetic moment is \( a = -0.143 \). The fact that its spin is 1 it means that it has both a vector and a tensor polarization which can complicate its detection. The fact that its anomalous magnetic moment is negative means that the electric field direction needs to be radially outward, in opposite direction than the muon case.

The statistical accuracy of the deuteron experiment is estimated to be

\[ \sigma_d \approx \frac{6.5}{\sqrt{\tau_p E_R (1 + a \gamma^2)} AP \sqrt{N_c} T_{Tot}} \]  

where \( \tau_p \approx 10 \text{s} \) is the spin coherence time of the stored beam, \( A \approx 0.3 \) is the left/right asymmetry observed by the polarimeter [30] when the deuteron beam is completely vertically polarized, \( P \approx 0.55 \) the polarization of the beam, \( N_c \approx 10^{11} \text{ d/cycle} \) the total number of stored particles per cycle, \( f \approx 0.01 \) the useful event rate fraction, and \( T_{Tot} \approx 10^7 \text{s} \) the total running time of the experiment, and \( E_R \approx 3.5 \text{ MV/m} \) the radial electric field strength. Then \( \sigma_d \approx 5 \times 10^{-28} \text{e} \cdot \text{cm} \) but it is estimated [31] that due to the presence of the tensor polarization there will be a total loss in running time due to the need to run for systematic error determinations of about a factor of 16, or a factor of 4 in statistical error, i.e. \( \sigma_d \approx 2 \times 10^{-27} \text{e} \cdot \text{cm} \).

The current status of the deuteron EDM effort is that the collaboration is considering writing a proposal to do this experiment with the above sensitivity. There are three candidate places to host it: Brookhaven National Lab, Groningen University-KVI in The Netherlands, and Indiana University Cyclotron Facility.

A deuteron EDM at the \( 10^{-27} \text{e} \cdot \text{cm} \) level constitutes an improvement in the sensitivity of the T-odd nuclear forces by a factor of 100 over the \(^{199}\text{Hg} \) EDM experiment, a factor of 100,000 improvement over the current proton EDM limit and a factor of 50-100 over the current neutron EDM experiment [32].

REFERENCES

1. W.G. Penny, Phil. Mag. 11, 602 (1931).
2. www.cerncourier.com/main/article/39/8/16, October 1999.
3. “Violation of CP Invariance, C Asymmetry, and Baryon Asymmetry of the Universe”, A.D. Sakharov, 1967. Reprinted in Kolb, E.W. (ed.), Turner, M.S. (ed):
The early universe 371-373, and in Lindley, D. (ed.) et al.: Cosmology and particle physics 106-109, and in Sov. Phys. Usp. 34 (1991) 392-393 [Usp. Fiz. Nauk 161 (1991) No. 5 61-64]. Published in Pisma Zh.Eksp.Teor.Fiz.5:32-35,1967, JETP Lett.5:24-27,1967, Sov.Phys.Usp.34:392-393,1991, Usp.Fiz.Nauk 161:61-64,1991 (No.5).

4. Fortson’s talk at Lepton-Moments, Cape Cod, 9-12 June 2003, [http://g2pc1.bu.edu/leptonmom/program.html].

5. L.I. Schiff, Phys. Rev. 132, 2194 (1963).

6. V.F. Dmitriev, I.B. Khriplovich, and V.B. Telitzin, Phys. Rev. C50, 2358 (1994) and references therein.

7. P.G.H. Sandars, Phys. Lett. 14, 194 (1965); Phys. Lett. 22, 290 (1966).

8. B.C. Regan et al., “New Limit on the Electron Electric Dipole Moment”, Phys. Rev. Lett. 88, 071805 (2002).

9. D. Kawall et al., hep-ex/0309079

10. M.V. Romalis et al., Phys. Rev. Lett. 86, 2505 (2001).

11. M.V. Romalis, ICAP 2003 proceedings.

12. V. der Grinten, talk at Lepton-Moments, Cape Cod, 9-12 June 2003.

13. S. Lamoreaux, talk at Lepton-Moments, Cape Cod, 9-12 June 2003.

14. J. Bailey, K. Borer, F. Combley, H. Drumm, F.J.M. Farley, J.H. Field, W. Flegel, P.M. Hatterley, F. Krienen, F. Lange, E. Picasso, and W. von Rüden, J. Phys. G4, 345 (1978); J. Bailey et al., Nucl. Phys. B150, 1 (1979).

15. G. W. Bennett et al. [Muon g-2 Collaboration], “Measurement of the positive muon anomalous magnetic moment to 0.7 ppm,” Phys. Rev. Lett. 89, 101804 (2002) [hep-ex/0208001].

16. F.J.M. Farley et al., hep-ex/0307006, submitted to PRL.

17. Y.K. Semertzidis et al., hep-ph/0012087, Proceedings of HIMUS99 Workshop, Tsukuba, Japan (1999).

18. W. Marciano, HIMUS99 Workshop, Tsukuba, Japan (1999).

19. M. Graesser and S. Thomas, “Supersymmetric relations among electromagnetic dipole operators,” hep-ph/0104254.

20. J. L. Feng, K. T. Matchev and Y. Shadmi, “Theoretical expectations for the muon’s electric dipole moment,” hep-ph/0107182.

21. G. W. Bennett et al. [Muon g-2 Collaboration], “Measurement of the negative muon anomalous magnetic moment to 0.7 ppm,” submitted Phys. Rev. Lett. (2004).

22. M. Davier, S. Eidelman, A. Höcker, Z. Zhang Aug 2003, Eur. Phys. J. C 31, 503 (2003).

23. S. Ghozzi and F. Jegerlehner, hep-ph/0310181, Phys. Lett. B, in Press, (2004).

24. A. Pilaftsis, Nucl. Phys. B644, 263 (2002).

25. K.S. Babu, B. Dutta, and R.N. Mohapatra, Phys. Rev. Lett. 85, 5064 (2000).

26. J.L. Feng, K.T. Matchev, and Yael Shadmi, Nucl. Phys. B613, 366 (2001).

27. J.R. Ellis et al., Phys. Lett. B528, 86 (2002).

28. A. Romanino and A. Strumia, Nucl. Phys. B622, 73 (2002); B. Dutta and R.N. Mohapatra, Phys. Rev. D68, 113008 (2003); A. Bartl et al., Phys. Rev. D68 053005 (2003); T. Feng et al., Phys. Rev. D68, 016004 (2003); I. Masina, Nucl. Phys. B671, 432 (2003); G.C. Branco and D. Delepine, Phys. Lett. B567, 207 (2003); I. Masina, Nucl. Phys. B661 365 (2003).

29. K. S. Babu, B. Dutta and R. N. Mohapatra, “Enhanced electric dipole moment of the muon in the presence of large neutrino mixing,” Phys. Rev. Lett. 85, 5064 (2000) [hep-ph/0006329].

30. L.M.C. Dutton, et al., Phys. Lett. 16, 331 (1965); L.M.C. Dutton, et al., Phys. Lett. B25, 245 (1967); K.S. Chadha and V.S. Varma, Phys. Rev. C13, 715 (1976); L.M.C. Dutton, et al., Nucl. Phys. A343, 356 (1980); B. Bonin, et al., NIM A288, 389 (1990); V.P. Ladygin, et al., NIM A404, 129 (1998); J. Arvieux, et al., NIM A273, 48 (1988).

31. Y.K. Semertzidis et al., hep-ex/0308063, CIPANP proceedings (2003).

32. V.V. Flambaum, I.B. Khriplovich, and O.P. Sushkov, Phys. Lett. B162 (1985) 213; I.B. Khriplovich and R.A. Korkin, Nucl. Phys. A665 (2000) 365; M. Pospelov et al., private communication (2003).