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Searches for Permanent Electric Dipole Moments

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1   Introduction

The Standard Model (SM) of particle physics provides a theoretical framework which allows to describe all observations in particle physics to date. Even those recent observations in neutrino physics which strongly indicate the existence of neutrino oscillations can be accommodated with small modification. However, contrary to this the great success of the SM there remains a number of most intriguing questions in modern physics to which the SM can not provide further clues about the underlying physical processes, although the facts are can be described often to very high accuracy. Among those puzzling issue are the existence of exactly three generations of fundamental particles, i.e. quarks and leptons, and the hierarchy of the masses of these fundamental fermions. In addition, the electro-weak SM has a rather large number of some 27 free parameters, which all need to be extracted from experiments [1].

In modern physics - and in particular in the SM - symmetries play an important and central role. We know that global symmetries relate to conservation laws and local symmetries give forces [2]. Within the SM the physical origin of the observed breaking of discrete symmetries in weak interactions, e.g. of parity (P), of time reversal (T) and of combined charge conjugation and parity (CP), remains unrevealed, although the experimental findings can be well described.

In order to gain deeper insights into the not well understood aspects of fundamental physics, a number of speculative models beyond the present standard theory have been proposed. Those include such which involve Left-Right symmetry, fundamental fermion compositeness, new particles, leptoquarks, supersymmetry, supergravity, technicolor and many more. Interesting candidates for an all encompassing quantum field theory are string or membrane (M) theories which among other features may include supersymmetry in their low energy limit. Independent of their mathematical elegance and partial appeal all of these speculative theories will remain without status in physics unless secure experimental evidence for them being reality can be gained in future. Experimental searches for predicted unique features of those models - such as breaking of discrete symmetries - are therefore essential to steer the development

of theory towards a better and deeper understanding of fundamental laws in nature. Such experiments must be carried out not only at high energy accelerators, but also in complementary approaches at lower energies. Typically the low energy experiments in this context fall into the realm of atomic physics and of high precision measurements. Searches for permanent Electric Dipole Moments (EDMs), are an important subset of such low energy precision particle physics experiments.

2   Discrete Symmetries

A permanent electric dipole moment (EDM) of any fundamental particle or quantum system violates both parity (P) and time reversal (T) symmetries [3] and if one assumes unbroken combined CPT symmetry, it also violates CP. The violation of P is well established in physics and its accurate description has contributed significantly to the credibility of the SM. The observation of neutral currents together with the observation of parity non-conservation in atoms were important to verify the validity of the SM. The fact that physics over several orders of magnitude in momentum transfer - from atoms to highest energy scattering - yields the same electro-weak parameters may be viewed as one of the biggest successes in physics to date. However, at the level of highest precision electro-weak experiments questions arose, which ultimately may call for a refinement.

2.1   Parity

The running of the weak mixing angle $sin^2\Theta_W$ appears not to be in good agreement with observations [4]. If the value of $sin^2\Theta_W$ is fixed at the Z^0-pole, deep inelastic electron scattering at several GeV appears to yield a considerably higher value. A new round of experiments is being started with the Q_{weak} experiment [6] at the Jefferson Laboratory in the USA. For atomic parity violation [5] in principle higher experimental accuracy will be possible from experiments using Fr isotopes [7, 8] or single Ba or Ra ions in radio frequency traps [9]. Experiments with Fr atoms in magneto-optical traps were started at INFN Legnaro, Italy, and at Stony Brook, USA. Pioneering work on single Ba ions has been started at the University of Washington, Seattle, USA, and based on this experience a Ra ion experiment has been started at KVI, Groningen, The Netherlands. The full exploitation of the advantage of larger weak effects in these heavy atom systems (compared to Cs) due to their high power dependence on the nuclear charge, will require improved atomic wave function calculations, as the observation of weak effects is always through an interference of weak and electromagnetic effects. [10]

Lines of attack towards an EDM

Free Particles

neutron
muon
deuteron
bare nuclei ?
…

Hg   Xe
Tl
Cs   Rb
Ra   Rn
…

Atoms

→ particle EDM
→ unique information
→ new insights
→ new techniques
→ challenging
    technology

Electric
Dipole
Moment

goal:
new source of CP

→ nuclear EDM
→ electron EDM
→ enhancements
→ challenging
    technology

→ electron EDM
→ strong enhancements
→ new techniques
→ poor spectroscopic
    data available

YbF
PbO
PbF
HfF⁺,ThF⁺
…

garnets
$(Gd_3Ga_5O_{12})$
$(Gd_3Fe_2Fe_3O_{12})$
lq. He ?

→ electron EDM
→ strong enhancements
→ systematics ??
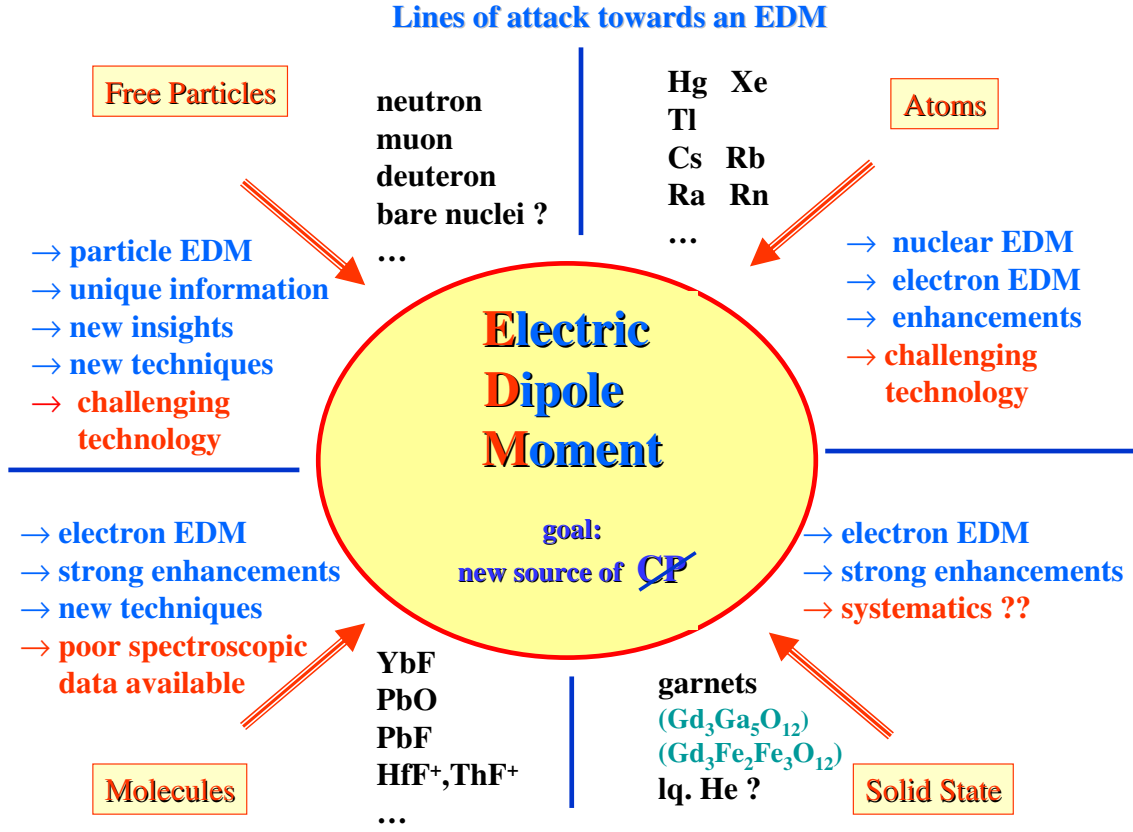
Molecules

Solid State

Figure 1: The experimental searches for an EDM follow a number of significantly different lines.

2.2   Time Reversal and CP

CP violation as observed first in the neutral Kaon decays can be described with a single phase factor in the Cabbibo-Kobayashi-Maskawa formalism [11]. Because of its possible relation to the observed matter-antimatter asymmetry in the universe, CP violation has attracted a lot of attention. [1] CP violation as described in the SM is however not sufficient to explain the excess of baryons. This provides a strong motivation to search for yet unknown sources CP symmetry violation. It is in particular a major driving force behind theEDM searches going on at present.

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[1]A. Sakharov [12] has suggested that the observed dominance of matter could be explained via CP-violation in the early universe in a state of thermal non-equilibrium and with baryon number violating processes. We note here that the existence of additional sources of CP-Violation is not a necessary condition to explain the matter-antimatter asymmetry. Other viable routes could lead through CPT violation and there without the need of thermal non-equilibrium [13].

3

EDMs have been searched for in various systems with different sensitivities (Table 1). [3, 14–18]. Distinctively different precision experiments to search for a EDM are under way in many different system.A large number of ideas for significant improvements have been made public. Still, the electron and the neutron get the largest attention of experimental groups, although besides tradition there is little which singles out these systems. Nevertheless, there is a large number of efforts in the USA and in Europe using different approaches which all have unique promising features.

In composed systems, i.e. molecules, atoms or nuclei, fundamental particle dipole moments of constituents can be significantly enhanced [14]. For the electron significant enhancement factors are planned to be exploited such as those associated with the large internal electric fields in polar molecules [19].

The physical systems investigated fall in six groups (see Fig. 1), i.e.

(i) 'point' particles (e, μ, τ),

(ii) nucleons (n, p),

(iii) nuclei (^{2}H, ^{223}Fr, ...),

(iv) atoms (Hg, Xe, Tl, Cs, Rn, Ra,...) and

(v) molecules (TlF, YbF, PbO,HfF$^+$, ThF$^+$ ...),

where each investigated object has its own particular advantages. Among the methods employed are

(i) Classical approaches using optical spectroscopy of atoms and molecules in cells, as well as atomic and molecular beams or with contained cold neutrons,

(ii) Modern atomic physics techniques such as atomic and ion traps, fountains and interference techniques;

(iii) Innovative approaches involving radioactive species, storage rings, particles in condensed matter (garnets, superfluid helium) , nuclear spin masers [20], and a few more.

From an unbiased point of view there is no preferred system to search for an EDM. In fact, many different systems need to be examined in order to be able to extract unambiguous information on the nature of EDMs, because depending on the underlying yet unknown processes different systems have in general quite significantly different susceptibility to acquire an EDM through a particular mechanism (see Figure 2). As a first approach an EDM may be considered an "intrinsic property" of an elementary particle as we know them, because the mechanism causing an EDM is not accessible at present. However, an EDM can also arise from CP-odd forces between the constituents under observation, e.g. between nucleons in nuclei or between nuclei and

4

electrons. Such EDMs could be much higher [31] than such expected for elementary particles originating within the presently popular New Physics models.

Particle	Limit/Measurement [e cm]	Reference	SM limit [factor to go]	possible New Physics [factor to go]
e	$< 1.6 \times 10^{-27}$	[21]	10^{11}	≤ 1
μ	$< 2.8 \times 10^{-19}$	[22]	10^{8}	≤ 200
τ	$(-2.2 < d_\tau < 4.5) \times 10^{-17}$	[23]	10^{7}	≤ 1700
n	$< 2.9 \times 10^{-26}$	[24]	10^{4}	≤ 60
p	$(-3.7 \pm 6.3) \times 10^{-23}$	[25]	10^{7}	$\leq 10^{5}$
Λ^0	$(-3.0 \pm 7.4) \times 10^{-17}$	[26]	10^{11}	10^{9}
$\nu_{e,\mu}$	$< 2 \times 10^{-21}$	[27]		
ν_τ	$< 5.2 \times 10^{-17}$	[28]		
Hg-atom	$< 2.1 \times 10^{-28}$	[29]	$\leq 10^{5}$	various

Table 1: Some actual limits on EDMs and the improvement factors necessary in experiments to reach SM predictions. For electrons, neutrons and muons the region where speculative models have predicted a finite value for an EDM can be reached with presently proposed experiments in the near future. There is a number of new ongoing activities, e.g. in neutral and charged molecules or radioactive atoms, which have no reported limit yet. However, they are similarly promising.

3   Some New Developments in the Field of EDM Searches

The highly active field of EDM searches has very recently seen a plurality of novel ideas. Theoretical work has made very clear that one needs a number of measurements in various systems, in order to identify underlying mechanisms of CP-Violation and EDM generation, once the existence of an EDM has been proven. On the experimental side, novel ideas led to new activities in systems not investigated so far. Among those are in particular radioactive atoms and charged particles. The latter had been excluded by the community for several decades, because of a misinterpretation of the role of the Lorentz force, which only recently could be convincingly cleared up [14,30].

3.1   Radioactive Systems

New facilities around the world make more short-lived radioactive isotopes available for experiments. Of particular interest for EDM searches is the Ra atom. This atom has has as a unique feature in heavy atoms rather close lying states of opposite
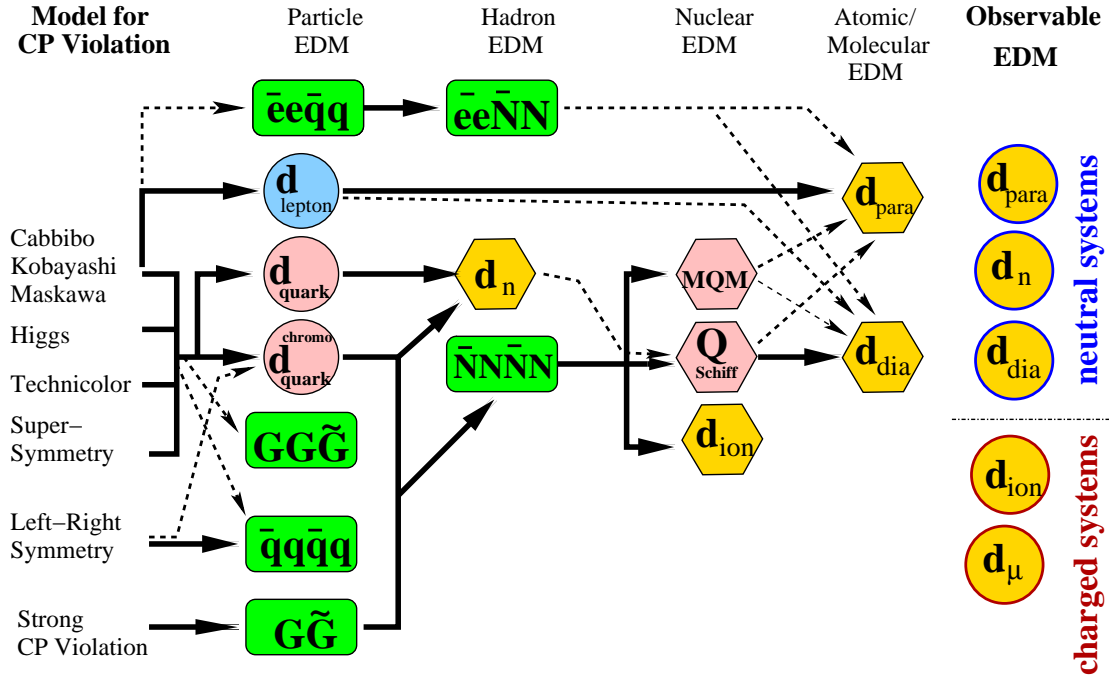
Figure 2: A variety of theoretical speculative models exists in which an EDM could be induced through different mechanisms or a combination of them into fundamental particles and composed systems for which an EDM would be experimentally accessible.

parity. This accidental almost degeneracy of the $7s7p^3P_1$ and $7s6d^3D_2$ states has led to the prediction of a significant enhancement for an electron EDM [32] - much higher than for any other atomic system. An additional advantage of Ra arises from the fact, that for many of its isotopes their nuclei fall are within in a region where (dynamic) octupole deformation occurs, which also enhances the effect of a nucleon EDM substantially, i.e. by some two orders of magnitude [33]. From a technical point of view the Ra atomic levels of interest for an experiment are well accessible spectroscopically and the isotopes can be produced in sufficient quantities in nuclear reactions. The advantage of an accelerator based Ra experiment is apparent, because nuclear EDMs are only possible nuclei with spin and all Ra isotopes with no-vanishing nuclear spin are relatively short-lived [34]. Recently most significant progress towards a Radium EDM experiment has been reported from the Argonne National Laboratory, USA, where successfully a small number of some 10 Ra atoms from an atomic beam source could be stored in a magneto-optical trap (MOT) [35]. Plans were reported to search for a ground state end hence nuclear EDM using a far off resonance optical trap. Activities towards the excited state EDM of the Ra atoms are under way at

KVI , Groningen, The Netherlands [34, 36, 37].

The generic statistical sensitivity of an EDM experiment is given by

$$\delta d = \frac{\hbar}{P\varepsilon T\sqrt{N\tau}E},\tag{1}$$

where P is the polarization, ε the efficiency, T the measurement time, N the flux of particles, τ the spin coherence time and E the applied electric field. With typical values achievable in most experiments ($P \approx 1, \varepsilon \approx 1, N = 10^6/s, \tau \approx 1s, E = 10^5 V/cm$) one gets $\delta d \approx 7 \cdot 10^{-29} e\,cm$ in a day ($T = 10^5 s$). Therefore statistics is not expected to be a serious problem even with exotic and radioactive systems. However, one should note that systematic effects must be expected the more severe limitations and therefore they need to be in the center of the attention.

3.2   Searches for EDMs in charged Particles

A very novel idea was introduced recently for measuring an EDM of charged particles directly. For such experiments the high motional electric field is exploited, which charged particles at relativistic speed experience in a magnetic storage ring. In such a setup the Schiff theorem can be circumvented (which had excluded charged particles from experiments due to the Lorentz force acceleration), because of the non-trivial geometry of the problem [14]. With an additional radial electric field in the storage region the spin precession due to the magnetic moment anomaly can be compensated, if the effective magnetic anomaly a_{eff} is small, i.e. $a_{eff} << 1$ [38].

The method was first considered for muons. For longitudinally polarized muons injected into the ring an EDM would express itself as a spin rotation out of the orbital plane. This can be observed as a time dependent (to first order linear in time) change of the above/below the plane of orbit counting rate ratio. For the possible muon beams at the future J-PARC facility in Japan a sensitivity of 10^{-24} e cm is expected [30, 39]. Other than for most other EDM searches, in such an experiment the possible muon flux is a major limitation. For models with nonlinear mass scaling of EDM's such a muon EDM experiment would already be more sensitive to some certain new physics models than the present limit on the electron EDM [40]. For certain Left-Right symmetric models a value of d_μ up to 5×10^{-23} e cm would be possible. An experiment carried out at a more intense muon source could provide a significantly more sensitive probe to CP violation in the second generation of particles without strangeness. [2]

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[2]A New Physics (non-SM) contribution a_μ^{NP} to the muon magnetic anomaly and a muon EDM d_μ are real and imaginary part of a single complex quantity related through $d_\mu = 3 \times 10^{-22} \times (a_\mu^{NP}/(3 \times 10^{-9})) \times \tan\Phi_{CP} e\,cm$ with a yet unknown CP violating phase Φ_{CP}. The problems around the SM model value for a_μ [41], which cause difficulties for the interpretation of the recent muon g-2 experiment in terms of limits for or indications of New Physics, make a search for d_μ attractive as an important alternative, as the SM value is negligible for the foreseeable future.

The deuteron is the simplest known nucleus. Here an EDM could arise not only from a proton or a neutron EDM, but also from CP-odd nuclear forces [42]. It was shown very recently [31] that the deuteron can be in certain scenarios significantly more sensitive than the neutron . The situation is evident for the case of quark chromo-EDMs, where the EDMs induced into deuteron and neutron are $d_{\mathcal{D}} = -4.67\,d_d^c + 5.22\,d_u^c$ and $d_n = -0.01\,d_d^c + 0.49\,d_u^c$; i.e. the deutron could have a much higher sensitivity to quark chromo-EDMs arising from the proton-neutron interaction within the deuteron. It should be noted that because of its rather small magnetic anomaly the deuteron is a particularly interesting candidate for a ring EDM experiment and a proposal with a sensitivity of 10^{-27} e cm exists [43]. In this case scattering off a target will be used to observe a spin precession. As possible sites of an experiment the Brookhaven National Laboratory (BNL), and KVI are considered. A further novel approach concerns the search for an electron EDM in charged molecular ions such as HfF$^+$ and ThF$^+$ where the advantage of easy trapping for ions and the strong enhancement factors for electron EDMs in polar molecules are combined [44]. The EDM experiments directly using charged particles are still in the exploratory and feasibility study phase, however, the progress reports are very encouraging.

4   T-violation Searches other than EDMs

There are many more possibilities to find T-violation besides through searches for EDMs. Among the presently ongoing activities certain correlation observables in nuclear β-decays offer excellent opportunities to find new sources of CP violation [16, 17, 45, 46]. In β-neutrino correlations the 'D'-coefficient [45] (for spin polarized nuclei) offer a high potential to observe new interactions in a region of potential New Physics which is less accessible by EDM searches. However, the 'R'-coefficient [45] (observation of β-particle polarization) would explore the same areas as present EDM searches or β-decay asymmetry measurements. Such experiments are underway at a number of laboratories worldwide [46].

5   Conclusions

There is a large field of searches for EDMs on a variety of systems. They all are well motivated and have unique and robust discovery potentials. Novel ideas have emerged in the recent past to use yet not studied systems and new experimental approaches, which have emerged in the recent past offer excellent opportunities to complement the more traditional experimental approaches on neutron-, atom- and electron-EDMs. Any successful search in the future will have to be complemented by experiments on other systems in order to pin down eventually the mechanisms leading to the observed

EDMs. The highest predicted values in beyond SM speculative theories are well within reach of presently ongoing and planned experiments.

Bibliography

[1] W.-M. Yao et al., Journal of Physics **G 33**, 1 (2006)

[2] T.D. Lee and C.N. Yang, Phys. Rev. **98**, 1501 (1955)

[3] I.B. Khriplovich and S.K. Lamoreaux, "CP Violation Without Strangeness", Springer, Berlin (1997)

[4] A. Czarnecki and W. Marciano, Int.J.Mod.Phys. **A13**, 2235 (1998)

[5] W.C. Haxton and C.E. Wieman, Ann.Rev.Nucl.Part.Sci. **21**, 261 (2001); see also: J. Sapirstein and K.T. Cheng, physics/0409147 (2004) and refrences therein.

[6] D. Armstrong et al, Eur.Phys.J. **A24S2**, 155 (2005)

[7] S.N. Atutov et al., Hyperfine Interactions **146-147**, 83 (2003)

[8] E. Gomez et al., physics/0412073 (2004)

[9] N. Fortson, in: "Parity Violation in Atoms and Polarized Electron Scattering", B. and M.Bouchiat (eds.), World Scientific, Singapore, p. 244 (1999)

[10] J. Sapirstein and K.T. Cheng, physics/0409147 (2004)

[11] J.W. Cronin, Rev.Mod.Phys. **53**, 373 (1981); M. Neubert, Int.J.Mod. Phys. **A11**, 4173 (1996); O. Long, hep-ex/0412047 (2004)

[12] A. Sakharov,JETP **5**, 32 (1967); M. Trodden, Rev.Mod.Phys. **71**, 1463 (1999)

[13] O. Bertolami et al., Phys.Lett. **B395** 178 (1996)

[14] P.G.H. Sandars, Contemp. Phys. **42**, 97 (2001)

[15] Y. Semertzidis, Proceedings SIGHAD03 Workshop, Pisa, Italy, hep-ex/0401016 (2004)

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[3]This conference review of recent developments in the field of EDM searches draws significantly on earlier write-ups [18, 46].

[16] K. Jungmann et al., in: "NuPECC Long Range Plan 2004", M.N. Harakeh et al. (eds.), (2004)

[17] T. Akesson et al., hep-ph/0609216 (2006)

[18] K. Jungmann, physics/0501154 (2005)

[19] M.G. Kozlov and D. DeMille, Phys.Rev.Lett. **89**, 133001 (2002); D. Kawall et al., Phys.Rev.Lett.**92**, 13307 (2004)

[20] A. Yoshimi et al., Hyperfine Interactions **159**, 401 (2005)

[21] B.C. Regan et. al., Phys. Rev. Lett., **88**, 071805 (2002)

[22] R. McNabb et al., hep-ex/0407008 (2004)

[23] K. Inami et. al., Phys. Lett. B, **551**, 16 (2002)

[24] C.A. Baker et. al., Phys. Rev. Lett, **97**, 131801 (2006)

[25] D. Cho et. al., Phys. Rev. Lett., **63**, 2559 (1989)

[26] L. Pondrom et. al., Phys. Rev. D, **23**, 814 (1981)

[27] F. del Aguila and M. Sher, Phys. Lett. B, **252**, 116 (1990)

[28] R. Escribano and E. Masso, Phys. Lett. B, **395**, 369 (1997)

[29] M. Romalis, W. Griffith and N. Fortson,Phys.Rev.Lett. **86**, 2505 (2001)

[30] F.J.M. Farley et al., Phys. Rev. Lett. **93**, 052001 (2004)

[31] C.P Liu and R.G.E. Timmermans, Phys.Rev.C **70**, 055501(2004); see also: O. Lebedev et al., Phys. Rev. D **70**, 016003 (2004)

[32] V. Dzuba et al., Phys. Rev. A **63**, 062101 (2001)

[33] J. Engel, this volume; J. Engel et al.,Phys. Rev. **C 68**, 025501 (2003)

[34] K. Jungmann, Acta Phys. Pol., **33** 2049 (2002)

[35] J.R. Guest et al., Phys.Rev.Lett. **98** , 093001 (2007)

[36] E. Traykov et al., Nucl.Instrum.Meth. **A572**, 580 (2007); G.P. Berg G.P. Berg et al., Nucl.Instrum.Meth. **A560**, 169 (2006)

[37] L. Willmann et al., physics/0602022 (2006)

[38] I.B. Khriplovich, Phys.Lett. **B444**, 98 (1998)

[39] Y. Semertzidis et al., J-PARC Letter of Intent L22 (2003)

[40] K.S. Babu, B. Dutta and R. Mohapatra, Phys.Rev.Lett. **85** 5064 (2000); B. Dutta and R. Mohapatra, Phys. Rev. **D68** (2003) 113008

[41] G.W. Bennett et al., Phys. Rev. **D 73**, 072003 (2006) G.W. Bennett et al., Phys. Rev. Lett.**92**, 168102 (2004) see also: Phys. Rev. Lett. **89**,101804 (2002) and H.N. Brown et al., Phys.Rev.Lett.**86**, 2227 (2001)

[42] J. Hisano, hep-ph/0410038 (2004)

[43] Y. Semertzidis et al., AIP Conf. Proc. **698**, 200 (2004); see also: Y.F. Orlov et al., Phys.Rev.Lett. **96**, 214802 (2006)

[44] L. Sinclair et al., APS AMO March Meeting 2007, N32.00001 (2007); E. Cornell, at Lepton Moments III International Symposium, Cape Cod (2007)

[45] P. Herczeg, Prog. Part. and Nucl. Phys. **46**, 413 (2001); N. Severijns et al., Rev. Mod. Phys. **78**, 991 (2006)

[46] K. Jungmann, Nucl.Phys.**A751**, 87 (2005) and K. Jungmann, Eur.Phys.J.**A25**, 677 (2005)