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The search for electric dipole moments of light ions in storage rings

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Abstract. The Standard Model (SM) of Particle Physics is not capable of accounting for the apparent matter-antimatter asymmetry of our universe. Physics beyond the SM is required and is searched for by *(i)* employing highest energies (e.g., at LHC), and *(ii)* striving for ultimate precision and sensitivity (e.g., in the search for electric dipole moments (EDMs)). Permanent EDMs of particles violate both time reversal (T) and parity (P) invariance, and are via the CPT-theorem also CP-violating. Finding an EDM would be a strong indication for physics beyond the SM, and reducing upper limits further provides crucial tests for any corresponding theoretical model, e.g., SUSY. Direct searches for proton and deuteron EDMs bear the potential to reach sensitivities beyond 10^{-29} e·cm. For an all-electric proton storage ring, this goal is pursued by the US-based **srEDM** collaboration [1], while the newly founded Jülich-based **JEDI** collaboration [2] is pursuing an approach using a combined electric-magnetic lattice, which shall provide access to the EDMs of protons, deuterons, and ^{3}He ions in the same machine. In addition, JEDI has recently proposed making a direct measurement of the proton and/or deuteron EDM at COSY using resonant techniques involving Wien filters.

1. Introduction

Electric dipole moments (EDMs) are one of the keys to understand the origin of our universe. The universe as we know it has a microscopic net baryon number of about 0.2 baryons per cubic meter, or $\sim 10^{-10}$ of the density of relic photons. In 1967 Andrei Sakharov formulated three conditions for baryogenesis [3]:

(i) Early in the evolution of the universe, the baryon number conservation must have been violated sufficiently strongly.

(ii) The C and CP invariances, and T invariance thereof, must have been violated.

(iii) At the point in time when the baryon number is generated, the evolution of the universe must have been far from thermal equilibrium.

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CP violation in kaon decays is known since 1964, it has been observed in B-decays and in charmed meson decays, and based on the existing data can be described by the CP-violating phase in the Cabibbo-Kobayashi-Maskawa matrix [4] (for a review of recent developments in the charmed sector, see Ref. [5]). CP and P violation entail non-vanishing P and T violating EDMs of elementary particles. Although extremely successful in many aspects, the SM has at least two weaknesses: neutrino oscillations call for extra parameters, and, most importantly, the SM mechanisms fail miserably in the expected baryogenesis rate: the CKM matrix of the SM amounts to the relevant effective coupling $\leq 10^{-20}$ [6], much too feeble to account for the observed baryon density $n_{\rm B}/n_\gamma = (6.19 \pm 0.15) \times 10^{-10}$ [7]. Simultaneously, the SM predicts an exceedingly small electric dipole moment of nucleons $10^{-33}\,\mathrm{e}\cdot\mathrm{cm} < d_n < 10^{-31}\,\mathrm{e}\cdot\mathrm{cm}$, way below the current upper bound for the neutron EDM, $d_n < 2.9 \times 10^{-26}$ e·cm [8], and also beyond the reach of future EDM searches [9]. In the quest for physics beyond the SM one may either follow the high-energy trail or look into new methods, which offer very high precision and sensitivity. Supersymmetry is one of the most attractive extensions of the SM as S. Weinberg emphasized in 1992 [10]: "Endemic in supersymmetric (SUSY) theories are CP violations that go beyond the SM. For this reason it may be that the next exciting thing to come along will be the discovery of a neutron electric dipole moment." The SUSY predictions span typically a range of $10^{-29}\,\mathrm{e}\cdot\mathrm{cm} < d_n < 10^{-24}\,\mathrm{e}\cdot\mathrm{cm}$ and precisely this range is targeted in the new generation of EDM searches [9] discussed here.

There is consensus among theorists that measuring the EDM of the proton, deuteron and helion is as important as that of the neutron. The EDMs could have a non-trivial isospin dependence and $d_d \neq d_p + d_n$, even if the CP-violation comes from the isoscalar QCD θ-term [11]. Furthermore, it was argued some 25 years ago that T-violating nuclear forces could substantially enhance nuclear EDMs [12, 13]. At the moment, there are no significant *directly* determined upper bounds available on d_p or d_d.

Non-vanishing EDMs give rise to a precession of the spin of a particle in an electric field. While ultra-cold electrically neutral atoms and neutrons can conveniently by stored in traps, direct measurements of EDMs of charged particles have hitherto been impossible because the required new class of dedicated, primarily electrostatic storage rings does not yet exist.

An ambitious quest for a measurement of the EDM of the proton with envisioned sensitivity down to $d_p \sim 10^{-29}$ e·cm per year has been proposed at BNL [14]. The principal idea is to store protons with longitudinal polarization in a purely electrostatic ring. The EDM would cause a precession around the radial electric field and thus lead to a build-up of transverse polarization, which could be measured by employing standard polarimetry [15]. The new idea proposed by the srEDM collaboration is to freeze the horizontal spin motion, *i.e.*, the particles' spins point always along the direction of motion, which cancels the $(g-2)$ precession. During the spin coherence time, the observed build-up of a vertical polarization component in the beam would be interpreted in terms of an EDM limit of the orbiting particles [14].

The proposed new method employs radial electric (and magnetic) fields to steer the particle beam in the ring, magnetic or electric quadrupole magnets to form a strong focusing lattice (e.g., FODO), and internal polarimeters to probe the beam polarization as a function of storage time. An RF-cavity and sextupole magnets will be used to prolong the spin coherence time of the beam. For protons, it requires building a storage ring with a highly uniform radial electric field with strength of $\approx 17\,\mathrm{MV/m}$ between field plates about $\approx 2\,\mathrm{cm}$ apart. The bending radius will be $\approx 30\,\mathrm{m}$ (see Table 1). At the so-called magic momentum of $700.740\,\mathrm{MeV}/c$ ($232.792\,\mathrm{MeV}$) the $(g-2)$ precession frequency vanishes.

Related ideas on dedicated storage rings for the proton, deuteron, and helion EDM are pursued at IKP of Forschungszentrum Jülich by the newly founded JEDI collaboration [2], aiming at the determination of direct EDM limits for the proton and other charged particles in a storage ring [16].

Particle	p (GeV/c)	$G = \frac{g-2}{2}$	E (MV/m)	B (T)
Proton	0.701	1.792847	13.977	0.000
Deuteron	1.000	-0.142987	-3.361	0.135
^{3}He	1.211	-4.183963	13.943	-0.042

Table 1. Parameters for the radial electric and the vertical magnetic fields required to freeze the spin in an EDM storage ring of radius $r = 30$ m.

2. Status of EDM searches

The question whether particles possess permanent EDMs has a long-standing history, starting from the first measurement by Smith, Purcell, and Ramsey for the neutron [17] as a signature for parity (P) and time-reversal (T or CP) violation, which, over the last 50 years or so, resulted in ever decreasing upper limits [18]. In Table 2, current and anticipated EDM bounds and sensitivities for nucleons, atoms, and the deuteron are given. It should be noted that the upper bound for the proton EDM as part of a nucleus in an electrically neutral atom, $|d_p| < 7.9 \times 10^{-25}$ e cm, derives from the theoretical reinterpretation of the upper bound for the EDM of ^{199}Hg [19]. The second-to-last column of Table 2 provides a rough measure of the probing power relative to that of the neutron (d_n). At this level, storage ring EDM measurements bear the potential of an order of magnitude higher sensitivity than the currently planned neutron EDM experiments at SNS (Oak Ridge), ILL (Grenoble-France), and PSI (Villigen, Switzerland) [20].

Particle	Current limit	Goal	d_n equivalent	Ref.
Electron	$< 1.85 \times 10^{-27}$	$\approx 10^{-29}$		[21]
Neutron	$< 2.9 \times 10^{-26}$	$\approx 10^{-28}$	10^{-28}	[8]
^{199}Hg	$< 3.1 \times 10^{-29}$	10^{-29}	10^{-26}	[19]
^{129}Xe	$< 6.0 \times 10^{-27}$	$\approx 10^{-30}$ to 10^{-33}	$\approx 10^{-26}$ to 10^{-29}	[22]
Proton	$< 7.9 \times 10^{-25}$	$\approx 10^{-29}$	10^{-29}	[19]
Deuteron		$\approx 10^{-29}$	$\approx 3 \times 10^{-29}$ to 5×10^{-31}	

Table 2. Current EDM limits in units of [e·cm], long-term goals for the neutron, ^{199}Hg, ^{129}Xe, proton, and deuteron are given. Neutron equivalent values indicate the value for the neutron to provide the same physics reach as the indicated system.

3. Direct search for EDMs at COSY

Before jumping into the design and construction of dedicated storage rings, it is imperative to get to first base by performing a direct measurement of proton and/or deuteron EDM at an existing machine such as the cooler synchrotron COSY at Forschungszentrum Jülich. COSY is a world-wide unique facility, which provides essentially everything necessary for EDM searches: polarized beams, spin manipulators and polarimeters. Here we review two ideas for so-called precursor experiments which could be performed at COSY, and which are subject to very modest additions or modifications to the existing machine.

Wien filters, either static or radio-frequency driven, provide large horizontal (radial) electric fields. They exert no Lorentz force on the beam particles, i.e, are EDM *transparent*, because the net electric field in a Wien filter is zero. The interaction of the magnetic dipole moment

(MDM) with the combined direct and motional magnetic fields, however, causes a kick in the spin precession phase. In conjunction with the additional interaction of the EDM in the motional electric field of COSY, this MDM kick rotates the spin around the radial axis and generates a CP-violating horizontal in-plane polarization, which increases linearly with time. Without the Wien filter, the same EDM interaction in the COSY ring causes only a small tilt which does not grow with time. Therefore, such a device would allow one to accumulate during the spin coherence time the coherent build-up of the EDM-generated P and T non-invariant in-plane polarization which can be determined from the up-down asymmetry of the scattering of stored particles on suitable polarimeters (see e.g., Ref. [15]). Unless show stoppers pop up, one could theoretically aim for an upper bound for the proton or deuteron of $d < 10^{-24}$ e·cm, where it should be noted that in particular for the deuteron, such a limit would be as valuable as the existing upper bounds on d_n [12, 13].

The accumulation time of a storage ring EDM experiment is limited by the spin coherence time (SCT). Therefore, it is of prime importance to find ways to make the SCT as long as possible. To this end, a series of investigations is presently carried out at COSY [16, 23, 24].

3.1. Precursor experiments at COSY

In Ref. [25] we have reviewed a number of possible first *direct* measurements of an upper limit for the proton and/or deuteron EDM using a normal magnetic storage ring like COSY. In the subsequent two sections we present numerical estimates for the two most promising ideas. Both ideas are based on the exploitation of spin resonances, i.e., the motion of the particle on the orbit is in sync with its spin motion.

3.1.1. RF Wien filter The RF Wien filter provides a radial electric (E_x) and a vertical magnetic (B_y) field. It is operated on some harmonic K of the spin motion,

$$f_{\rm HV} = (K + G\gamma) f_{\rm rev} \,, \tag{1}$$

where $f_{\rm HV}$ is the frequency of the harmonically excited RF Wien filter and $f_{\rm rev}$ is the orbit frequency. The Wien filter shall avoid the coherent excitation of betatron oscillations in the machine. Imperfections in the alignment and field quality of the Wien filter, and also in the alignment of the magnetic elements in COSY play an important role for the systematics involved. We have started to study their effects, but here we will sketch the basic idea. The calculation is carried out for deuterons injected with vertical polarization, $\vec{P} = (P_x, P_y, P_z) = (0, 1, 0)$. The main parameters are summarized in Table 3.

The accumulation of the polarization components P_x, P_z, and the total in-plane polarization $P_{xz} = \sqrt{P_x^2 + P_z^2}$ as function of time is illustrated in Fig. 1, top panel. Assuming a deuteron EDM of $d = 10^{-22}$ e·cm, the extrapolation of the initial slope of the in-plane polarization to a total accumulation time of $t = 1000$ s under the conditions listed in Table 3 yields a value of $P_{xz} = 0.10$. It should be noted that technically, one can measure P_{xz} down to 10^{-5} to 10^{-6} per year of operation [15].

3.1.2. Static Wien filter on the $G\gamma = 2$ imperfection resonance Instead of using an RF Wien filter to excite the spin resonance, for protons it is also possible to operate COSY on a so-called imperfection resonance, for which the resonance condition is given by $G\gamma = n$, where $n = 2, 3, \ldots$ Imperfection resonances for deuterons are outside the energy range of COSY. In that case and only for protons, the Wien filter can be operated in a static mode and the pattern of accumulation of the polarization components is similar to the one of the RF Wien filter (see Fig. 1, bottom panel). Operating in static mode, larger electric fields are possible compared to the RF Wien filter, for an electric field of 10 MV/m, the extrapolation of the accumulated

	RF Wien filter	Static Wien filter
particle	deuteron	proton
length of element [m]	3	3
assumed EDM limit [e·cm]	10^{-22}	10^{-23}
beam kinetic energy [MeV]	250	108.412
$\gamma \cdot G$	-0.162	2.000
electric field E_x [MV/m]	1	10
magnetic field B_y [T]	7.089×10^{-3}	7.526×10^{-2}
Extrapolated in-plane polarization P_{xz} to $t = 1000$ s	0.10	0.06

Table 3. Parameters used to evaluate the magnitude of the CP-violating in-plane polarization components P_{xz} in the two Wien filter scenarios with the device operated in RF and static mode.

in-plane polarization component after $t = 1000$ s yields $P_{xz} = 0.06$. The operation of a machine on an imperfection resonance requires to reduce the strength of this resonance by making the closed orbit close to perfect, and by avoiding alignment errors of the magnetic elements.

4. Conclusion

Direct mesurements of proton and deuteron EDMs do not yet exist. When COSY is supplemented with an RF Wien filter, the CP violating in-plane polarization component of the deuteron, accumulated for a time interval of 1000 s, could be as large as $P_{xz} = 0.10$, corresponding to an upper bound of $d_d = 10^{-22}$ e·cm. For protons, an option to use a static Wien filter on the imperfection $G\gamma = 2$ resonance, where larger electric fields are possible, a proton EDM limit of $d_p = 10^{-23}$ e·cm corresponds to an in-plane polarization of $P_{xz} = 0.06$.

Regarding the systematics of such experiments, we have presently touched only the tip of the iceberg in a very crude analytic approach and much more scrutiny is required. Specifically, one badly needs spin tracking tools capable of handling with controlled precision up to $\sim 10^{11}$ turns in a realistically modeled machine. With all reservations, the Wien filter experiments at COSY look promising. We especially emphasize again here the importance of in-situ studies at COSY using very slow RF magnetic Wien filters to study systematic effects.

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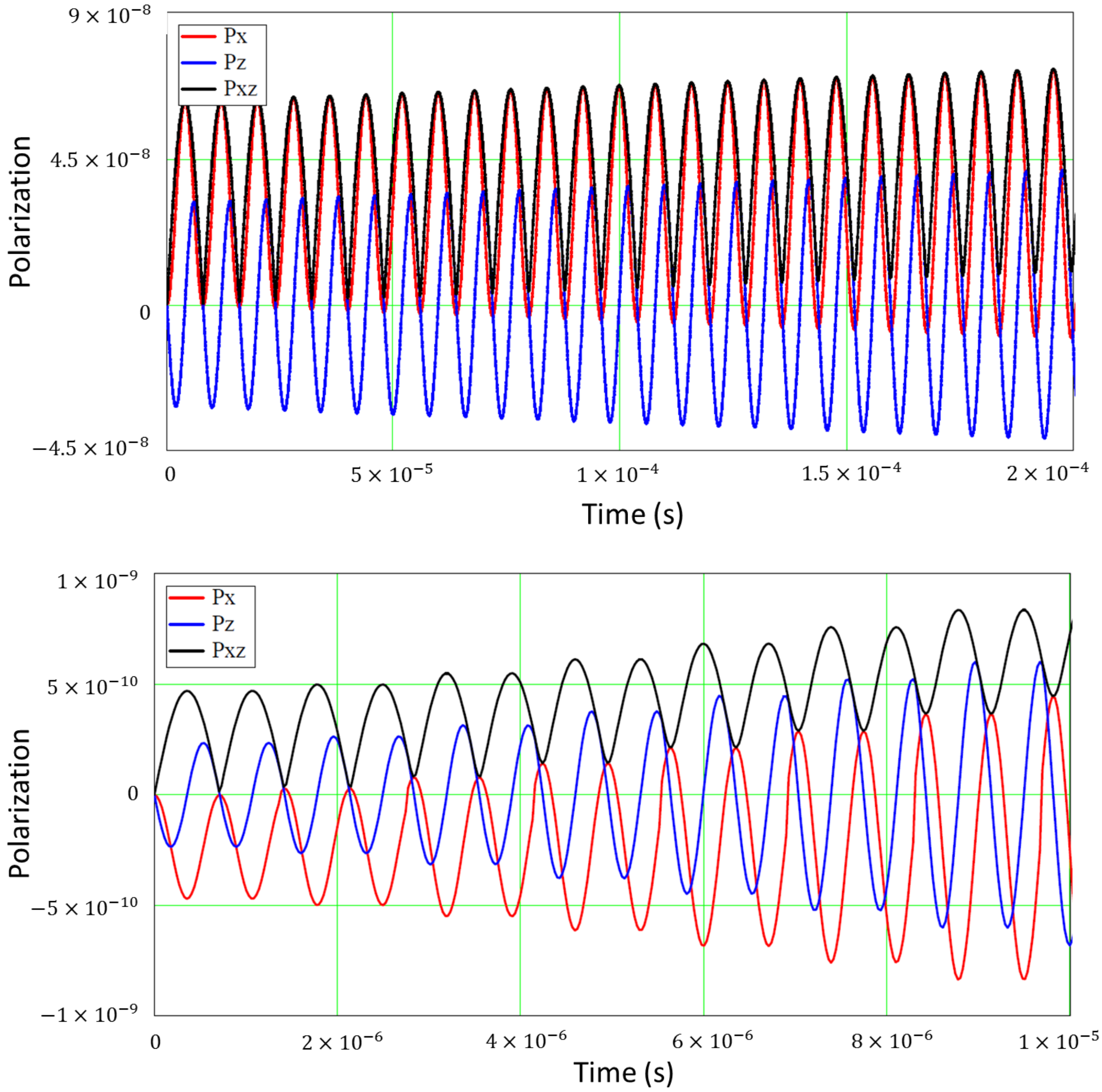

Figure 1. Top panel: Accumulation of the in-plane polarization component P_{xz} (black line) when an *RF Wien* filter is operated for deuterons at a beam energy of $T = 250$ MeV. **Bottom panel:** Accumulation of the in-plane polarization component for protons P_{xz} (black line) when a *static Wien filter* is operated on the $G\gamma = 2$ imperfection resonance ($T = 108.412$ MeV). Other conditions for both cases are listed in Table 3.

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