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Precision Tests of Discrete Symmetries at Low Energies

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Low energy precision measurements provide for precise testing of the Standard Model, e.g. in searches for violations of the discrete symmetries charge conjugation (C), parity (P) and time reversal (T) as well as their combinations CP and CPT. We focus here on new experiments concerning atomic parity violation (APV) and searches for a permanent electric dipole moment (EDM) in atoms. In particular, we address precision APV experiments on Ba$^+$ and Ra$^+$ single ions that will enable the extraction of the Weinberg angle at lowest presently accessible momentum transfer. They are expected to contribute towards searches for new particles such as dark Z-bosons. We also review experimental programmes in which an EDM is searched for and we compare them in a common framework. We describe latest EDM searches in heavy effective two-electron atoms such as Xe and Hg. We also indicate possible future prospects of searches for a permanent EDM of the electron using molecules with large enhancement factors.

KEYWORDS: precision measurements, atomic parity violation, permanent electric dipole moments

1. Introduction

The Standard Model can be considered the best theory in modern in physics. It describes all confirmed observations up to date. However, this powerful model must be considered incomplete, because many observations lack a deeper explanation beyond description. Among the open questions are the number of three particle generations, the fundamental particle masses, the origin of known fundamental symmetry violations such as parity and time reversal as well as the apparent asymmetry between matter and antimatter in the universe [1]. For important conservation laws such as lepton or baryon numbers we do not know the associated symmetry. In this context precision experiments with antiprotons [2], muons [3] or neutrons [4] are very advanced examples of accelerator or reactor based experiments at low energies, which aim to provide data and new observations towards resolving the open puzzles. Precise experiments on atomic parity violation [5] or searches for electric dipole moments on fundamental particles [6] are typically carried out in small scale laboratory experiments. Such approaches are complemented by searches for CPT or Lorentz invariance violations [7] which cover the full range of experimentally accessible energies.

In this article we concentrate on a few selected examples of low energy small laboratory projects which concern measurements of discrete symmetries and searches for their violation. In particular, every measurement of APV, which is conducted in order to determine a precise value of the electroweak mixing angle (i.e. $\sin^2\Theta_W$), also establishes a search for hints of new fundamental particles beyond the Standard Model; searches for time reversal violation as it could be signaled through permanent electric dipole moments (EDMs) on fundamental systems could provide for an ansatz to explain, e.g., the matter-antimatter puzzle.

2.   Atomic Parity Violation

As a result of a long and tedious search trajectory the definitive observation of APV in Cs [8] has been a crucial landmark on the road towards the acceptance of the Standard Model as an all encompassing theory for particle physics. Such experiments have culminated in the precise measurement of the weak charge at low momentum transfer in a Cs atomic beam [9], which provides for extraction of the weak mixing (Weinberg) angle to sub-% accuracy. In addition, in this very experiment also for the first time a nuclear anapole moment could be observed. At present several projects are ongoing worldwide which aim towards improving further on these results [5].

Weak interaction effects in atoms and ions scale with Z^3, where Z is the nuclear charge in the atomic system, or even stronger [10]. Therefore heavy atoms are typically preferred for experiments. However, presently only for a few systems such as alkali atoms or alkali-like ions atomic theory provides for calculations to sufficient, i.e. sub-%, accuracy of the relevant quantities, and in particular of the weak charge. Unfortunately in such atoms the weak effects are rather small, typically of relative order 10^{-9} of the electromagnetic interaction. Atomic or molecular systems with rather large parity violating effects, such as in Yb atoms [11] or in SrF [12] molecules, can be very well exploited for measuring, e.g., anapole moments. In these cases differences between isotopes can be utilized and atomic or molecular theory are required with rather moderate precision. The extraction of $\sin^2\Theta_W$ requires, however, highest possible accuracy in atomic theory calculations. Such are possible for the heavier atomic and ionic systems Cs, Fr, Ba^+ and Ra^+ [13].

At the Van Swinderen Institute of the University of Groningen in The Netherlands a project is ongoing which aims to measure $\sin^2\Theta_W$ from atomic parity violation in a single heavy alkali earth ion. For Ba^+ the APV effects are 2 times larger than in atomic Cs and in Ra^+ they are 50 times larger. We set up, characterize and debug the experiment with Ba^+. Thereby we prepare an enhanced experiment with Ra^+, where all isotopes are radioactive.The Weinberg angle can be extracted from precise light shift measurement in the forbidden $6s\,^2S_{1/2}$-$5d\,^2D_{3/2}$ transition in Ba^+ (see Fig. 1) and $7s\,^2S_{1/2}$-$6d\,^2D_{3/2}$ transition in Ra^+, respectively. For this a single ion is stored in a Paul radio frequency ion trap where it needs to be localized to within a fraction of an optical wavelength [14]. In preparation of the parity measurement available spectroscopy data on Ra^+ has been critically compiled [15], the atomic theory on the heavy alkaline earth atoms is being refined [13], measurements of atomic transition frequencies and isotope shifts [16] and atomic state lifetimes [17] have been conducted in order to test the accuracy of atomic theory on which the success of the project depends [20].
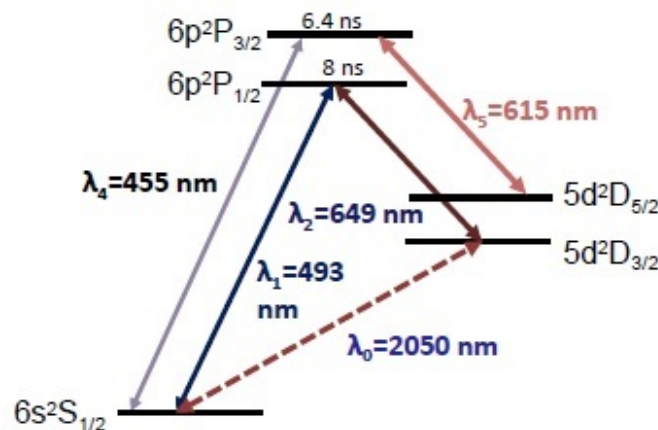
Fig. 1.   Lowest S, P, and D levels in Ba^+ ion. Isotopes without nuclear spin have no hyperfine structure such as $^{138}Ba^+$ which has been used in our measurements on single trapped ions.

Table I.   Frequencies of transitions in a single laser cooled $^{138}Ba^+$ ion. The measurements of Dijck et al. [18] improve by more than two orders of magnitude of previous measurements by Karlsson and Litzen [19].

Ba^+ transition	Karlsson and Litzen	Dijck et al.
$6s^2S_{1/2}$-$6p^2P_{1/2}$	607 426 290(100)	607 426 262.5 (0.2)
$5d^2D_{3/2}$-$6p^2P_{1/2}$	461 311 880(100)	461 311 878.5 (0.1)
$6s^2S_{1/2}$-$5p^2D_{3/2}$		146 114 384.0 (0.1)

The most recently measured lifetime of the $5d^2D_{5/2}$ state in Ba^+ of

$$\tau_{5D_{5/2}} = 27.6(0.8) \text{ s} \tag{1}$$

agrees within 3 σ with independent measurements and within 2.5 σ with recent calculations [21, 22]. A measurement of the transition frequencies $\Delta\nu_{6s^2S_{1/2}-6p^2P_{1/2}}$, $\Delta\nu_{6p^2P_{1/2}-6d^2D_{3/2}}$ and $\Delta\nu_{6s^2S_{1/2}-6d^2D_{3/2}}$ improves previous measurements by more than two orders of magnitude (see Table I). The signal shape and center frequency position depends next to external static fields on the laser intensities and their polarization. The accuracy has been achieved by fully describing by a set of 8 level optical
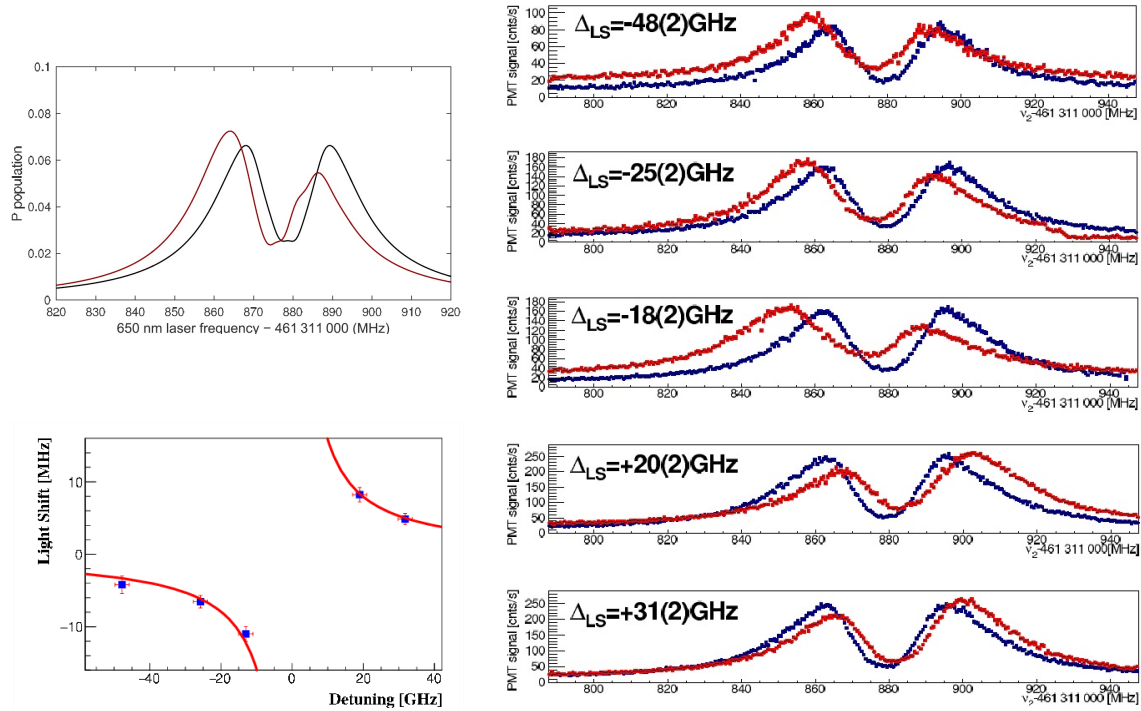
Fig. 2.   Left top: Calculated line shape for the $5d^2D_{3/2}$-$6p^2P_{1/2}$ transition in a trapped Ba^+ ion for magnetic field $510\,\mu$T. With additional intense laser light, red detuned by -18 GHz from resonance, and with intensity $110\,W/cm^2$ the spectrum red-shifts. Left bottom: Scaling of light shift for detuning of the shift inducing laser light Δ_{LS} from resonance. The observed light shift amounts to $\Delta\nu_{LS}$=0.16(3) GHz^2/Δ_{LS} Right: Measured resonance for the $5d^2D_{3/2}$-$6p^2P_{1/2}$ transition in a trapped Ba^+ ion for $510\,\mu$T magnetic field. The invariant signal (blue) in the five spectra were recorded with the light shifting light turned off. The shifted (red) spectra were recorded for different frequency detuning of the light shifting light from the resonant transition. Δ_{LS} varied between -48(2) GHz and +31(2) GHz. Δ_{LS} has been chosen always to be large compared to the power broadened linewidth of 0.4 GHz [22].

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Bloch equations [18]. For this measurement it has been particularly important that we were able to record also the part of the spectrum at higher frequencies than the atomic resonance by appropriately switching the red laser light on a fast time scale between frequency measurement and significant red detuning for sufficient laser cooling [18].

Experiments towards extracting the Weinberg angle from such measurements are coming up. Within one week of actual measurement time, the statistical uncertainty will provide for a fivefold improvement in the Weinberg angle at low momentum transfer. The experiment has robust discovery potential for effects caused by, e.g., dark Z bosons [23], in which case it can be more sensitive than parity violation experiments at higher momentum transfer, in particular for dark Z masses below $100\,\mathrm{MeV/c^2}$.

In Fig. 2 the sensitivity of trapped laser cooled $\mathrm{Ba^+}$ ions to additional near resonant light fields with detunings of several $10\,\mathrm{GHz}$ from the $5d^2D_{3/2}$-$6p^2P_{1/2}$ transition center is demonstrated. The detuning is large compared to the power broadened linewidth of $0.4\,\mathrm{GHz}$. The spectra have been recorded with blue laser light driving the $6s^2S_{1/2}$-$6p^2P_{1/2}$ transition while staying tuned to a fixed frequency below resonance for constant laser cooling, and with the red light driving the $5d^2D_{3/2}$-$6p^2P_{1/2}$ transition being scanned across resonance.

3. Permanent Electric Dipole Moments

Permanent electric dipole moments (EDMs) violate P and T symmetry and with the validity of the combined CPT symmetry they also violate CP. They exist in the Standard Model through higher order processes which include CP violating elements. The CP violating mechanisms known within the Standard Model cause EDMs which are for the foreseeable future far too small to be observed. Therefore searches for EDMs are a possibility to find sufficient CP violation that could explain the matter-antimatter asymmetry. EDMs are searched for since the 1950ies, even before the first violations of discrete symmetries had been found. The enormous progress that has been made since is displayed in Fig. 3. Along with the ever increasing precision in experiments numerous suggested speculative models beyond the standard theory of the time could be ruled out. At present, pressure is increasing on minimal supersymmetric models from improved limits on the EDM of various particles [6]. In fact, there is little room left in parameter space for such models.

Table II. EDM limits from selected experiments. The achieved experimental results for the neutron [24], the diamagnetic atoms ^{225}Ra [25], ^{199}Hg [26] and ^{129}Xe [27], the diatomic molecules YbF [28] and ThO [29] are within about one order of magnitude consistent with the expectations based on the figure of merit in eqn(3). As the neutron and diamagnetic atoms are not used to search for an EDM n theelectron, we use here $\eta = 1$ for evaluating M. Within this frame there are excellent perspectives to challenge the best electron EDM searches for a planned experiment on BaF with realistic parameters [30, 31].

| Particle	Particle Number N	Coher. Time τ [s]	Meas. Time T [d]	Efficiency $\times$ Polariz. $\varepsilon \cdot P$	E-Field E [kV/cm]	Enhance. eEDM η	Fig. of Merit M [arb.]	EDM limit established [10^{-30}e cm]
n	$6 \cdot 10^6$	$2 \cdot 10^2$	≈ 600	$4 \cdot 10^{-1}$	10		$9 \cdot 10^{10}$	29 000
^{225}Ra	10^3	$4 \cdot 10^1$	≈ 67	$7 \cdot 10^{-5}$	100		$1 \cdot 10^6$	$5 \cdot 10^8$
^{199}Hg	10^{14}	$2 \cdot 10^2$	≈ 284	$8 \cdot 10^{-2}$	10	$(-1.4 \cdot 10^{-2})$	$5 \cdot 10^{13}$	7.4
^{129}Xe $^{\$)}$	10^{21}	$5 \cdot 10^3$	≈ 100	$5 \cdot 10^{-6}$	3	$(-8 \cdot 10^{-4})$	$9 \cdot 10^{12}$	4 100
YbF	10^5	$1.5 \cdot 10^{-3}$	≈ 26	$3 \cdot 10^{-2}$	10	$2 \cdot 10^6$	$1 \cdot 10^{12}$	1 050
ThO	$1.5 \cdot 10^5$	$1.1 \cdot 10^{-3}$	≈ 14	$2 \cdot 10^{-2}$	< 0.1	$1 \cdot 10^9$	$3 \cdot 10^{12}$	87
BaF $^{\#)}$	$7 \cdot 10^5$	$1.5 \cdot 10^{-2}$	≈ 14	$1 \cdot 10^{-1}$	10	$6 \cdot 10^5$	$6 \cdot 10^{12}$	

$^\$$ an ongoing experiment (MiXed) has already established sensitivity in the 10^{-28} e cm range within a T$\approx$ 5 h test [32]. $^{\#)}$ planned new experiment [31].

In the absence of larger systematic uncertainties the statistical limit δd on a potential permanent electric dipole moment (EDM) is

$$\delta d = \frac{\hbar}{E\varepsilon P\eta \sqrt{\tau TN}} \quad . \tag{2}$$

Here N is the number of particles in the sample during a period that corresponds to the coherence time τ. They have polarization P and several samples of this size are under investigation within a total measurement time T. Here one may assume that individual measurements can be repeated within the total measurement time T for up to T/τ times. E is the applied external electric field, ε comprises all efficiencies for detection in the experiment and η is an *enhancement* factor for an EDM on the electron. The latter arises from details of the particular electronic structure of the system under investigation. From this we can define a general statistical figure of merit for experimental searches [33]

$$M = E\varepsilon P\eta \sqrt{\tau TN} \quad . \tag{3}$$
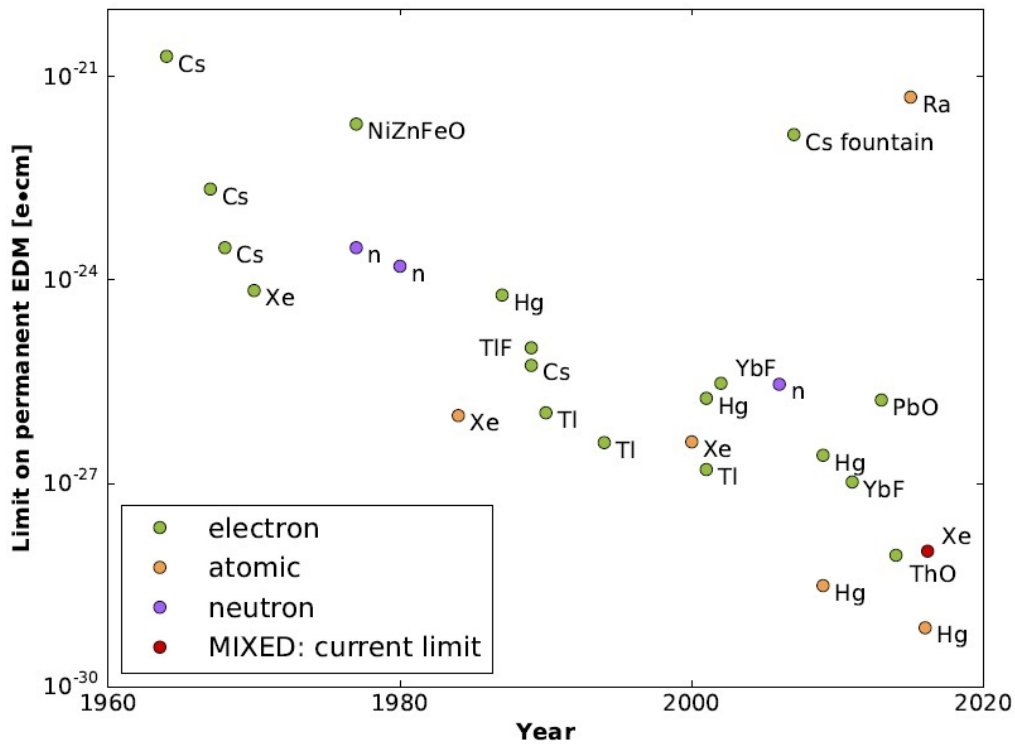
Fig. 3. Within the past 5 decades searches for a permanent EDM have been performed in cesium (Cs), xenon (Xe), neutron (n), nickel-zinc ferrite (NiZnFeO), mercury (Hg), thallium fluoride (TlF), thallium (Tl), ytterbium fluoride (YbF), lead oxide (PbO) and thorium oxide (ThO). The presently most sensitive experiments are on atoms such as ^{129}Xe and ^{199}Hg where recently significant progress has been booked concerning sensitivity to an atomic EDM. The recent limit on ^{225}Ra may be translated into a between 50 and a few 100 times better limit on nucleons, once the nuclear octupole deformation causing EDM enhancement will be confirmed also for Ra isotopes with finite nuclear spin. Experiments such as on radioactive Fr [34] will have to find their entry in an area of strong competition. The EDM on the electron is best limited from measurements in molecules such as YbF and TlF. We note that the achieved limits fall within an order of magnitude of the expectations from a model taking achieved experimental parameters and theoretical enhancement factors into account [33].

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Table II displays the relevant parameters for a selection of ongoing experiments on free neutrons (n), atoms with two valence electrons (^{225}Ra, ^{129}Xe and ^{199}Hg) and diatomic molecules where significant *enhancement* factors for an electron EDM exist (YbF, ThO, BaF) exist [30]. Note, for ThO molecules the electric field is relatively small, because the EDM enhancement effect saturates and the rather large enhancement factor η does hence not provide per se an advantage in sensitivity of similar scale over other experiments. Saturation therefore causes that systems with smaller intrinsic enhancement are still suited for competitive experiments, if higher electric fields are employed. In general, eq. (3) can serve to judge on the relative potential of various existing and planned EDM experiments. In particular it demonstrates that it is the combination of relevant parameters which is important, rather than only one or two of them. Parameters in which M is linear, i.e. E, ε, P, and η, have stronger impact than the ones under the square root, i.e. τ, T and N, as long as they are independent.

A collaboration between the German Universities of Mainz and of Heidelberg, the Dutch University of Groningen and the German Research Center (FZ) Juelich is performing a search for a permanent electric dipole moment in ^{129}Xe in a passive magnetically shielded room at FZ Juelich (see Fig. 4). A central cylindrical glass cell contains a gas sample of ^{129}Xe and ^{3}He as a co-magnetometer, which occupies the very same fiducial volume, and SF$_6$ as buffer gas. Since the co-magnetometer atoms are in the very same volume as the atoms in which an EDM is searched for, moderate magnetic field fluctuations and drifts are accounted for and only a minuscule residual systematic effect remains which arises on very long time scales from gravitation induced separation of the centers of gravity of both gases. The spin precession of both the polarized gases in a plane perpendicular to the magnetic
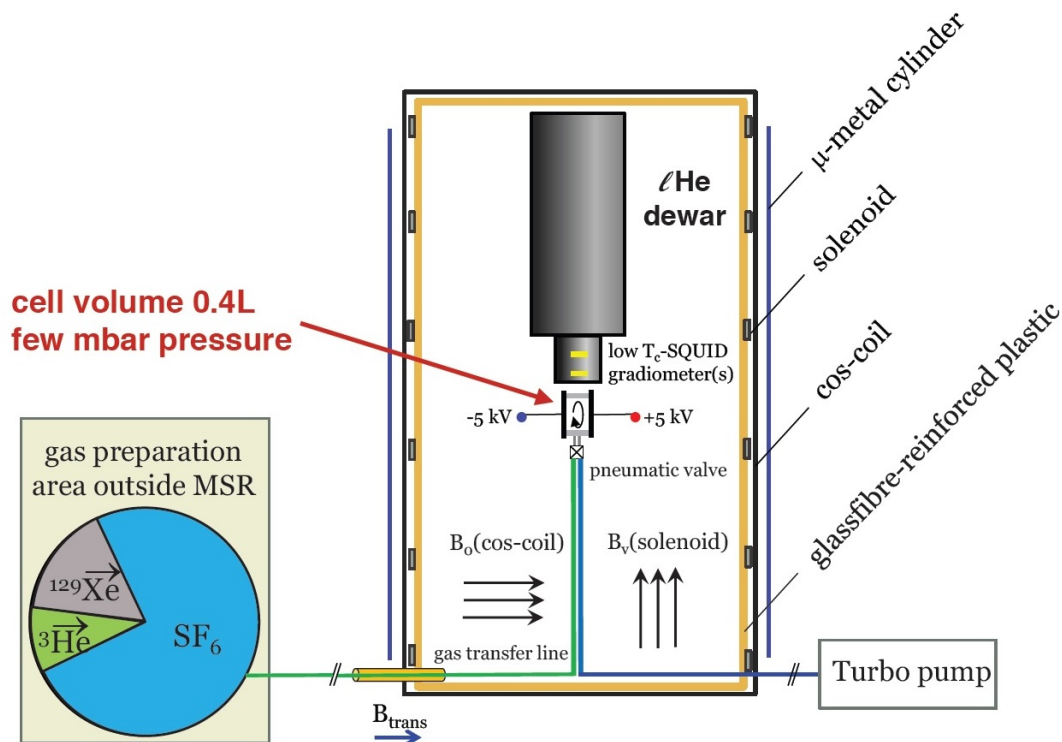
Fig. 4. The MiXed collaboration conducts the ongoing search for an EDM on ^{129}Xe using a mixture of the polarized gases ^{129}Xe and ^{3}He in SF$_6$ buffer gas, which are exposed to an electric field which is parallel or antiparallel to a small magnetic field which is transverse to the polarization of the gases. The spin precession of both species is observed by a SQUID assembly and can be followed for typically several hours. The whole setup is housed inside a μ-metal cylinder inside of a magnetically well-shielded laboratory room (MSR). The externally hyper-polarized gases ^{129}Xe and ^{3}He can be transferred to the measurement cell via a transfer line with a polarization maintaining guiding field from outside of the magnetic shielded room [32, 35].

field is continuously monitored by a SQUID detector system. The major advantage of the experiment is the technology that provides for maintaining the polarization of the noble gases ^{129}Xe and ^{3}He for several hours [36]. Even transportation over distances of hundreds of kilometers is possible [35]. In spring 2016 a first data test has been carried out. Within measurement time T= 5 h improved sensitivity to the EDM $|d_{129_{Xe}}|$ on ^{129}Xe atoms could be established of order 10^{-28} e cm [32]. At present a longer dedicated data run is being prepared. It promises significantly higher sensitivity. The experiment is expected to challenge the record numbers recently reported for ^{199}Hg [26] from University of Washington, Seattle, USA on the atom's EDM, but also on a number of derived stringent limits from this value such as the parameter Θ_{QCD} the small value of which is one of the mysteries in particle physics.

4. Conclusion

Low energy precision measurement of discrete symmetries continue to provide sensitive tests of the standard theory, to guide model building beyond the Standard Model and to select among the variety of speculative models, which are offered in order to provide deeper explanations of facts not fully understood or explained in the Standard Model. The experiments described above concern P and T (and CP) symmetry and are fully complementary to discrete symmetry tests performed with antiprotons and atomic systems that contain antiprotons. For the coming years we can expect significant refinements of experimental apparatus and improved limits on models beyond standard theory or decisive discoveries in measurements at highest possible precision.

Acknowledgments

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