A new search for the atomic EDM of $^{129}$Xe at FRM-II

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Abstract

Permanent electric dipole moments (EDMs) arise due to the breaking of time-reversal or, equivalently, CP-symmetry. Although EDM searches have so far only set upper limits, which are many orders of magnitude larger than Standard Model (SM) predictions, the motivation for more sensitive searches is stronger than ever. A new effort at FRM-II incorporating a $^3$He co-magnetometer can potentially improve the current limit significantly. The noble gas mixture of $^{129}$Xe and $^3$He is simultaneously polarized by spin-exchange optical pumping and then transferred into a high-performance magnetically shielded room. Inside, both species can freely precess in the presence of applied magnetic and electric fields. The precession signals are detected by LTc SQUID sensors. In prototype EDM cells we observed spin lifetimes in excess of 2500 s without and with high-voltage applied. This meets one requirement to achieve our goal of improving the EDM limit on $^{129}$Xe by several orders of magnitude

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1 Introduction

Experimental limits on EDMs offer a valuable probe of physics beyond the Standard Model, as a non-zero value of an EDM directly implies violation of time-reversal (T) symmetry. Assuming CPT symmetry, a non-zero EDM is also a manifestation of new sources of CP violation providing possible solutions to profound issues of the Standard Model. As an example the observed matter-antimatter asymmetry yields an eight order of magnitude disagreement to the prediction from the Standard Model [8,10]. Experimental results obtained from EDM searches, in particular the $^{199}$Hg EDM experiment [7] lead to the strongest constrains on fundamental nuclear CP-odd parameters. Although the current EDM limit on $^{129}$Xe [9] is at least two orders behind the $^{199}$Hg measurement, recent work strongly motivates the need for more sensitive measurements of $^{129}$Xe and other systems [5,4]. The state-of-the-art method used in EDM searches looks for deviations in Larmor spin precession frequency $\delta\nu$ when an electric field $E$ is applied in parallel to a magnetic holding field $B$. Assuming the magnetic field $B$ to be constant, subtraction of observed precession frequencies for reversed applied electric fields $E^{\uparrow\uparrow}$ and $E^{\uparrow\downarrow}$ yields the relation to the EDM $d$ as

$$d = \frac{\hbar \Delta\nu}{2(E^{\uparrow\downarrow} - E^{\uparrow\uparrow})},$$  

(1)

where $\hbar$ is Planck’s constant. A nHz frequency resolution in $\Delta\nu$ corresponds to an EDM sensitivity of $10^{-28}$ emu assuming typically applied electric fields of several kV/cm. An expression of the achievable frequency sensitivity for a sinusoidal signal of amplitude $S$ at a spectral noise density $\epsilon$ is given by the Cramer-Rao lower bound [3,6]. For an observation time $T$ the achievable frequency sensitivity is limited to

$$\sigma_\nu \geq \frac{\sqrt{3}}{\pi} \frac{\epsilon}{S \cdot T^{3/2}} \cdot C(T, T^*_2).$$  

(2)
In the case of an exponentially decaying signal with time constant $T^*_2$ and an observation time $T = T^*_2$ the modification factor $C \approx 1.7$. With our new EDM search we aim to improve the EDM limit on $^{129}$Xe by several orders of magnitude, requiring a frequency sensitivity in the sub-nHz range in a single measurement.

2 Experimental setup

To tackle this challenge our experiment is located inside an ultra-low noise and highly stable magnetically shielded room (MSR). See Fig. 1 for a scheme of the setup and [1] for details on the MSR. Previous to the measurement both noble gases are simultaneously polarized by spin-exchange optical pumping (SEOP) [11]. The polarizing setup is located outside, but close to the back wall of the MSR. Two pairs of Helmholtz coils of 40 cm diameter provide a reasonably homogenous holding field inside an oven heated to up to 160 °C by hot air. The light emitted from a water-cooled diode array (100 W, 794.8 nm) is narrowed to a linewidth of 0.4 nm by using Bragg-reflection from a volume holographic grating. Typically valved optical-pumping (OP) cells contain several grams of rubidium and are filled to about 1 bar total pressure with a mixture of $^3$He, natural or enriched Xe and $N_2$ at ratios of 17:2:1 respectively. For measurements at low magnetic fields a cart on a rail system is used to transport cells with highly polarized gas into the MSR. The guiding field during transport is provided by the holding field in the polarizing setup and the magnetic field along the transport axis inside the MSR. For the measurement magnetic fields are generated by three pairs of Helmholtz coils of diameters of 130, 140 and 150 mm. $^3$He acts as a co-magnetometer to compensate for residual magnetic field instabilities and other systematics. We use an array of six LTc SQUID sensors ($x_1, x_2, y_1, y_2, z_1, z_2$) to simultaneously detect free spin precession of both $^3$He and $^{129}$Xe. The SQUID sensors are mounted on the sides of a cube of 30 mm sidelengeth. The arrangement is described in [2], but inside a much smaller dewar.

3 Preliminary results as of June 2015

During a test run in 2014 we observed simultaneous spin precession of $^3$He and $^{129}$Xe in applied magnetic and electric fields inside sealed double-chambered prototype EDM cells. These cells have a polarizing bulb and a cylinder with silicon electrodes attached at the faces. Both chambers are connected by a bent tube. However, transverse spin lifetimes were only on the order of several hundred seconds and the double-chambered layout lead to strong beat signals.

In our test run in June 2015 we started using valved EDM prototype cells. To extract highly polarized gas from the polarizer we introduced a large OP cell (50 mm diameter, GE180) with two high-vacuum glass valves (Borofloat). $^3$He was typically polarized for several hours at high temperatures (140-160 °C) before lowering the temperature to 80-100 °C to effectively polarize $^{129}$Xe for several minutes. After cell transport using the rail system we recorded precession signals either after a non-adiabatic field switch or a spin-flip pulse. From the six independent SQUID sensors we can form both magnetometer and gradiometer signals in x,y and z directions. However, the closest SQUID sensor in the liquid helium dewar...
Fig. 2 (a) Spin precession signals of the $^3$He comagnetometer and $^{129}$Xe at frequencies of 40.8 Hz and 14.8 Hz, respectively, detected by the LTc SQUID sensor (z1) at a distance of about 110 mm to the center of the EDM cell. (b) Free precession decays of $^3$He (red) and $^{129}$Xe (blue) (signals were filtered by a software FIR bandpass filter of 4 Hz width centered at the corresponding Larmor frequencies) (c) EDM prototype cell mounted on the transport system.

is mounted at a distance as large as 110 mm to the center of the EDM prototype cells resulting in a huge loss of signal strength. Also gradiometer signals are less favourable, since the non-optimal baseline suppresses the signal by another factor of two.

Nevertheless, we observed signals of pT amplitudes (noise floor of 15 fT/$\sqrt{\text{Hz}}$) with transverse spin lifetimes $T_2^* > 2700$ s for both $^3$He and $^{129}$Xe (Fig. 2). This represents a tenfold improvement of signal size compared to previous runs, attributed to better, more reliable cell transport and an improved SEOP setup. First test runs with applied voltages of up to 10 kV yielded similar $T_2^*$ times. However, the prototype cells had to be filled from the same OP cell, hence the total pressure dropped with each filling leading to high-voltage breakdowns and significantly reduced signal sizes. Observation of increased spin lifetimes with subsequent refills may be attributed to decreased magnetization in the EDM cells due to lower (partial) pressures. Possible effects related to varying magnetization or shifts due to self-interaction of spins need to be addressed in further measurements.

4 Conclusion

The presented results demonstrate very long spin precession times in our newly designed EDM prototype cells and the feasibility of polarization preserving cell transport into a large magnetic shield. A new detection system with optimized gradiometer baseline and at least fourfold reduced distance between superconducting pickup coil and sample is under construction and is anticipated to increase the ratio $S/\epsilon$ by one to two orders of magnitude. Using Eqn. 2 the resulting fundamental frequency sensitivity of a single measurement is projected to be on the order of nHz, corresponding to an EDM sensitivity as low as $10^{-28}$ cm (Eqn. 1).
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References


