SEARCH FOR THE ELECTRIC DIPOLE MOMENT OF RADIUM-225

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The nuclear Schiff moment and its resulting atomic electric dipole moment (EDM) are signatures of time-reversal and parity violation. They represent an important window onto physics beyond the Standard Model. We are developing a next generation experiment to search for the Schiff moment and EDM of ^{225}Ra ($t_{1/2} = 15$ d) based on laser-cooled and -trapped radium atoms. Due to octupole deformation of the nucleus, ^{225}Ra is predicted to be 2-3 orders of magnitude more sensitive to T-violating interactions than ^{199}Hg (stable), which currently sets the most stringent limits in the nuclear sector. In addition, the rigid deformation in ^{225}Ra also ensures that its Schiff moment is more reliably understood. At present, ^{225}Ra samples at the level of a few mCi ($\approx 10^{14}$ atoms) are available from the decay of the long-lived ^{229}Th in stock. The FRIB facility could deliver 1-2 orders of magnitude more ^{225}Ra. It holds the potential to further improve the EDM search sensitivity.

I. EXCECUTIVE SUMMARY

The quest for nonzero permanent electric dipole moments (EDMs) represents an outstanding opportunity to search for new physics beyond the Standard Model. The four general classes of EDM searches are the neutron, nuclei (either bare or embedded in diamagnetic atoms), the electron (in paramagnetic atoms or molecules), and the muon. Searches in these areas compete against each other for the first discovery of a nonzero EDM. At the same time, they are also complementary to each other as each is sensitive to different classes of new physics. In order to fully understand the origin of a nonzero EDM, it is perhaps necessary to measure the EDMs in all these systems. Despite the ever increasing search sensitivity, EDM measurements in the past five decades have yielded results consistent with zero. Nevertheless, the non-observation of EDM has provided important guidance to developing new theories beyond the Standard Model, and has complemented other studies on fundamental symmetries in both nuclear and high-energy physics [1, 2]

We are developing a next generation experiment to search for the Schiff moment and EDM of ^{225}Ra ($t_{1/2} = 15$ d) based on laser-cooled and -trapped radium atoms. Due to octupole deformation of the nucleus, ^{225}Ra is predicted to be 2-3 orders of magnitude more sensitive to T-violating interactions than ^{199}Hg (stable), which currently sets the most stringent limits in the nuclear sector. In addition, the rigid deformation in ^{225}Ra also ensures that its Schiff moment is more reliably understood. At present, ^{225}Ra samples at the level of a few mCi ($\approx 10^{14}$ atoms) are available from the decay of the long-lived ^{229}Th in stock. The statistical uncertainty of an EDM signal for the near-term phase of the experiment, to be carried out within the next five years, is projected to be 10^{-26} $e \cdot$ cm for 10^4 trapped atoms and a measurement time of 10 days. Due to the large enhancement factor of ^{225}Ra, the near-term goal should already be competitive with the current best limits set by the ^{199}Hg experiment in terms of sensitivity to T-violating interactions. In the future, the FRIB facility could deliver 1-2 orders of magnitude more ^{225}Ra, which holds the potential to further improve the EDM search sensitivity. In a second phase of the experiment, to be carried out in 5-10 years, the aim is to increase the number of atoms to 10^6 and the measurement time to 100 days in order to achieve a limit of 3×10^{-28} $e \cdot$ cm. In order to take advantage of the production of ^{225}Ra and other enhancer isotopes at FRIB, it is critical to support a dedicated program to develop the expertise and infrastructure needed to extract these isotopes. In addition, further theoretical effort is needed to better interpret results from EDM searches in diamagnetic species including ^{225}Ra and ^{199}Hg.

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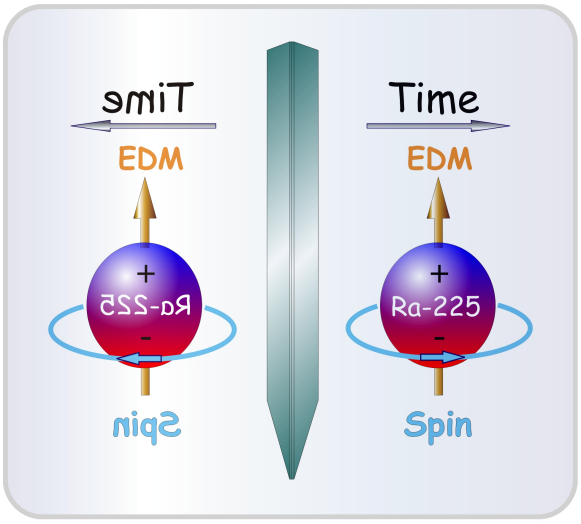

FIG. 1: A non-zero electric dipole moment violates both time-reversal and parity.

II. INTRODUCTION

The quest for nonzero permanent electric dipole moments (EDMs) represents an outstanding opportunity to search for new physics beyond the Standard Model. The four general classes of EDM searches are the neutron, nuclei (either bare or embedded in diamagnetic atoms), the electron (in paramagnetic atoms or molecules), and the muon. Searches in these areas compete against each other for the first discovery of a nonzero EDM. At the same time, they are also complementary to each other as each is sensitive to different classes of new physics. In order to fully understand the origin of a nonzero EDM, it is perhaps necessary to measure the EDMs in all these systems. Despite the ever increasing search sensitivity, EDM measurements in the past five decades have yielded results consistent with zero. Nevertheless, the non-observation of EDM has provided important guidance to developing new theories beyond the Standard Model, and has complemented other studies on fundamental symmetries in both nuclear and high-energy physics [1, 2]

We describe the progress in a search for a nonzero EDM in the diamagnetic ^{225}Ra atom. Its atomic ground-level has $J = 0$, resulting in a null electronic magnetic moment. Its nuclear spin $I = 1/2$, and its nuclear magnetic moment is $-0.75\mu_N$. In a neutral atom, the nuclear EDM is shielded by the atomic electrons, but the shielding is imperfect due to the difference in spatial distributions of charge and EDM over the nucleus. The remaining measurable quantity characterized by a radially weighted EDM of the nucleus is called the nuclear "Schiff moment." It induces a proportional and measurable atomic EDM. The conversion between these two moments can be calculated using atomic structure theories.

III. ADVANTAGES OF RADIUM-225

Sensitive measurements on EDMs of diamagnetic atoms have been performed on stable isotopes such as ^{199}Hg and ^{129}Xe. The most sensitive measurement to date was recently performed on ^{199}Hg, whose EDM was found to be less than 3×10^{-29} $e\cdot$cm at the 90% confidence level [3]. This is four orders of magnitude above the approximate EDM value (10^{-33} $e\cdot$cm for ^{199}Hg according to the Standard Model. P-odd and T-odd effects in the ^{225}Ra atom should be greatly enhanced because of its nuclear octupole deformation[4], which leads to a collectivity effect as well as near parity doublets that enhance strongly the Schiff moment. Indeed, both collective and mean-field calculations have predicted that the EDM of ^{225}Ra is 2-3 orders of magnitude larger than that of ^{199}Hg [5]. From the nuclear structure point of view, the EDM of ^{225}Ra is not only enhanced, but also better understood than ^{199}Hg [6]. Further theoretical effort is needed to better interpret results from EDM searches in diamagnetic species including ^{225}Ra and ^{199}Hg.

There are additional experimental advantages that make ^{225}Ra an exceptional candidate for EDM searches: it has a reasonably long half-life (15 d) so that the experiment can be performed off-line; its nuclear spin is 1/2 so that electric quadrupole effects are eliminated; and, as has been demonstrated recently, radium atoms can be laser trapped and cooled [7, 8]. ^{225}Ra is a decay product of the long-lived ^{229}Th ($t_{1/2}$ = 7340 yr). With a stock sample of ^{229}Th, ^{225}Ra is constantly generated, and can be chemically extracted on a regular basis. ^{225}Ra sources at the level of a few mCi ($\approx 10^8$ atoms/s, or a total of $\approx 10^{14}$ atoms) can be purchased from the DOE isotope program located at Oak Ridge National Laboratory. The FRIB facility could deliver one order of magnitude more ^{225}Ra ($\approx 10^9$ atoms/s) using a ^{238}U beam by recovering the ^{225}Ra produced in and collected from the water beam dump [9]. This operation can be carried out parasitically in parallel to other active experiments. Alternatively, FRIB could deliver two orders of magnitude more ($\approx 10^{10}$ atoms/s) with dedicated operation using a ^{232}Th beam [9]. The FRIB facility, currently under construction, holds the potential to significantly improve the EDM search sensitivity. In order to take advantage of the production of ^{225}Ra and other enhancer isotopes at FRIB, it is critical to support a dedicated program to develop the expertise and infrastructure needed to extract these isotopes.

IV. EXPERIMENT STATUS & OUTLOOK

Here we describe an experiment that exploits both the enhancement of EDM due to the nuclear octupole deformation of ^{225}Ra and the beneficial properties of optically trapped atoms. Optically trapped atoms exhibit a small velocity ($\approx$ 1 mm/s), form a compact cloud ($\approx$ 0.1 mm), and have a long spin-coherence time ($\approx$ 100 s). Laser trapping and cooling of radium atoms on both ^{225}Ra and the long-lived ^{226}Ra ($t_{1/2}$ = 1600 yr, $I = 0$) have been realized at Argonne National Laboratory [7, 8]. The experimental apparatus is shown in Figure 1. At present, the development is complete for a multi-step process that prepares cold, trapped ^{225}Ra atoms for an EDM measurement. ^{225}Ra atoms are first chemically reduced in a hot oven and physically evaporated into a collimated atomic beam. Transverse cooling is applied to enhance the forward atomic beam flux by a factor of 50. The atoms are slowed from approximately 60 m/s down to 1 m/s, and are captured into a magneto-optical trap (MOT) [7]. The trapped atoms are then transferred to a movable optical dipole trap (ODT) that is controlled by a lens mounted on a translation stage [8]. The ODT carries the cold ^{225}Ra atoms into a neighboring vacuum chamber, and hands the atoms off to a stationary, standing-wave ODT. The atoms are cooled to a temperature of 40 μK, and confined in a trap of 50 μm across and a trap depth of 400 μK. The lifetime of atoms in the trap is 20 s. By improving vacuum to 10^{-11} Torr, the atom storage time can be lengthened to 100 s. Possible systematic uncertainties of the proposed EDM measurements have been analyzed by Romalis and Fortson [10]. The authors concluded that the systematic uncertainties can be suppressed down to the level of 10^{-30} $e\cdot$cm. The statistical uncertainty of an EDM signal for the near-term phase of the experiment, to be carried out within the next five years, is projected to be 10^{-26} $e\cdot$cm for 10^4 trapped atoms and a measurement time of 10 days. Due to the large enhancement factor of ^{225}Ra, the near-term goal should already be competitive with the current best limits set by the ^{199}Hg experiment in terms of sensitivity to T-violating interactions. In a second phase of the experiment, to be carried out in 5-10 years, the aim is to increase the number of atoms to 10^6 and the measurement time to 100 days in order to achieve a limit of 3×10^{-28} $e\cdot$cm. A scheme that makes use of the much stronger atomic transition ($^1S_0$ $^1P_1$) is being evaluated as a means to increase the radium atoms in the trap by a factor of 100. Although additional repump lasers would be necessary, this scheme has already been demonstrated at KVI for trapping barium atoms [11]. In the future, a dramatic increase in the availability of ^{225}Ra made possible by FRIB would enable further improvements in the search sensitivity.

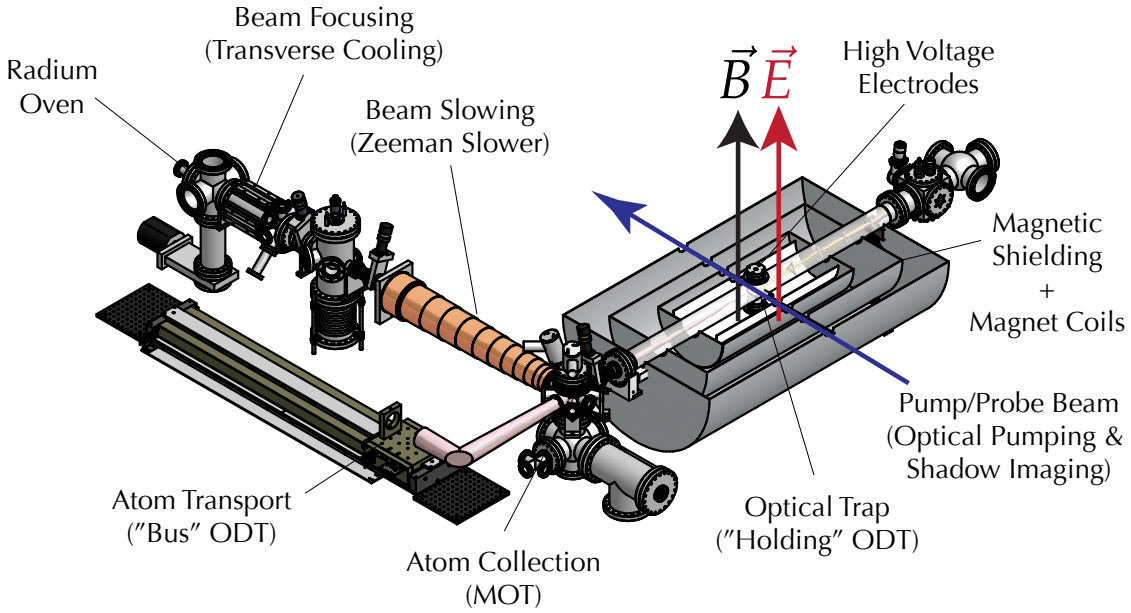

FIG. 2: Schematic diagram of the setup for laser trapping and EDM measurement of ^{225}Ra. The overall length is approximately 2 m.

Acknowledgments

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