Atomic Parity Violation in Ytterbium

Keqin Yan
Department of Physics and Astronomy, University of California–Los Angeles, Los Angeles, California 90095, USA

This paper summarizes the investigations of atomic parity violation in Ytterbium from DeMille's prediction in 1995 to Budker and his team's experiments on an individual Yb and a chain of Yb isotopes in the next few decades. The parity violation effects in Yb does not only serve as a stringent test for the Standard Model, but it also opens the door to new physics beyond the Standard Model.

I. INTRODUCTION

Parity describes the state of being equal under spatial inversion. For example, the law of gravity would still hold in a mirrored world. Among the four fundamental forces, however, the weak force is an exception. The weak interactions, specifically the exchange of Z^0 bosons between the nucleus and the electrons, can cause atomic parity violations/non-conservation, which can be very useful for studying electroweak interations and exploring new physics beyond the Standard Model. It therefore unsurprisingly involves an important Standard Model parameter: the weak charge, Q_W, which is associated with the couplings between the quarks and the electrons. The predicted value of Q_W related parameter was most accurately measured in Cesium [1] by Wood et al, yet it is also necessary to verify another Standard Model's prediction about the variation of Q_W in a chain of isotopes. Thus, since Dzuba et al. [2] had recommended the rare-earth atoms, which have proximate opposite-parity states that intensify the atomic parity violation effects, the investigations regarding Ytterbium (Yb) have made many important progress, which will be presented in this paper.

II. THEORY

For a chain of isotopes, precise calculations of the atoms are not necessarily required to understand atomic parity violation measurements, because the uncertainties in the atomic structure cancel in the ratio of atomic parity violation effects in different isotopes. This convenient feature is also why studying a chain of isotopes is useful. DeMille [3] pointed out that this kind of measurement would be different from the ones on one isotope in several ways. First, the atomic parity violation of each isotope has to be measured to high precision to ensure that the slight difference between them can be detected, which is also why atoms with a wide range of isotopes are preferred. Also, isotopic ratios of atomic parity violation are more sensitive to different radiative corrections, which allows them to provide unequivocal evidence for new tree-level interactions, such as new Z bosons [4][5]. In addition, the ratios could also represent neutron distributions and facilitate related measurements.

With these considerations, DeMille suggested Ytterbium as a promising candidate for observing the atomic parity violation along a chain of isotopes. This is not only because it has a wide range of isotopes, but also because its $6s^{2}\,{}^1S_0 \longrightarrow 5d6s\,{}^3D_1$ transition could provide an around 100 times larger parity violation effect compared to Cesium [3]. This significant difference, as DeMille pointed out, is due to the fact that electric dipole (E1) transition amplitude of Ytterbium is about 100 times larger than the one of Cesium, and the magnetic dipole (M1) transition of Yb is greatly suppressed and "appears only as a contribution to systematic effects." Hence, after discussions with DeMille, D. Budker and his team started to investigate Ytterbium isotopes on atomic parity violations.

III. EXPERIMENT

A. Single Isotope Experiment

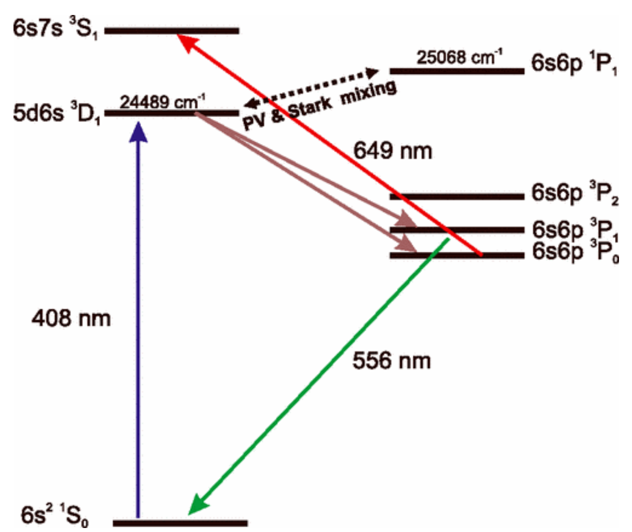

FIG. 1. The relevant energy eigenstates and transitions of Yb for the Single Isotope Atomic Parity Violation experiment [6]. The 408 nm light is in blue and excites the "forbidden" ${}^1S_0 \longrightarrow {}^3D_1$ transition. The 649 nm light is in red and excites the ${}^3P_0 \longrightarrow {}^3S_1$ transition. The green 556 nm light is used for "initial selection of the atomic resonance and for monitoring purposes" [6] as it is released from the decay of ${}^3P_1 \longrightarrow {}^1S_0$. The dotted line indicated the mixing of the odd-parity ${}^1P_1$ state and the nominally even-parity ${}^3D_1$.

In 2009, K. Tsigutkin et al. [6] reported their investigations on the atomic parity violation effects in different hyperfine components of the same odd-neutron-number isotope, specifically, ^{174}Yb. This kind of parity violations in an individual isotope is sensitive to the nuclear anapole moments, while the effects in a chain of isotopes are sensitive to the neutron distributions, and the former sensitivity could be used to explore physics such as the nuclear skin measurements [7]. Their experiment enabled the usually forbidden transition, $6s^{21}S_0 \longrightarrow 5d6s^3D_1$, and mixed the odd-parity $6s6p^1P_1$ state with the nominally even-parity $^3D_1$ by resonant 408 nm lasers. Then, to distinguish the parity violation effects from the the dominant Stark-induced amplitude and other systematics, the team also employed the Stark-PV interference technique and harmonically modulated the applied electric field. To obtain the transition rate of the Stark-PV interference term, the team then utilized the fact that, 65% of the atoms at $^3D_1$ state would spontaneously decay to the $6s6p^3P_0$ metastable state. Next, they excited these atoms to $6s7s^3S_1$ state using a resonant laser of 649 nm, and collect the fluorescence of the decays from $^3S_1$ to $^3P_0$, $^3P_1$ (which then decays to $^1S_0$ with a 556 nm transition [8]), and $^3P_2$ states, which is proportional to the transition rate as long as the 408 nm transition is not saturated. This mechanism is also shown in Fig. 1.

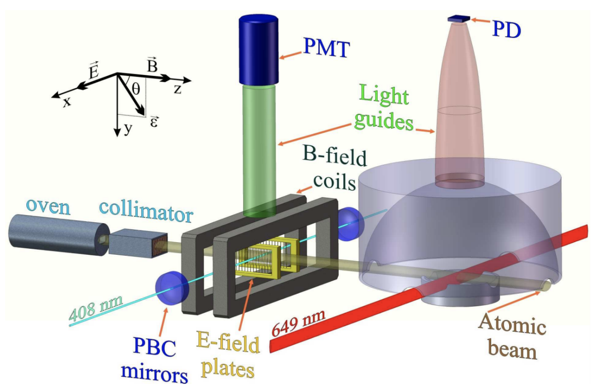

FIG. 2. The setup for the atomic parity violation experiments for single isotope experiment [6]. The Ytterbium atoms are in the oven, and the vacuum chamber that contains the setup is not included here. PMT stands for photomultiplier, PD stands for photodiode, and PBC stands for power buildup cavity. The PBC has a finesse of 9000 and a circulating power of 8 W. The 408 and 649 nm lasers are applied in the x direction. The pair of rectangular coils generates a uniform magnetic field up to 100 G [6], yet there are also coils outside of the chamber that assist to adjust the strength of the magnetic field. The electric field is generated by the pair of wire-frame electrodes consist of gold-plated copper wires. This design minimizes the surface area of the electrodes and thus reduces the amount of charge that accumulates on the electrodes.

The setup of the experiment is presented in Fig. 2. The electric field, $\boldsymbol{E}$, was applied in the x direction and served as a reference for the transition amplitude due to Stark-mixing of the same states interfered with the parity violation amplitude. The magnetic field, $\boldsymbol{B}$, was aligned in the z direction. The parity violating term has an amplitude that is proportional to $(\epsilon \cdot \boldsymbol{B})[(\boldsymbol{E} \times \epsilon) \cdot \boldsymbol{B}]$, where ϵ represents the electric field of the laser. Furthermore, when the angle between the magnetic field and the light polarization reaches a multiple of $\frac{\pi}{2}$, the atomic parity effects disappears. Because of this field arrangement, the magnetic dipole transition amplitude and the Stark-induced amplitudes are out of phase [9], and their interference is therefore greatly suppressed. The power buildup cavity also enhanced the suppression. This design, nonetheless, is not perfect. After taking the imperfections in creating and aligning the fields and the "parasitic frequency excursions" of the 408 nm excitation, the team concluded that the systematic uncertainty is 8% and the statistical one is 9% [8].

This experiment did confirm the theoretical prediction of the significantly large E1 amplitude of the parity violations in Ytterbium; its accuracy, however, was not adequate to exhibit the isotopic or hyperfine structure differences. Therefore, although improvements were made, such as the stability of their optical references were enhanced, the team still moved on to studying the chain of Ytterbium isotopes.

B. Chain of Isotopes Experiment

In 2019, D. Antypas et al. reported that they have successfully observed the parity violation effects in four of the nuclear-spin-zero isotopes of Ytterbium. Specifically, these isotopes are ^{170}Yb, ^{172}Yb, ^{174}Yb, ^{176}Yb, with corresponding abundance of 3.1, 21.9, 31.8 and 12.7% [10]. The experiment inherits the basic setup from the last experiment, yet the team had put a lot of efforts into improving the quality of the data. One of the major changes is that, instead of having the 408 nm laser sweeping through the entire spectrum and fitting a curve to the data (as done in the previous experiment), they moved on to stabilizing the laser to the peak of the desired transition and directly taking data from there. This change not only made the transition more effective, but it also reduced the sensitity of the data to the noises in the PBC. Along with this improvement, the team also lowered the frequecy of the noises in the PBC and increased the power of the laser. Consequentially, their signal-to-noise ratio became 18 times better compared to the single isotope experiment. Moreover, the team also added more detailed auxiliary experiments to study more systematic effects, such as evaluating the effects of imperfect magnetic or electric fields and checking the consistency of the transition profiles. In addition, they also created more uniform fields by enhancing their coils and plates. With these improvements, the team eventually reported 0.5% uncertainty for three of the four isotopes measured, which got fairly close to the most accurate experiment done on Cesium with a 0.35% uncertainty.

The result of the experiment confirmed the predicted fractional change of Q_W per neutron by the Standard Model: the predicted value was 1% per neutron, and the calculated result was 0.96% per neutron. Furthermore, the team also pointed out that their measurements could potentially lead to the exploration of "parity violating electron–nucleon interactions mediated by a light vector boson Z" [10], which is beyond the prediction of the Standard Model.

IV. CONCLUSION

In conclusion, the investigation of the atomic parity violation in Ytterbium over the past few decades has made some exciting progress. The prediction of the significant parity violation effect in Ytterbium, the confirmation of the prediction, and following those, the greatly improved investigations of a chain of Ytterbium isotopes, are all wonderful achievements that help scientists to acquire further understanding of the Standard Model, Atomic Molecular Physics, and the world itself.

[1] CS Wood, SC Bennett, Donghyun Cho, BP Masterson, JL Roberts, CE Tanner, and Carl E Wieman. Measurement of parity nonconservation and an anapole moment in cesium. *Science*, 275(5307):1759–1763, 1997.

[2] VA Dzuba, VV Flambaum, and IB Khriplovich. Enhancement ofp-andt-nonconserving effects in rare-earth atoms. *Zeitschrift für Physik D Atoms, Molecules and Clusters*, 1(3):243–245, 1986.

[3] David DeMille. Parity nonconservation in the $6s^{21}s_0 \rightarrow 6s5d^3D_1$ transition in atomic ytterbium. *Phys. Rev. Lett.*, 74:4165–4168, May 1995.

[4] Michael E. Peskin and Tatsu Takeuchi. Estimation of oblique electroweak corrections. *Phys. Rev. D*, 46:381–409, Jul 1992.

[5] S. J. Pollock, E. N. Fortson, and L. Wilets. Atomic parity nonconservation: Electroweak parameters and nuclear structure. *Phys. Rev. C*, 46:2587–2600, Dec 1992.

[6] Konstantin Tsigutkin, D Dounas-Frazer, A Family, Jason E Stalnaker, Valeriy V Yashchuk, and D Budker. Observation of a large atomic parity violation effect in ytterbium. *Physical review letters*, 103(7):071601, 2009.

[7] B. A. Brown, A. Derevianko, and V. V. Flambaum. Calculations of the neutron skin and its effect in atomic parity violation. *Phys. Rev. C*, 79:035501, Mar 2009.

[8] K. Tsigutkin, D. Dounas-Frazer, A. Family, J. E. Stalnaker, V. V. Yashchuk, and D. Budker. Parity violation in atomic ytterbium: Experimental sensitivity and systematics. *Phys. Rev. A*, 81:032114, Mar 2010.

[9] Eugene D Commins. Parity nonconservation in atoms and searches for permanent electric dipole moments. In *Amazing Light*, pages 125–141. Springer, 1996.

[10] Dionysis Antypas, A Fabricant, Jason Evan Stalnaker, Konstantin Tsigutkin, VV Flambaum, and Dmitry Budker. Isotopic variation of parity violation in atomic ytterbium. *Nature Physics*, 15(2):120–123, 2019.