Review of Parity Violation in Atoms and Molecules

Fikri Abdillah*
Student, Physics Study Program, Institut Teknologi Kalimantan

Ritik Sarraf†
Student, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, CO 80309

David Calderon‡
Student, National Park College, Hot Springs, AR 71913

Swarnim Gupta§
Student, S.G.T.B Khalsa College, University of Delhi

I. Abstract

Parity violation is a phenomenon in which interactions between subatomic particles do not behave the same way when the spatial coordinates of the system are mirrored. Precision tests of parity violation in atoms provide critical insights into the workings of the Standard Model of particle physics, and can lead to discoveries of new physics. The goal of our project is to create a comprehensive review of past and proposed parity violation measurements. We will present a brief history of parity violation measurements performed in low-energy atomic systems, detailing their impact on the field of physics.

II. Introduction

Parity is the inverse transformation operator. The parity transformation, denoted as P, is equivalent to a mirror reflection followed by a rotation of 180°. The eigenvalues of this operator are $+1$ and -1, referred to as even and odd, respectively. In mathematics, symmetry implies that an object is identical to another after being rotated, flipped, or translated. In physics, a system is symmetric if it remains unchanged under a specific transformation. For instance, if we apply a parity transformation to Coulomb's Law, then

$$\mathbf{F} = \frac{1}{4\pi\epsilon_0}\frac{(-q)(-q)}{r^2}\hat{r} = \mathbf{F}(r) \tag{1}$$

From the previous equation, we know that the Coulomb's law is symmetry under parity. Parity transforms the Cartesian coordinates as $(x, y, z) \to (-x, -y, -z)$ (see Fig. 1).

Parity violation is a profound concept in particle physics that challenges the notion of mirror symmetry in fundamental

*Student, Physics Study Program, Institut Teknologi Kalimantan
†Student, Ann and H.J. Smead Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, CO 80309
‡Student, National Park College, Hot Springs, AR 71913
§Student, S.G.T.B Khalsa College, University of Delhi

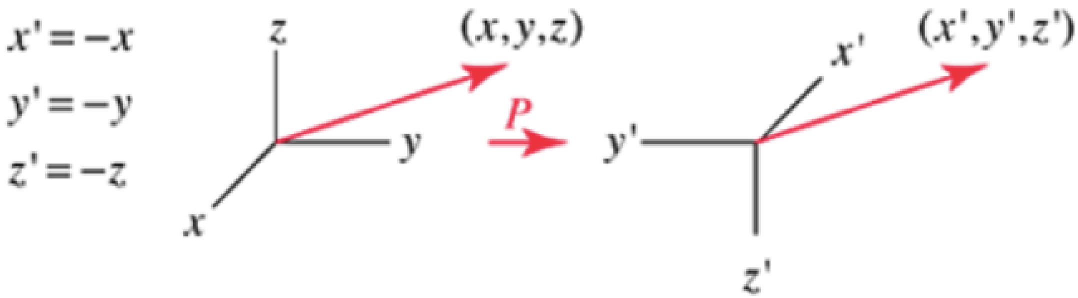

Fig. 1 Cartesian coordinates before and after parity transformation

interactions. It reveals a fascinating phenomenon where the laws governing certain particle behaviors do not remain unchanged under a "spatial transformation" resembling a mirror reflection. In other words, the universe exhibits a preference for specific directions in certain interactions, defying the expected symmetry.

III. Methodologies

There are a lot of experiments scientists have done to detect parity nonconservation, like nuclear β decay by Chien-Shieng Wu in 1957 [1] and electric dipole moment (EDM) by Wiemann in 1997 [2]. In 2013, Fortson et al. proposed measurement of single trapped atomic ions of Ba^+ [3] and DeMille et al. in 2017 also proposed by using the BaF molecule .

The Wu Experiment

Chien-Shiung Wu, a Chinese-American physicist, conducted a definitive parity violation (PV) experiment in 1957 using unstable ^{60}Co. The objective of this experiment was to measure the angular distribution of electrons emitted from the beta decay of polarized nuclei.

If an asymmetry in the distribution is observed between θ and $180° - \theta$ (where θ is the angle between the orientation of the parent nuclei and the momentum of the electrons), it provides unequivocal proof that parity is not conserved in beta decay. The results demonstrated that parity is violated when the ^{60}Co decays within a magnetic field; specifically, the emission was not symmetric under a parity transformation (see Fig. 2). This experiment provided the empirical evidence required to support the theoretical statement by Lee and Yang that parity is not conserved in weak interactions.

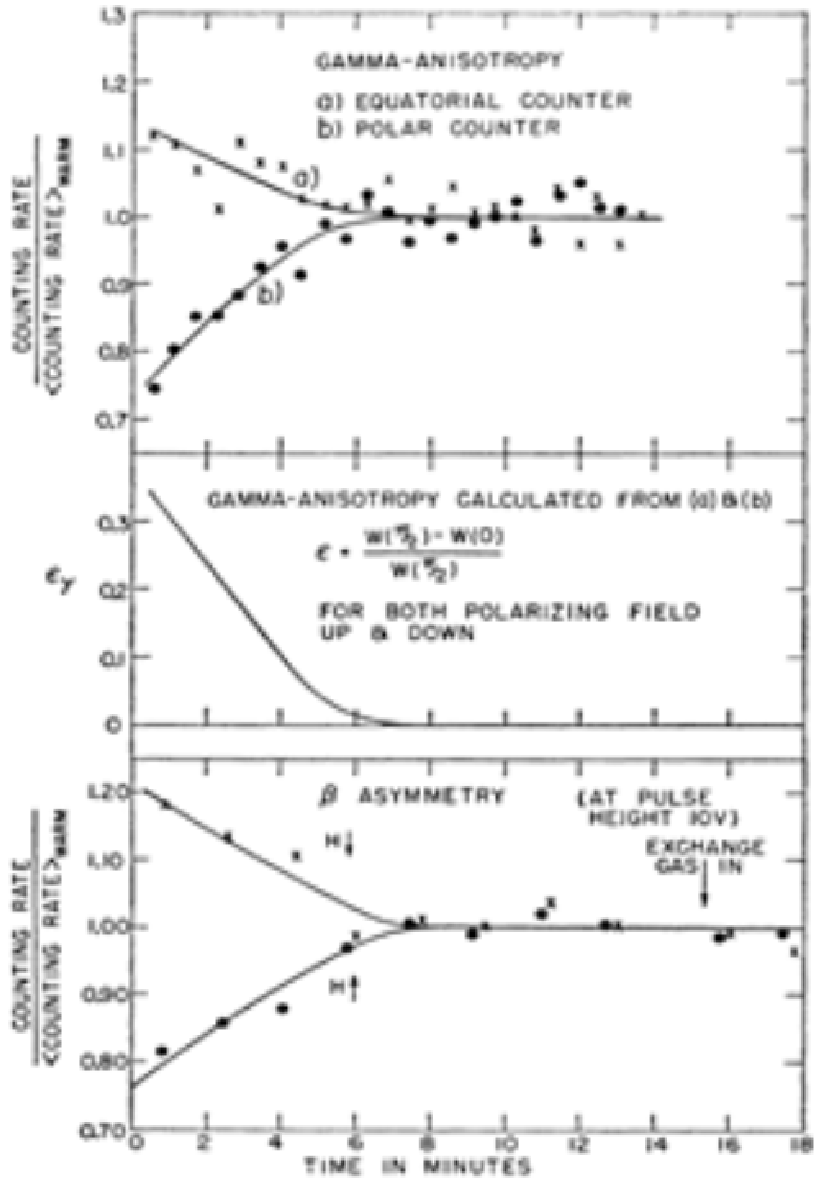

FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

Fig. 2 The Result of Wu Experiment

In 1997, Wiemann and his colleague conducted an experiment on electron dipole moment by using Cesium (Cs). Cs is an alkali atom with one electron outside of a tightly bound inner core. This experiment involved a PBC tool to reduce errors and improve the transition rate. When Cs beams through the diode lasers 1 and 2, the Cs atoms are pumped up from 6S to 6P. The apparatus has a magnetic field to create a hyperfine structure. This experiment used Stark Interference technique, which is applied at the Cs when through the Interaction Region. This effect amplified the parity-violation signal. At the interaction region, Cs atoms undergo an excited state from 6S to 7S due to the Dye laser (Fig. 3).

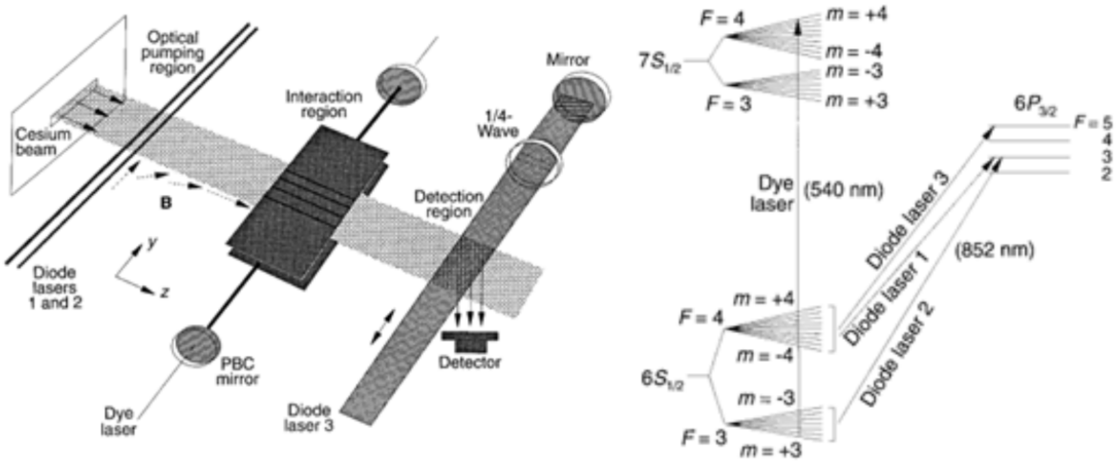

Fig. 3 Schematic of the Apparatus and Cs Energy Diagram

IV. Results

$$R = |A_E + A_{PNC}|^2 \tag{2}$$

Experimental Comparison

The term A_{PNC} represents the transition amplitude of the electric dipole ($E1$), whereas A_E is the "Stark-induced" $E1$ transition amplitude.

Figure 5 illustrates the historical progression of PNC experiments. The shaded band represents the Standard Model (SM) prediction for the average, including radiative corrections. In this plot, the squares denote values for the $4 \rightarrow 3$ transition, the open circles represent the $3 \rightarrow 4$ transition, and the solid circles indicate averages over the hyperfine transitions.

As shown in Table 1, when comparing the experiment conducted by Wood et al. to previous measurements, the associated error is significantly smaller and aligns closely with the Standard Model prediction. This suggests that this work remains one of the most precise and accurate measurements of parity violation to date (see Fig. 5).

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Table 1 List of PV experiments and its result

No	Source	Year	$-\mathrm{Im}(E1)/\beta$ (mV/cm)	Object	Transition
1	Wood et al.	1997	1.63 ± 0.0078	Cs	$6S \rightarrow 7S$
2	JILA	1988	1.576 ± 0.034	Cs	$6S \rightarrow 7S$
3	JILA	1986	1.65 ± 0.13	Cs	$6S \rightarrow 7S$
4	ENS	1986	1.52 ± 0.18	Cs	$6S \rightarrow 7S$

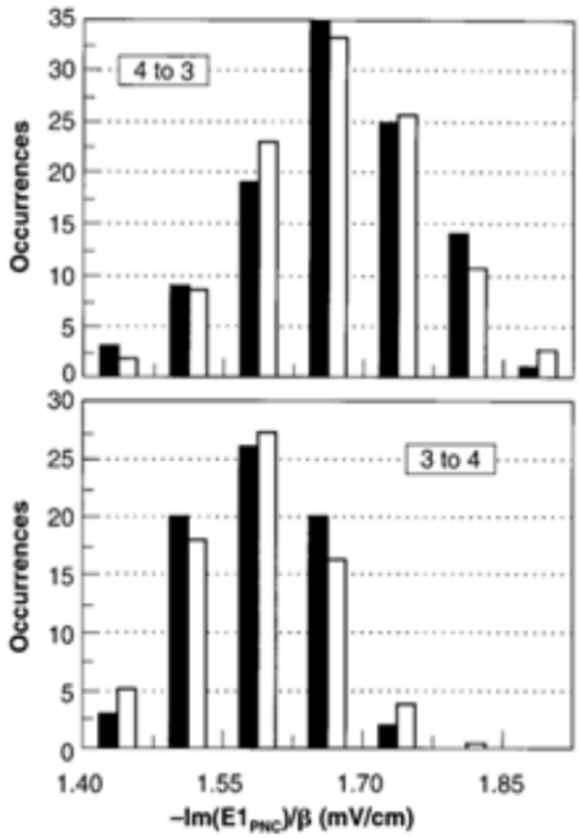

Fig. 4 Transition Rate of 6S to 7S with different hyperfine

Proposed Ba^+ Experiment

In 2013, Fortson from the University of Washington proposed a parity violation (PV) experiment to measure the magnetic dipole ($M1$) and electric quadrupole ($E2$) moments using a Ba^+ ion. The objective of this experiment is to measure the $M1$ transition moment of the $6S_{1/2}(m = -1/2) \leftrightarrow 5D_{1/2}(m = -1/2)$ transition in a single trapped ion by exploiting the distinct symmetries in the $E2$ and $M1$ couplings between these states.

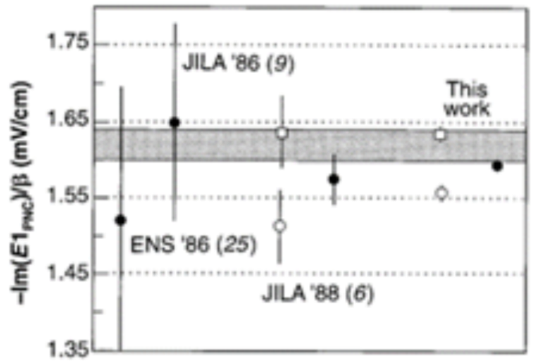

Fig. 5 Historical experiment and recent experiment of APV

The researchers utilized shelving techniques to measure all necessary Rabi frequencies. Figure 6 illustrates the lowest state ($6S$), the metastable state ($5D$), and the transition between them. The 2051 nm transitions are the primary focus of their research to determine both $E2$ and $M1$ amplitudes. Furthermore, in addition to $E2$ and $M1$, the electric dipole moment ($E1$) also contains a small contribution from parity violation.

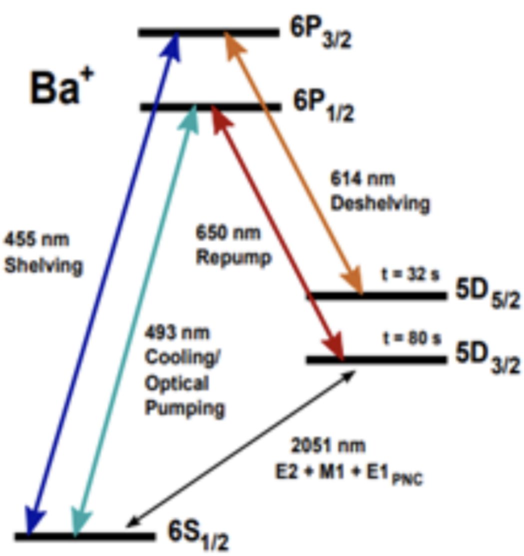

Fig. 6 A partial energy structure of Ba^+

V. Discussion

There are many predictions that can be made based off results from different experiments using parity violation. APV is a low energy method to study the Standard Model in ways other methods are not exactly able to. It is looked at as a promising candidate when looking for axions and other theoretical dark matter particles, like dark bosons, etc. One could measure the amount of parity violation over time with respect to the position of the Earth as it relates to possible axion nodes and antinodes. For this reason, we think APV may be the key to shedding more light on the dark sector, especially when it comes to axions. Fig. 7. illustrates where in the Standard Model in relation to energy APV experiments using specifically Cs are able to probe the Standard Model, and shows other types of experiments for reference.

Something else worth noting is that past predictions, especially those made by people who have conducted APV experiments have come true. APV results and theory are a good way to predict certain things. As one example the nuclear anapole moment was predicted in the 50's and was found in the 90's. So with this precedent it is reasonable to think that current predictions people studying APV make, are worth consideration and investigation.

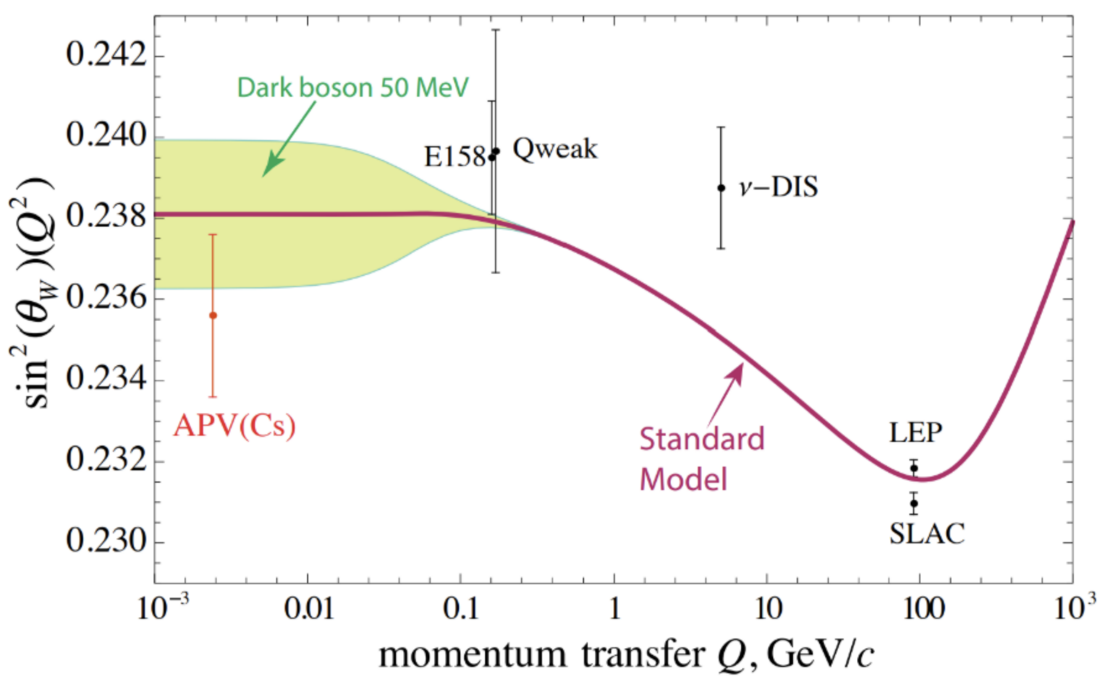

Fig. 7 APV Probes: The Standard Model

VI. Conclusion

The review of parity violation measurements highlights the central role in advancing our understanding of fundamental interactions within the Standard Model of particle physics. Beginning with Chien-Shiung Wu's seminal 1957 experiment on the decay of polarized ^{60}Co nuclei, the discovery of parity non-conservation fundamentally reshaped modern particle physics and firmly established the chiral nature of weak interactions.

Subsequent atomic parity violation (APV) experiments have significantly refined both experimental techniques and theoretical interpretations. In particular, the high-precision cesium measurements performed by Wood, Wieman, and collaborators in 1997—utilizing Stark interference to probe the $6S \rightarrow 7S$ transition—remain a benchmark in the field. Their result, 1.63 ± 0.0078, demonstrates remarkable agreement with Standard Model predictions and stands as one of the most accurate low-energy tests of electroweak theory to date.

Beyond confirming existing theory, APV experiments provide a uniquely sensitive probe for physics beyond the Standard Model. Proposed measurements involving single trapped ions such as Ba^+ and molecular systems promise further reductions in systematic uncertainty and enhanced sensitivity to weak interaction effects. These next-generation experiments open new pathways to explore phenomena such as nuclear anapole moments, dark-sector particles, and possible time-varying fundamental interactions.

In summary, atomic and molecular parity violation experiments serve not only as stringent tests of established theory but also as powerful tools for discovery. As experimental precision continues to improve, PV measurements are poised to play an increasingly important role in revealing subtle deviations from the Standard Model and deepening our understanding of the underlying symmetries of nature.

VII. References

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