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Analysis of the State-of-art CP Violation Evidence: Cobalt-60, K Mesons and B Mesons Experiments

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Abstract:
As a matter of fact, the CP violation investigations remain a hot topic in theoretical physics in recent years. With this in mind, this study briefly introduces how three basic discrete symmetries (CPT) are defined, as well as the findings towards the violation of respective P symmetry and combined CP symmetry, with the further indication of T symmetry. At the same time, three experiments are described to provide a full spectrometer of the findings, i.e., Fitch-Cronin experiment, Belle experiment as well as Babar experiment. By analyzing and discussing previous articles and some famous experimental results, the article covers approximately 60 years of Particle physics improvements under one of its branch-CP violation. According to the analysis and estimations, the evaluations of famous experiments along with their settings convey the idea of accuracy of modern particle physics. In the meantime, the current limitations are demonstrated. Overall, these results shed light on guiding further exploration and investigations of CP violation.

Keywords: Parity-symmetry; CP violation; K meson decay; Belle experiment; Babar experiment.

1. Introduction

The standard Model (SM) depicts how subatomic physics works and the relationships between particles. It sets a common ground for discussions and predictions about the fundamental mechanism of these particles. One major discovery in the development of the Standard Model is the phenomenon of CP violation, which implements significant findings such as Cabibbo-Kobayashi-Maskawa mechanism (CKM mechanism), while also reveals more profound insights into the universe human beings are living in [1].

Just like how the Standard Model (SM) was explored by scientists, discovering CP violation wasn't easy. About 60 years ago, when scientists believed that all physics principles were symmetric about left and right (along with conservation of momentum) and conservation of energy), it was reasonable to think so as there seemed no difference between you and another you in the mirror. However, in 1956, Wu and colleagues' experiment of cobalt-60, along with the theoretical verification of Li and Yang's deduction, challenged this widely granted belief. The experiment not only announced the breakdown of this parity rule., but also disclosed larger asymmetric properties of the universe, opening a door for more surprising asymmetries, including CP (Charge-Parity conjugation) violation [2]. A few years later, in 1964, James Cronin and colleagues revealed the very first evidence about this violation using K mesons and were hence awarded the Nobel Prize in 1980 for its ground-breaking implications. In 2001, when SLAC in Japan was capable of building the B factories, a group of scientists there illustrated the inconsistency of this rule again using B mesons [3]. Furthermore, recent findings, including D mesons, move forward a single step to provide valid examples of this far-reaching breaking symmetry.

As larger energy is gradually becoming technically applicable in larger hadron colliders and sensors detect signals with higher precision, later experiments change from light particles towards heavier mesons and rarer experiments. In LHCb , $B_S^0 \rightarrow D_S^+ + D_S^-$, and $B^0 \rightarrow D^+ + D^-$. Decays are measured and carefully analyzed by groups of scientists at CERN [4]. In addition, scholars previous thought of CP symmetry among neutrinos, electrons, and similar leptons is possibly overturned by recent findings by T2K Collaboration, where a substantial proportion of electron neutrinos are detected from the accelerator and far exceeds the proportion of its antineutrinos [5].

The aim of this article is primarily to provide a comprehensive introduction to CP violation and its significance in the physics field. By first presenting the overall history of CP violation, the definition of three discrete symmetries, and several new experimental evidence, including the latest experimental discoveries, the article aims to enhance a deeper understanding of this complex phenomenon. Then, implications about the initial picture of the Universe are presented with an evaluation of unsolved problems. CP violation also implies the underlying breaking of time reversal (T asymmetry), which in turn provides a way for justification of CP violation. Besides, the article highlights the importance of continued research and advanced technology in this field as it may lead to discoveries and a more fundamental comprehension of the laws of the universe in the future.

2. Description of CPT Symmetry

In physics, three discrete fundamental symmetries refer to C, P, and T. Among them, C represents charge conjugation (Charge conjugation), and its core meaning lies in that it is a unique operation that can directly replace a particle with its corresponding antiparticle. P stands for parity, which refers to reflection operation in terms of spatial coordinates. An object that rotates clockwise in real space rotates counterclockwise in a mirror. If the physical laws are the same for clockwise and counterclockwise rotations, then parity symmetry is held during this rotation process. A sketch is shown in Fig. 1 [6]. T is time reversal. Simply put, it is an operation of reversing the direction of time. As time runs backward, all movements of particles will also orient backward if time symmetry is held.

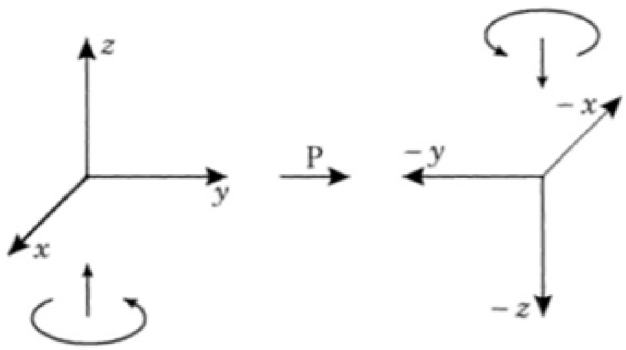

Fig. 1 Illustration of parity conjugation [6].

3. CP Violation

CP-symmetry simply states that as charge and parity are both rotated, the resultant particles or reactions should show no slightly different properties. CP violation was early implied from the discovery of P-violation, which was revealed by Wu's experiment in 1956. Wu used radioactive cobalt atoms to examine parity conjugation. They placed a pile of cobalt atoms inside a magnetic field produced by an electricity-conducting coil. As cobalt decays, it emits electrons and neutrinos. By altering the direction of the current inside the coil, Wu and her collaborators achieved altering parity conjugation. Surprisingly, the result showed that electrons in the plane and the mirror plane emerged in the same direction [7]. If parity conjugation conserves all physical laws, electrons should flow in opposite direction after Wu changed the spin of cobalt 60. The observed phenomenon challenges the strict law.

One type of neutral K meson is composed of a down quark and a strange antiquark. This type of K meson has strangeness 1 thus. Because strangeness is conserved in the strong nuclear force. Thus, when a positive one K meson is produced, there should be a negative 1 strangeness K meson (In certain circumstances, K mesons can be produced with other particles, not breaking this rule). This allows us to massively produce a lot of K mesons in the accelerator. Besides, when producing a particle of strangeness 1 (one of its quantum numbers), it can transform into a particle of different strangeness. An antiquark of K

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meson will be produced thus by emitting and absorbing W bosoms. This is called the mixing of K mesons. Both ways enable manufacturing K mesons.

When K meson is produced with its antiparticle (the particle with different strangeness), they split apart quickly, so there is not enough space for them to connect with the strong force except for weak interaction. Then, James Cronin and his collaborators found that the K meson can decay into two or three π mesons. Because of this higher energy stored in each π mesons, the K meson that decays into three π mesons would have quite a long life. One calls it K_L, which has 100 times longer expectancy than that of a slow one. If CP is held in weak interactions, all K mesons and their antiparticles will decay half to 2π mesons and the other two to 3 mesons. However, when Cronin set out a long tube for long-life K mesons to decay, they found a tiny percent of long-life K mesons decay into two π mesons, which contradicts the estimated number of mesons, that half of initial number of total K mesons will turn into long-life meson which then decays into three π mesons [8]. For each π meson, $CP=-1$. For short-lived K mesons, $CP=(-1)\times(-1)=1$. While for long-lived K mesons, $CP=(-1)\times(-1)\times(-1)=-1$. This is the direct CP violation presented in the experiment. Another rarer decay can also illustrate the same idea:

$$K_L^0 \to \pi^+ + e^- + \bar{\nu}_e \tag{1}$$

$$K_L^0 \to \pi^- + e^+ + \nu_e \tag{2}$$

Here, a single K meson with a high expectancy can decay into a pi meson, an electron, and an antineutrino (1). The opposite Eq. (2) also occurs to form all antiparticles of Eq. (1). Two decays listed above cause apparent CP conjugation (rotate their spin and replace particles with antiparticles), and the result turns out to lead to the same conclusion, that CP is not strictly conserved. This is because if K_L^0 has only one CP state of -1, two equations should yield equal possibilities. However, according to James and colleagues' analysis, K_L^0 decaying into positron has 0.33% more chance than decaying into electrons.

In addition, direct evidence of charge and parity violation did not appear until 2001, when SLAC in Japan could produce large amounts of B mesons in its "B factories". The target decay involves the B meson and its antiparticle decaying into the K meson and Pi meson, both of which belong to low effect. For example, particle B meson has a branching ratio of 1.85×10^{-5}. Two reactions are respectively listed as

$$B^0 \to K^+ + \pi^- \tag{3}$$

$$\bar{B}^0 \to K^- + \pi^+ \tag{4}$$

Since the products of equation 3 are the antiparticles of equation 4, one creates a perfect CP symmetry experiment. The result of different probabilities between the mirror reactions. Specifically, Eq. (3) yields a probability 13% higher than the probability of Eq. (4) [9].

4. Facilities and Experiments

4.1 Wu's Experiment

The experiment team set up a pile of specimen of ^{60}Co and applied a low temperature of the specimen, using strong magnet to achieve demagnetization of ^{60}Co. As the temperature becomes lower, nuclei is then polarized. The electrons are repelled away from the surrounding of the nuclei. In order to measure the distribution of electrons from the β decay of ^{60}Co, the team uses an anthracene crystal to detect the particles emitted. Receiving the electrons, the crystal scintillates and sends away light through the Lucite rod. The light finally enters the photomultiplier tube in Fig. 2 [10]. The total spin of ^{60}Co is 5, while the spin of the daughter nucleus ^{60}Ni is 4, each electron and anti-neutrino carry a spin of $1/2$. The initial left-handed β particles will turn to be right-handed, by their helicity. Opposite directions of ^{60}Co leads to the helicity. Via polarizing, the parity transformations is achieved under the change in directions and spin properties of the product electrons and antineutrinos. While conserving angular momentum, once the difference in the emitting rates of two experiments is measured, it shows a slight difference in β decay with its mirror experiment. The weak interaction is then proved violated (seen from Fig. 3) [11].

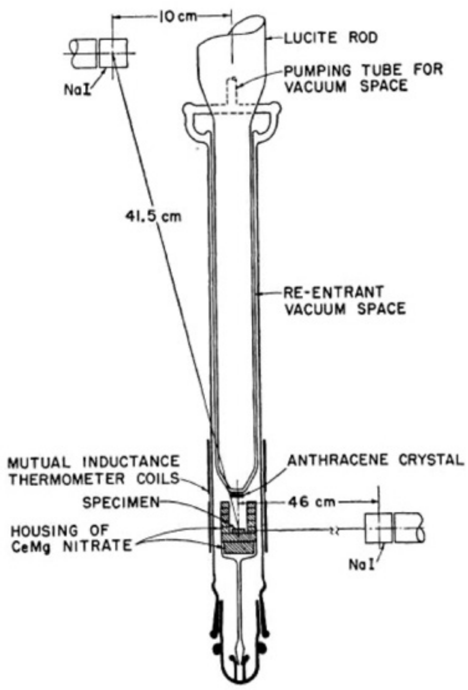

Fig. 2 The partial construction of the photomultiplier tube. The anthracene crystal sends away light beam towards the Lucite rod and is captured by the photomultiplier tube [10].

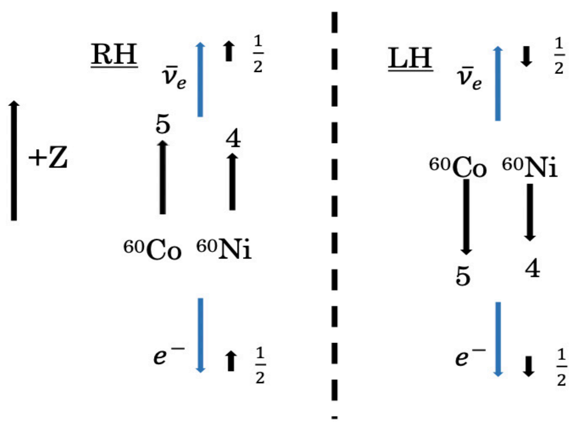

Fig. 3 The spin of each particles changes to align with the conservation of angular momentum [11].

4.2 James Cronin's "K mesons" Experiment

K mesons are ejected down to a collimator (shown in Fig. 4), down to a 57-foot collimator, into a chamber of Helium which consists of a spark chamber to determine direction, a scintillator used to determine mass, and a timing water Cerenkov machine. An angle of 22° that matches the mean angle of K meson decay [8]. The Fig. 5 shows the partial result of the abnormal branching ratio of 2 π mesons production, strongly suggesting that some long-lived K mesons eventually wrongly decay into 2 π mesons [8].

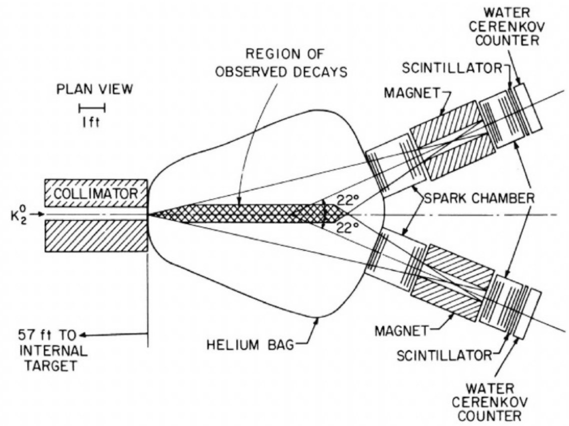

Fig. 4 The image demonstrates the cross-sectional view of the plan, involving the collimator and the spark chambers used to detect the product particles to draw the way of passing [8].

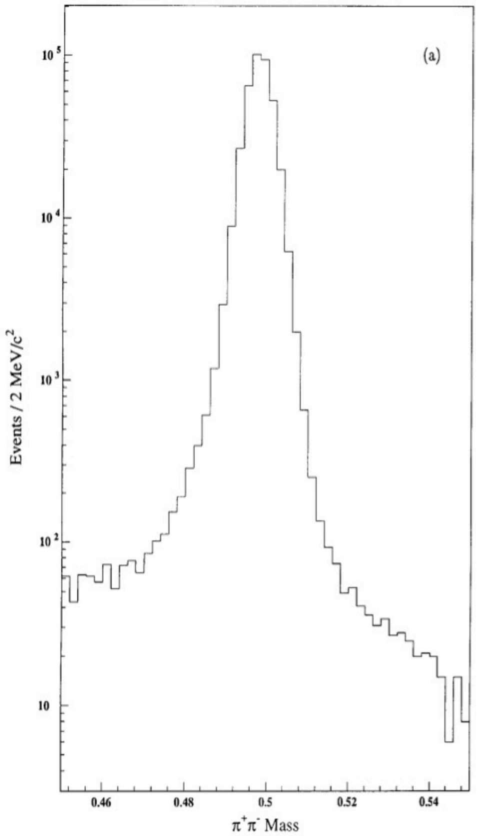

Fig. 5 The partial result of the abnormal branching ratio of 2 π mesons production,

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strongly suggesting that some long-lived K mesons eventually wrongly decay into 2 π mesons [8].

4.3 Belle Experiment

Many years later, the reason for this mystery of violation of weak interactions is still unsolved. The weak interaction provides the only possibility for this violation or so-called "broken symmetry". CP violation remains an active research area. With experiments of the Belle experiment, more informative evidence are provided to solve the deep question. The Belle experiment settings consist of detectors and an asymmetric energy $e^{+}e^{-}$ collider. It involves high luminosity and is able to integrate over 1000 fb^{-1} [12]. The detector is built around a iron structure, composed of a double-sided silicon vertex detector around a beryllium beam pipe. The experiment results confirm the CKM matrix mechanism by providing a wide range of solid experimental result of B decay (seen from Fig. 6) [12].

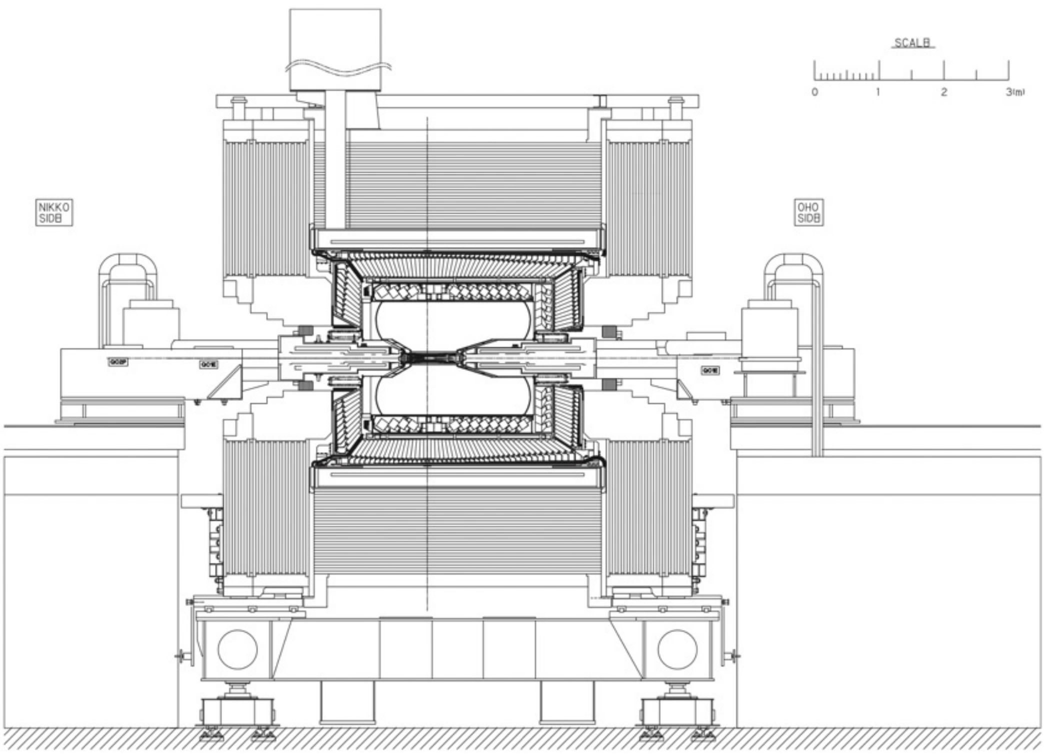

Fig. 6 The configuration of the Belle experiment [12].

5. Implications and Limitations

CP violation leads to a profound understanding of the formation of the initial universe. It helps to explain why the world is immersed of matter, instead of antimatter. Imagine if there is equal number of antimatter and matter at the beginning of the big bang, they would annihilate and emit immeasurable amount of energy (in the possible form of photons) and the world of matter would not exist at all. The order of magnitudes of so far discovered CP violation experiments is not enough to form the whole universe but able to sustain merely a galaxy. This implies the violation in other forces, such as that in strong interaction force. Only this would explain the matter-antimatter problem. CP violation is observed more than 60 years, still remaining the only asymmetry found by experimental verifications. However, this vital finding in particle physics history indicates more than the sole violation in Charge and Parity. CPT symmetry is long confirmed to be valid. Many of the theories including quantum field theory and relativity works just because of this important conservation. Otherwise, if CPT is not conserved, the human physics would start over again. This brings about the fact that time symmetry (T) should be non-conserved. With the many experimental evidence of CP violation, only with another violation would the total symmetry conserved again. It seems not possible if one is conserved while the other not conserved could the sum of them be conserved [13].

Scientists have searched for T violation for many years. Before 2012 when BaBar experiment confirms that time obeys the symmetry laws, many studies have been proposed but none of them suggest rigorous answers towards the question. BaBar utilizes the quantum entanglement of the B mesons to find the state of its partner at the time of the decay. Because the entanglement only involves the weak interaction, the non-asymmetry characteristic is attributed to the weak interaction. The number of times of the flipping is shown more than the opposite direction, resulting in the different mechanism of mirror in time, finally proving the asymmetry [14]. The surprising result of time asymmetry may contribute to the indirect evidence of CP violation, revealing more deep mechanism of the micro subatomic world. After the finding, scientist turn to T symmetry with EDM, where situations become more complex and special.

6. Conclusion

To sum up, CP violation is long regarded as a missing while important component of standard model. The first insight into this possible violation is attributed to the cleverness of a group of scientists back in 1960s. Fitch-Cronin experiment provides the first rigorous experimental evidence of CP violation. Further confirmation is provided by the BaBae and Belle experiment. The exploration of discrete symmetry remains a large branch of Particle Physics and to give out new ideas about the formation of the universe. As the energy of colliders gets higher, denser particles are examined to give more indications. With more studies related to universal discrete symmetry, particle physics would become an evergreen tree, breeding more and more important insights.

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