Historical review of symmetry violations and their experimental evidence

Yuchen Zhou
cb18945
QMUL Summer School 2019

Introduction

In the past fifty years, the frontier of particle physics has marched incredibly forward with the help of modern detector technology, putting almost all the puzzle pieces together: full identification of the most fundamental particles, successful quantum theories of their interactions, and Higgs mechanism which fixes the contradictories in particle mass. These accomplishments lead to the construction of Standard Model——an elegant structure that summarizes the most important conclusions achieved so far. All known particles could be regards as a combination of quarks except for leptons (they exist on themselves), while the forces between them are carried by gauge bosons.

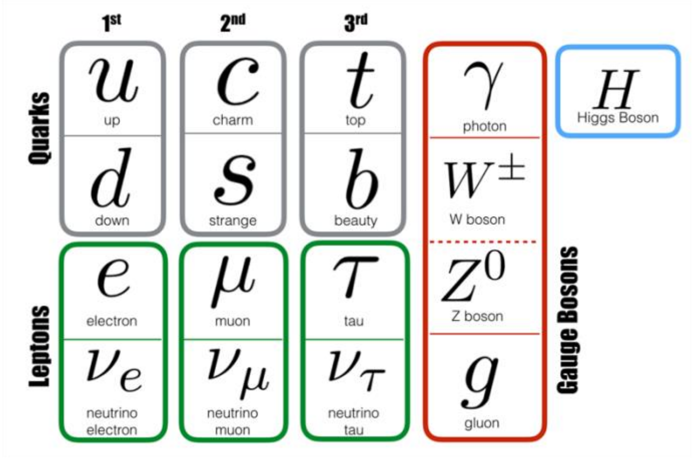

Figure 1: The Standard Model. (Source: https://www.physik.uzh.ch/en/research area/lhcb/outreach/StandardModel.html)

Symmetry refers to the equal probability of occurrence of particle interactions related by a given operator on wave functions. For a symmetry on a given operator to be conserved, the 2 interactions related by that operator shall be observed to take place under equal possibility. There are 3 different symmetries, correspondingly 3 operators, that have been proposed: Parity, Charge Conjugation, and Time. The conservation and violation of these symmetries, combined or on their own, give profound implications on the underlying mechanisms. Meanwhile, they throw light on unsolved problems beyond the Standard Model, for instance, matter-antimatter asymmetry.

In this essay, a brief history of symmetry studies and significant experiments associated are presented. As a historical review, this essay adopts a chronological manner with all the necessary concepts explained at the beginning. In the first section, the 3 symmetries are defined and described. In the second section, the proposition of these symmetries is put into the historical context along with the experiments that prompted the idea. In the third section, a summary is given and plausible future experiments are suggested.

Symmetries of the nature: C, P and T[1]

As mentioned, 3 symmetries have been included in the discussion: Parity (P), Charge Conjugation (C), and Time (T). Each of them could be regarded as a quantum mechanical operator acting on the wavefunction of a particle.

Parity

Parity (P) is an operator that inverses the spatial coordinates, namely transforming (x, y, z) into (-x, -y, -z). For a particle described by wavefunction $|\psi(r)\rangle$,

$$P|\psi(r)\rangle = |\psi(-r)\rangle = p_1|\psi(r)\rangle$$

$$P|\bar{\psi}(r)\rangle = |\bar{\psi}(-r)\rangle = p_2|\bar{\psi}(r)\rangle$$

where P is the parity operator, $|\bar{\psi}\rangle$ the wavefunction of antiparticle, p a linear constant for proportionality. Since the transformation from r to -r is linear, it is reasonable that $|\psi(r)\rangle$ and $|\psi(-r)\rangle$ are related by a constant. Therefore, p is considered as the eigenvalue of parity operation and all the particles are essentially eigenstates. Obviously, applying the operator twice will return the original wavefunction. Therefore,

$$p^2 = 1$$

$$p = \pm 1$$

For a fermion (spin = half-integer) , its wavefunction is antisymmetric, which implies

$$|\psi_f(-r)\rangle = -|\overline{\psi_f}(-r)\rangle$$

while for a boson (spin = integer), its wavefunction is symmetric hence

$$|\psi_b(-r)\rangle = |\overline{\psi_b}(-r)\rangle$$

This means

$$P\left|\psi_f(r)\right\rangle = -P\left|\overline{\psi_f}(r)\right\rangle$$
$$P\left|\psi_b(r)\right\rangle = -P\left|\overline{\psi_b}(r)\right\rangle$$

That is to say, the parity of a fermion is opposite to its antifermion, and contrarily, the parity of a boson is the same as its antiboson. Following $p = \pm 1$, we assign a fermion and a boson intrinsic parity of 1, antifermion -1, antiboson 1.

Parity is a multiplicative quantum number, thus for a system containing N particles at ground state, the parity of the system is:

$$p(system) = \prod_{i=1}^{N} p(i^{th}\ particle)$$

Since parity always inverts the momentum but never the spin, it changes the handedness of original particle.

To conserve parity, production of the same particle with opposite handedness shall be equally possible for a given channel.

Charge Conjugation

Charge conjugation is an operator that changes the particle to its antiparticle. It switches the electric charge, magnetic moment, leaving the energy, momentum and spin unchanged. For a particle described by wavefunction $|\psi(r)\rangle$,

$$C|\psi(r)\rangle = \left|\bar{\psi}(r)\right\rangle$$
$$C\left|\bar{\psi}(r)\right\rangle = |\psi(r)\rangle$$

where C is the charge conjugation operator. Charge conjugation Is a misnomer in the sense that it also acts on particles that are neutrally charged (i.e. neutron). In the neutron case, C simply changes each constituent quark into its antiquarks.

Since the wavefunction of the antiparticle differs from that of a particle more than a single sign, this means generally $\left|\bar{\psi}(r)\right\rangle$ cannot be related to $|\psi(r)\rangle$ by a single linear constant. Therefore, not all particles are eigenstates under C operation. For a particle to be eigenstate,

$$C|\psi(r)\rangle = \left|\bar{\psi}(r)\right\rangle = c_1|\psi(r)\rangle$$
$$C\left|\bar{\psi}(r)\right\rangle = |\psi(r)\rangle = c_2|\psi(r)\rangle$$

If we apply C twice, we will get back to the original particle, which is to say

$$c^2 = 1$$

$$c = \pm 1$$

It is then clear that with eigenvalue ± 1, the eigenstate particles must be their own antiparticles, restricting the eigenstates to photon and mesons consisting of a quark and its own antiquark. Due to the fact that not all particles are eigenstates, the charge conjugation of a particle is given by

$$C = (-1)^{l+s}$$

with l as the angular momentum while s the spin of particle.

Like parity, charge conjugation is a multiplicative quantum number. For a system containing N particles at ground state,

$$c(system) = \prod_{i=1}^{N} c(i^{th}\ particle)$$

To conserve charge conjugation, the antiparticle version of a given channel shall be equally possible to occur.

Time

Time is an operator that reverses the time. It does not directly act on individual particles in a physical way, so there is no point of developing the eigenvalues or eigenstates for time operator.

Time symmetry implies that given exactly the same conditions of energy, momentum and spin for the same set of particles, the reaction rate of a channel shall be the same in either direction, forward or backward. Thus, to conserve time symmetry, a given reaction with given kinematic parameters shall be observed to be reversible.

Chronology of Symmetry studies

Before 1950s, conservation of P symmetry and that of C symmetry was taken for granted. However, ‘tau-theta puzzle’ in early 50s first casted doubt on P conservation. Following Lee and Yang’s suggestion for P violation in weak interaction (1956), Wu’s Cobalt 60 experiment (1957) and Backenstoss’s pion decay experiment (1961) indicated the violations of C and P symmetry.

As physicists noticed after 1961 pion decay experiment, combining C and P into a single symmetry solves the problem. At this stage, physicists re-examined the neutral kaon decay experiment at Brookhaven (1956) which apparently supported the CP conservation. Promising as it sounds, neutral kaon decay experiment conducted by Cronin and Fitch in 1964 turned over this wishful thinking. Subsequent experiments in semileptonic decay of K mesons (Gjesdal et al, 1974) and neutral B mesons decays (Aubert et al, 2004; Chao et al, 2005) provided incontrovertible evidence for CP violation.

Finally, under the guidance of quantum field theory, physicists introduced the last symmetry——time——and combined the three symmetries into one——TCP. This symmetry stands on a firm theoretical ground and is substantiated rather securely by the measurement of $K^0 - \overline{K^0}$ mass difference.

The timeline of symmetry study is presented in **Figure 2**.

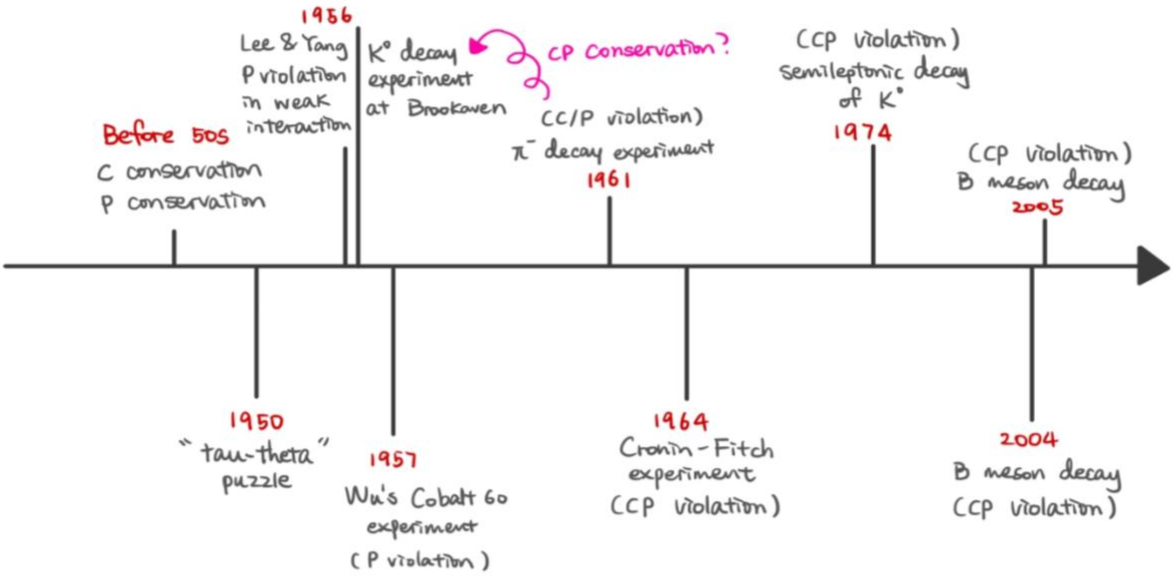

Figure 2: Timeline of symmetry study.

Experimental Evidence for C/P Violation

Cobalt 60 experiment (1957)

a) Background

Before 1950, P symmetry was considered to be conserved. Nevertheless, the 'tau-theta puzzle' in early 50s first implied the possibility of P violation.[2] Tau

(τ) and Theta (θ) were 2 exactly same particles except that they decay into products with completely opposite parity:

$$\theta^{+} \rightarrow \pi^{+} + \pi^{0} \qquad\qquad P = (-1)^{2} = 1$$

$$\text{or} \quad \begin{matrix} \tau^{+} \rightarrow \pi^{+} + \pi^{0} + \pi^{0} \\ \tau^{+} \rightarrow \pi^{+} + \pi^{+} + \pi^{-} \end{matrix} \qquad\qquad P = (-1)^{3} = -1$$

If Tau and Theta are the same particle, then they shouldn't decay into products with opposite parity given parity is conserved. Or they might be different particles, but except for the decaying product they seem to be identical. In 1956, Lee and Yang proposed that the 2 particles are same indeed, while parity is just not conserved in weak interactions, despite its conservation in strong and EM processes. To test the theory, Wu carried out the Cobalt 60 experiment.

b) Experimental Set-up

The set-up of Wu's experiment is shown in Figure 3.

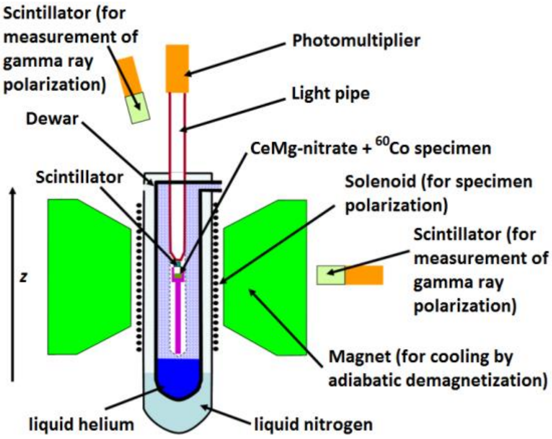

Figure 3: Experimental Set-up of Wu's Cobalt-60 experiment. *(Source: https://en.wikipedia.org/wiki/Wu_experiment)*

Parity was studied in the beta decay of Cobalt-60 which subsequently produces an excited Nickel-60 nucleus which then emits 2 gamma rays to get back to its ground state. The reaction could be expressed as:

$${}^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + e^{-} + \overline{\nu}_{e} + 2\gamma$$

Parity conservation predicts that electrons emitted in direction same as spin and opposite to spin shall be at equal amount.

Salt containing radioactive Cobalt-60 atoms were grown on a CeMg-nitrate base. Then, spins of these atoms were aligned by Rose-Gorter method: 1) Cool down the salt by adiabatic demagnetization with magnets and liquid helium/nitrogen. 2) External magnetic field from vertical solenoid aligns the spins. Electrons and gamma rays were observed using scintillators. As the reaction goes, it released energy and increased temperature, unaligning the spins. Observation was made before this warming phenomenon became significant. Degree of spin alignment was indicated by gamma-ray anisotropy (difference in gamma-ray counts between the 2 gamma-ray scintillators). [3]

To examine the electron emission from both same and opposite spin direction, experiment was carried out twice with opposite external magnetic field in the solenoid (cobalt spins were reversed for the same electron scintillator to measure opposite spin emission.)

c) Results

A significant preference of electrons decaying opposite to spin directions was found:

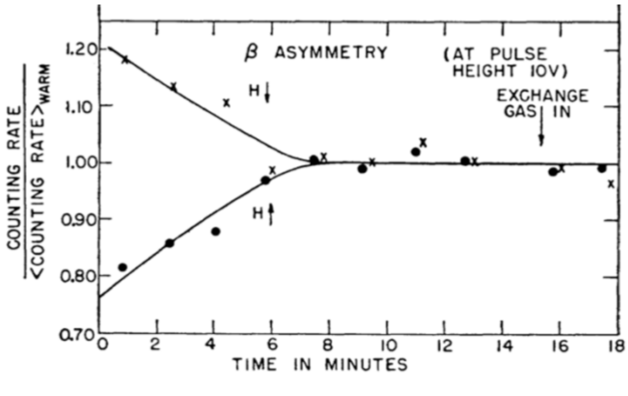

Figure 4: Normalized counting rate against time. It can be clearly seen that counting rate in opposite spin direction (the upper line) is significantly higher. The final convergence of two lines is due to loss of cobalt spin alignment caused by warming. *(Source: Wu et al, 1957)*

This strong asymmetry that favors electron emission opposite to Cobalt spin direction evidently showed P violation.

Pion Decay experiment (1961)

a) Background

The negative pion decay channel is:

$$\pi^- \to \mu^- + \overline{\nu_\mu}$$

Now consider the pion rest frame. The pion has spin=0. By spin conservation, muon and anti-muon neutrino shall have opposite spins. Meanwhile, to conserve momentum, the muon and muon neutrino must travel in opposite directions.

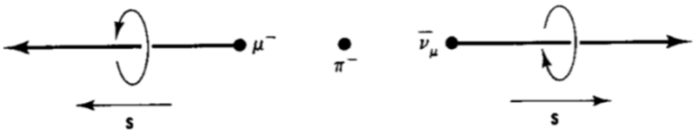

Figure 5: Pion decay in its own rest frame. *(Source: Introduction to Elementary Particles, D. Griffith, 2nd Edition.)*

If the spin and momentum of a particle are pointing toward each other, the particle is right-handed; if spin and momentum are pointing away, then it is left-handed. While the handedness of a particle with mass depends on observation frame, for massless particles (i.e. neutrinos) that travel nearly at the speed of light, it is impossible to find such an observational frame which changes their handedness. This is to say, handedness of a neutrino is Lorentz invariant hence independent of observation frame.

Following the definition of handedness and conservation laws, the pion decay channel indicates all muon neutrinos are right-handed. This is first supported by pion decay experiment in 1961 by Backenstoss and his collaboration.

b) Experimental Set-up

The set-up of Backenstoss' experiment is shown below:

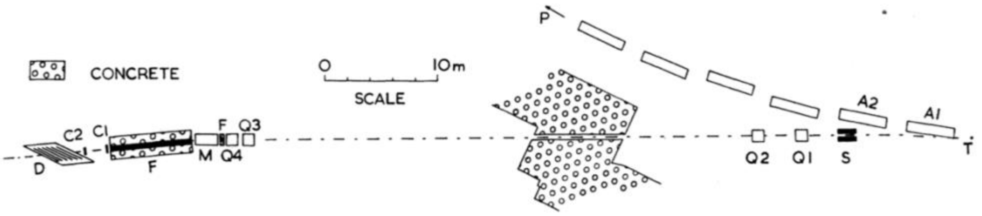

Figure 6: Set-up of Backenstoss' experiment. *(Source: Backenstoss et al, 1961)*

The helicity was indirectly measured. A model suggests that the cross-section of muon-electron interactions is related to the spin and energy of incident muons and knock-on electrons. By checking the consistency between actual cross-section and model prediction, the model was verified, which means the spin and momentum measurement of muons must be correct. Then the helicity could be calculated.

Negative pion beam was produced at T (target) and focused by synchrotron magnets A1 A2 onto a wide slot S and further focused by quadrupole magnets Q1 Q2 for collimation. Travelling for some further 45m, pions decayed into muons which were subsequently focused by quadrupole Q3 Q4, passing graphite filter F. A magnet M dispersed the beam. C1 C2 counted the events, while a total absorption shower detector D provided the electrons for muon-electron interactions and measured the energy of knock-on electrons. [4]

c) Result

Based on the experimental data, it was calculated that the helicity of muons is 1.17±0.32. This suggests right handedness of muons hence that of antimuon neutrino. [4]

Experiments afterward showed that all muon neutrinos are left-handed: this contradicts the previous belief of equal amount of right-handed and left-handed neutrinos/antineutrinos. Biased handed-ness of neutrinos suggest both P violation and C violation.

CP symmetry[5]

Soon after the 1961 experiment, most physicist realized that the combined CP symmetry is conserved and consistent with neutrino handedness.

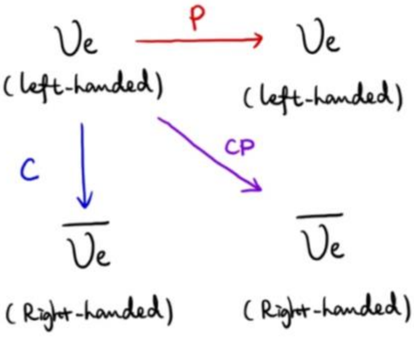

Figure 7: CP invariance in neutrinos.

CP invariance predicted 2 eigenstates of K mesons which decay into 2 pions and 3 pions respectively. Earlier experiments (i.e. Lande et al, Brookaven, 1956) support this prediction. So far CP invariance seemed to be very promising as a conserved underlying symmetry. Unfortunately, Cronin-Fitch experiment on K^0 decay in 1964 turned over this wishful thinking, followed by the later long-life kaon semileptonic decay experiment (Gjesdal et al, 1974) and B^0 decay experiments (Aubert et al, 2004; Chao Y et al, 2005).

Experimental Evidence for CP Violation

Historically, CP violation was only observed in K meson channels and B meson channels.

K^0 decay Experiment

a) Background

Neutral kaons were found to oscillate between K^0 and $\overline{K^0}$. Since

$$P|K^0\rangle = -|K^0\rangle, P|\overline{K^0}\rangle = -|\overline{K^0}\rangle$$

$$C|K^0\rangle = |\overline{K^0}\rangle, C|\overline{K^0}\rangle = |K^0\rangle$$

it follows that

$$CP|K^0\rangle = -|\overline{K^0}\rangle, CP|\overline{K^0}\rangle = -|K^0\rangle$$

Hence, the eigenstates of CP operator are

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K^0}\rangle\right), |K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K^0}\rangle\right),$$

K_1 has eigenvalue CP= 1 while K_2 has eigenvalue CP= -1. K^0 and $\overline{K^0}$ are both linear combination of the 2 eigenstates. K^0 can either decay into 2 pions or 3 pions. For 1 pion, CP= -1. Therefore, by CP conservation, K_2 can only decay into 3 pions while K_1 can only decay into 2 pions.

The idea above was first proposed by Gellman and Pais in 1955 [6] and a long-life K meson state corresponding to K_2 was predicted, which was confirmed in 1956 at Brookaven. However, Cronin and Fitch observed in 1964 that, rare though, long-life K mesons did decay into 2 pions which violated CP symmetry.

b) Experimental Set-up

The set-up of Cronin-Fitch experiment was set-up as below:

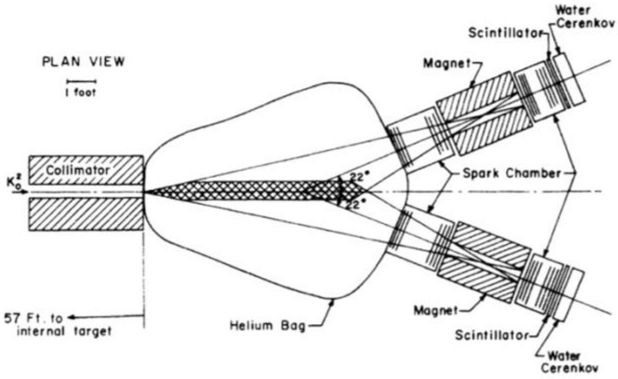

Figure 8: Set-up of Cronin-Fitch experiment. *(Source: Christenson et al, 1964)*

Neutral kaon beam passed through the collimator to travel parallel to the beamline. Then it entered the helium chamber where it decayed and the decay products were subsequently measured by the detectors. The magnets and scintillators measured the mass of particles. Spark chambers determined directions of particles while the water Cerenkov provided timing information.

Based on all the data above, the sum of angles from the horizontal could be calculated for decay products. For 2 pion decay, the sum of angles would be 0, while for 3 pion decay it is hardly 0. By this way, whether the long-life kaon went through 2 pion decay or 3 pion decay could be determined. [7]

c) Result

Cronin and Fitch found 45±9 two-pion decay events out of 22700 long-life kaon decay. They argued that the long-life kaon state, which was assumed as a K2 state, is not a perfect eigenstate of CP. This is clearly evidence for CP violation, and nature's deviation from perfect CP symmetry, Ɛ, was evaluated to be 2.3×10^{-3}. [7]

Semi-leptonic decay of K^0

The long-life kaon was known to decay in 3 ways:

$$K_l \to \pi^+ + \pi^- + \pi^0 \quad (1)$$

$$K_l \to \pi^+ + e^- + \overline{\nu_e} \quad (2)$$

$$K_l \to \pi^- + e^+ + \nu_e \quad (3)$$

Theoretically, there is a 32% chance of decaying into channel (1), and equal probability decaying into channel (2) and (3) which are related by CP symmetry. However, in 1974, Gjesdal and his collaboration found that the kaon decay favors positron channel by a factor of 3.3×10^{-3}. This suggests CP violation in semi-leptonic decay of long-life kaon. [8]

Neutral B meson decay

Neutral B mesons are known to decay in 2 ways:

$$B^0 \to K^+ + \pi^- \quad (1)$$

$$B^0 \to K^- + \pi^+ \quad (2)$$

Again the 2 decay channels are related by CP symmetry, thus were expected to be equally probable. Nevertheless, direct confirmation from 2 experimental groups (Aubert et al, 2004; Chao Y et al, 2005) shows that channel (1) is 13% more favorable than channel (2), which also suggests CP violation. [8]

TCP symmetry[9]

The violation of CP symmetry prompted physicists to define a new symmetry, and at this point, time symmetry (T) came into the picture, combined with CP to form TCP symmetry.

TCP theorem stands firmly in both theoretical and experimental ground. The conservation of TCP is built within quantum field theory since it is just impossible to construct any field theory without conservation of TCP. This implies T symmetry must be violated to conserve TCP when CP was violated.

TCP theorem predicts that mass and lifetime of particle are exactly the same as these of its antiparticle. Experimentally, the most precise measurement so far is in $K_0 - \overline{K_0}$, where difference in mass was measured to be smaller than 10^{-18}.

Therefore, TCP symmetry is currently the strongest candidate for the underlying symmetry that is always conserved.

Conclusion

The history of symmetry studies is essentially proposition, failure, and combination of symmetries. Physicists started with C and P symmetry separately and combined them when both violated in experiments. When CP was again violated, TCP was proposed and supported. Experimental evidence for CP violation keeps emerging, going beyond K and B meson systems. For example, CP violation was found in decays of neutral D mesons in 2011.

CP violation gives important implications of how the universe evolved into its current state——specifically, it might be able to explain the matter-antimatter asymmetry. Therefore, efforts for new and stronger evidence has never ceased, including the latest experiments on neutrino CP violations and construction of B factories. CP violation of particles haven't been detected yet (i.e. majorana neutrinos) is also of interests. In the future, more and more powerful detectors will certainly yield results which may or may not go beyond our expectation: in either way, we would need to keep an open mind on possibilities and a critical eye on interpretations.

Bibliography

---

[1] “Chapter 4: Symmetries.” *Introduction to Elementary Particles,* by David Jeffrey Griffiths, Wiley VCH Verlag, 2014, pp. 136–149.

[2] “Chapter 4: Symmetries.” *Introduction to Elementary Particles,* by David Jeffrey Griffiths, Wiley VCH Verlag, 2014, pp. 136–139.

[3] Wu, C.s., et al. “Experimental Test of Parity Conservation in Beta-Decay.” *The Theory of Beta-Decay*, 1969, pp. 160–165., doi:10.1016/b978-0-08-006509-0.50011-9.

[4] Backenstoss, G., et al. “Helicity Ofμ−Mesons Fromπ-Meson Decay.” *Physical Review Letters*, vol. 6, no. 8, 1961, pp. 415–416., doi:10.1103/physrevlett.6.415.

[5] “Chapter 4: Symmetries.” *Introduction to Elementary Particles,* by David Jeffrey Griffiths, Wiley VCH Verlag, 2014, pp. 144–145.

[6] Gell-Mann, M., and A. Pais. “Behavior of Neutral Particles under Charge Conjugation.” *Physical Review*, vol. 97, no. 5, 1955, pp. 1387–1389., doi:10.1103/physrev.97.1387.

[7] Christenson, J.h., et al. “EVIDENCE FOR THE 2π DECAY OF THE K20 MESON.” *CP Violation*, 1989, pp. 14–16., doi:10.1016/b978-0-444-88081-9.50008-4.

[8] “Chapter 4: Symmetries.” *Introduction to Elementary Particles,* by David Jeffrey Griffiths, Wiley VCH Verlag, 2014, pp. 145–147.

[9] “Chapter 4: Symmetries.” *Introduction to Elementary Particles,* by David Jeffrey Griffiths, Wiley VCH Verlag, 2014, pp. 147–149.