How Is Nature Asymmetric ?

2. Discrete Symmetries in Particle Physics and their Violation

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This two-part article considers certain fundamental symmetries of nature, namely the discrete symmetries of parity (P), charge conjugation (C) and time reversal (T), and their possible violation. Recent experimental results are discussed in some depth. In this second part, we discuss CP and T violation and arrive at a synthesis.


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In this second part we discuss the violation of two discrete symmetries, CP and T, which follows our discussion in general of the discrete symmetries C, P and T, and that of parity violation in Part 1. We conclude with a synthesis of the ideas presented in the two parts of this article.

CP-invariance

In the weak interactions, P and C are maximally violated simultaneously, such that the system is symmetric under the combined operation of CP. This is clear from the way massless fermions transform under P and C operations (*Figure* 1).

In nature only left-handed neutrino (ν_L) and right-handed anti-neutrino ($\bar{\nu}_R$) exist, which are CP transforms of each other. Hence, earlier it was thought that though weak interactions violate P and C they still possess CP-symmetry.

In 1964, Christenson, Cronin, Fitch and Turlay observed that decay of neutral kaon violates CP-symmetry minutely. Neutral kaons, K^0 and $\bar{K}^0$, are produced in pion-

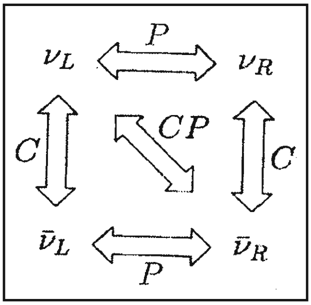

Figure 1. Transformation of massless fermions under P and C and their combined operation.

It is common in quantum mechanics to represent a state of a physical system by writing down certain of its characteristics inside the symbol | ⟩, called ket.

proton collisions via strong interaction,

$$\pi^- p \longrightarrow K^0\Lambda \qquad\qquad \pi^+ p \longrightarrow \bar{K}^0 K^+ p$$

and they decay primarily to two-pion and three-pion final states via the weak interaction with two different life-times. Based on the life-times of decays into these modes, kaons were renamed as K-short ($\tau = 0.89 \times 10^{-10}$sec) and K-long ($\tau = 5.17 \times 10^{-8} sec$). By conservation of angular momentum and intrinsic parity of pion, it is clear that the two-pion state, $|2\,\pi\rangle^1$, has $CP = +1$ and the three-pion state, $|3\,\pi\rangle$, has $CP = -1$. This implies that $|K^0\rangle$ and $|\bar{K}^0\rangle$ are not CP eigenstates, and in fact they transform into each other under CP operation i.e.,

$$|K^0\rangle \stackrel{CP}{\longleftrightarrow} |\bar{K}^0\rangle$$

With this property of neutral kaon states the CP eigenstates can be formed as the following linear superpositions (see *Box* 1),

$$|K_1^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\bar{K}^0\rangle\right) \qquad CP = +1$$

$$|K_2^0\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\bar{K}^0\rangle\right) \qquad CP = -1$$

Earlier K_1^0 (K_2^0) was identified as K_S (K_L), which decays into two (three)-pion or CP-even (odd) state, and CP is conserved. *But it was observed that K_L also decays occasionally into two-pions, which is CP-even and hence CP is violated.*

Part 1. Background and Parity Violation, *Resonance*, Vol.7, No.3, pp.10-17, 2002.

If we take a beam of K^0, which is produced by strong interactions, and which can be written as linear superposition of K_L and K_S, then the two-pion decay mode of K_L will interfere with that of K_S as a function of time. The intensity of the pion beam in two-pion decay mode varies with time as,

$$I_{2\pi}(t) = I_{2\pi}(0)\left[e^{-\Gamma_S t} + |\eta_{+-}|^2 e^{-\Gamma_L t} + 2|\eta_{+-}|e^{-(\Gamma_S+\Gamma_L)t/2}\cos(\Delta m t + \phi_{+-})\right] \quad (1)$$

Keywords
Discrete symmetries, massless fermions, *CP* and *T* violation.

Box 1. Superposition Principle of Quantum Mechanics

One of the postulates of Quantum Mechanics (QM) which makes it different from classical mechanics is the principle of superposition of quantum states. The state of the system is described by a *wave function*, say ψ, which satisfies the Schrödinger equation

$$i\hbar\frac{\partial}{\partial t}\psi(x,t) = -\frac{\hbar^2}{2m}\nabla^2\,\psi(x,t) + V(x)\psi(x,t),$$

where $V(x)$ is a potential. The probability of finding the system between x and $x+dx$ at time t is $|\psi(x,t)|^2dx$ and hence ψ is also called probability amplitude. The superposition principle states that *under logical OR operation it is the amplitudes which add and not the probabilities.* For example, if two possible solutions of the Schrödinger equation are ψ_1 and ψ_2 then probability of finding the system between x and $x+dx$ at time t in either of the two states is $|\psi_1(x,t)+\psi_2(x,t)|^2dx$, and not $(|\psi_1(x,t)|^2 + |\psi_2(x,t)|^2)dx$ as expected classically.

The concept of superposition in QM has an analogy in optics. If L_x and L_y denote the amplitudes of plane polarised light polarised along x and y directions respectively, then $L_\pm = (L_x \pm iL_y)/\sqrt{2}$ denote the amplitudes of right and left circularly polarised light. We know that light (or photons) has only two independent polarisation states, and both $\{L_x, L_y\}$ and $\{L_+, L_-\}$ are complete and equivalent descriptions of photon polarisation. We may choose either of them depending upon the symmetry of the system we are dealing with. In the same spirit if a system is described by a set of n different states denoted by $\{\psi_i,\ i=1,2,...,n\}$, then any other set $\{\phi_i,\ i=1,2,...,n\}$ describes the system equivalently if ϕ_i's are linearly independent when written as linear superposition of ψ_i's.

where $\Gamma_{L,S}$ = decay width of $K_{L,S}$, $\Delta m = m_L - m_S$, t is time and,

$$\eta_{+-} = |\eta_{+-}|e^{i\phi_{+-}} = \frac{\mathcal{M}(K_L \to \pi^+\pi^-)}{\mathcal{M}(K_S \to \pi^+\pi^-)},$$

where, $\mathcal{M}$s stand for the *matrix elements* signifying the transition probability amplitudes.

This interference was observed by Christenson and others in 1964. Similar to η_{+-}, we can define another quantity, η_{00}, which is ratio of amplitudes of decay in to $\pi^0\pi^0$ instead of $\pi^+\pi^-$ Nonvanishing of the η's implies that CP is violated. Further η's are written as,

$$\eta_{+-} = \epsilon + \epsilon' \qquad \eta_{00} = \epsilon - 2\epsilon'$$

and CP violation is generally expressed in terms of ϵ and ϵ'. Experimental values of these parameters are:

$$\epsilon = (2.271 \pm 0.017) \times 10^{-3}$$
$$\epsilon'/\epsilon = (2.1 \pm 0.5) \times 10^{-3}.$$

A non-zero value of ϵ' is referred to as direct CP violation. In the standard model (SM) (see *Box* 2) the quantity ϵ' is somewhat smaller as compared to the experimental values. But due to large calculational and experimental uncertainties, the SM predictions are not ruled out. The other place to see CP violation is the B-meson system, which is similar to the K-meson system, with the s-quark replaced by a b-quark. In SM the

Box 2. The Standard Model of Electroweak and Strong Interactions

Based on decades of experiments in the field of elementary particle physics, today a picture which is referred to as the standard model of interactions has come into being. It describes the interactions between several types of particles, which come in two varieties. The first variety are called leptons, which participate only in the electroweak interactions and not in the strong interactions, and the second variety are called hadrons which participate in both. For example, the electron and its neutrino are leptons. They have heavier cousins called the muons and τ leptons and their respective neutrinos. The hadrons themselves come in two classes, namely mesons and baryons. Among mesons we find the pions, kaons and the B-mesons, whereas the proton and neutron are examples of baryons. These are understood in the SM to be arising from the interactions of further constituents called quarks, which themselves come in six 'flavors,' the up, down, strange, charm, bottom and top quarks. These particles typically carry electric charge as do the charged leptons and also additional quantum numbers called colors through which they interact amongst themselves with the exchange of so-called gluons which mediate the strong interactions. The electroweak forces themselves are mediated by the well-known photon and other particles called $W^{\pm}$ and Z.

The SM, as proposed by Glashow, Weinberg and Salam, had only first four flavors of quarks and possesses CP symmetry. To explain CP violation in K-meson system two more quarks namely b and t were introduced. In SM, the source of CP violation is mixing between quarks which is described by Cabibbo–Kobayashi–Maskawa (CKM) matrix. The matrix elements of the relevant 2×2 sub- matrix are real if we have only four flavors of quarks and this implies that CP is a good symmetry. CP will be violated only if some of the CKM matrix elements are complex, which is possible when we have at least six quarks in nature (details are beyond the scope of this article). The present day SM contains six quarks and can accomodate CP violation in K and B meson systems.

source of CP violation is Cabibbo Kobayashi Maskawa matrix (*Box* 2 in Part 1). The CP violation effect in K must translate to B-mesons also. At several particle physics laboratories, 'asymmetric colliders' have been constructed to study the $B^0 - \bar{B}^0$ system (see *Box* 3).

Further, according to CPT-theorem, CP violation implies T violation, but there is no direct evidence for it in neutral kaon system. Thus the source of CP violation is not yet clear and the phenomenon needs better understanding as it may have been responsible for the net *baryon number* of the present day Universe (*Box* 4).

Box 3. The 'Asymmetric' B-factory.

Conventional cyclotron design of elementary particle colliders consists of a ring in which a beam of particles of a certain type, say electrons (protons), is accelerated in one sense, while the anti-particles, say positrons (anti-protons) are accelerated in the opposite sense in the *same* ring, which is guaranteed by the fact that the particle and anti-particle differ only in the sign of their electric charge, while their masses are equal. Many successful experiments for generations were based on this design, the latest include the large electron positron collider at CERN, which will be upgraded to the large hadron collider. However, the B-factories are based on a novel design which was forced upon us by the limitation of technology which required that the B-mesons should travel a distance larger than the spatial resolution of the silicon vertex detectors that are used. The asymmetric design uses one of the fundamental implications of Einstein's special theory of relativity, which is that of time-dilation as follows: the electron beam energy is significantly larger than that of the positron beam, each of which is now accelerated in a different ring and then brought together to a central detector region. The asymmetry of the energies ensures that the decay products are now boosted in the laboratory frame and therefore the particles generated 'live longer' and traverse a distance that is large enough for the detectors to resolve. As a concrete example, we consider the BELLE experiment at Japan's KEK laboratory. Here the electron energy corresponds to $E_e = 8$ GeV, (where the GeV unit corresponds roughly to the energy that would be generated if a proton were to be converted into energy), while the positron energy corresponds to $E_{\bar{e}} = 3.5$ GeV. This corresponds to $\beta = v/c = 0.391$, which is the boost velocity of the reaction products in the laboratory frame in units of the velocity of light and $\gamma = 1/\sqrt{1-\beta^2} = 1.18$, the *time dilation* factor (or the reciprocal of the *Lorentz-Fitzgerald* contraction factor). The life-time of the B-meson is 1.55×10^{-12} sec, which implies that in a symmetric collider it would have only traversed 35 μm, while in BELLE it traverses 290 μm, while the silicon vertex detector resolution corresponds to 50 μm. We thus illustrate with this example the interplay of the special theory of relativity, the needs of elementary particle physics research and present day technology.

Box 4. *CP* Violation and the Early Universe

The currently accepted picture of the origin of the Universe is often referred to as the Big Bang picture. The Big Bang out of which the known Universe is supposed to have arisen is based on solutions of Einstein's equations of General Relativity which correspond to an expanding, homogeneous and isotropic Universe, and which accounts for the recession of galaxies governed by Hubble's law, and for the nearly homogeneous cosmic microwave background radiation corresponding to a black body temperature of 2.7 K. In our Universe, we observe more matter than anti-matter ('baryon asymmetry'). One may pose a question as to whether in the Big Bang epoch this was the case. The well-known Russian physicist Andrei Sakharov answered this question as follows: a baryon symmetric Universe at the time of the Big Bang could have evolved into an asymmetric one if three conditions were necessarily met.

- there must be interactions present which violate baryon number in the first place,
- that the Universe be out of thermal equilibrium, and
- that CP be violated.

In this manner CP violation could possibly hold one of the keys to the origin of the matter-antimatter asymmetry in the Universe as we know it. In fact, one of the reasons cited for the award of the Nobel Prize to Fitch and Cronin is the connection of CP violation to this feature of the Universe.

T Reversal Violation

Soon after the discovery of parity violation in experiments following the suggestions of Yang and Lee, many authors considered the possibility of violation of the other discrete symmetries we have discussed earlier. The great Russian physicist L D Landau considered the possibility of elementary particles possessing a non-vanishing electric dipole moment (edm) which would imply the violation of T-reversal invariance. Note however that a complex system like a water molecule does possess an edm, but this does not come into conflict with T-reversal invariance. There are many atomic systems in which the edms of elementary particles such as neutrons or electrons can manifest themselves. However, these edms appear to be very small quantities and there has been no detection of such effects. This implies that experiments must seek higher levels of precision before they can announce a discovery, and it also implies that theoretical scenarios which predict large values of edms can be constrained or ruled out by the non-observation of edms. (The SM of the electroweak interaction gives a contribution to the neutron edm of the order of 10^{-31} to 10^{-33} e cm which, because it is second order in the weak interaction coupling constant, is very small.) Here we discuss one specific technique based on so-called ultracold neutrons, which is implemented at Rutherford Appleton Laboratories. Nuclear reactors serve as copious sources of neutrons which are used for a variety of experiments. Normally these neutrons emerge with a kinetic energy of about 1/40 eV, and are called thermal neutrons. In order to carry out very precise measurements of static and other properties of neutrons, it is necessary to slow them down to very low kinetic energies of the order 10^{-7} eV or even less. Such neutrons called ultra-cold neutrons provide an opportunity to carry out highly precise experiments.

'The Ramsey resonance technique' can be used to measure with very high precision the precession frequency of ultracold neutrons in a weak magnetic field. The precession frequency will change in the presence of an electric field if the neutron has an edm. The most recent results give an upper bound of the order of $d_n \leq 10^{-26}$ e cm.

Synthesis

In this two part article we have discussed the origins of the important discrete symmetries, C, P, T and CP, which are at the heart of the nature of space and time. In particular, the fundamental interactions between elementary particles and the mediators of forces between them must either respect these symmetries or violate them in a specific manner, but without coming into conflict with the CPT theorem, a rigorous consequence of the special theory of relativity. Of special interest are current and ongoing experiments that verify and constrain theories of these interactions at an ever increasing level of precision. Among these is the violation of P by the weak-interactions, which has recently been detected in a low-energy but high precision experiment involving the nuclear anapole moment. The violation of CP in the B-meson system is only the second example of such a phenomenon discovered in current experiments. The detection of direct T violation is an ongoing experimental challenge in such settings as the ultra-cold neutron facilities. CP violation is also crucial for the rise of baryon asymmetry from a baryon symmetric Universe in the standard Big Bang cosmology. In this brief article, we have examined and summarized all the aspects mentioned above of a fascinating and challenging aspect of the physical world in which we live.

Acknowledgements

JM, BS and SS thank the summer students programme of the Centre for Theoretical Studies, Indian Institute of Science which led to this article. We thank Dr. B P Das for innumerable discussions, and Dr. B Moussallam for a careful reading of the manuscript.

Suggested Reading

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Everything is made of atoms. That is the key hypothesis.

Richard P Feynman
The Feynman Lecture on Physics