Asymmetry in Nature – Discrete Symmetries in Particle Physics and their Violation

1. Background and Parity 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 the first part of this article we present a general background and discuss parity violation.

Introduction

In day-to-day life when we use the word *symmetry*, we mean a geometric property of an object by virtue of which it remains unchanged on performing some transformation on it. For example, a square looks the same when rotated by 90°, a circle remains unchanged when rotated by any angle about its center, a regular hexagon looks indistinguishable when rotated by multiples of 60°

In physics, if equations of motion for a given physical system remain unchanged after some kind of transformation on the system, then it is said to be symmetric on the basis of its physical behaviour which is unaffected by these transformations. Furthermore, we need to know the symmetries appropriate to a physical system because all conservation laws in physics are consequences of some underlying symmetries. For example, the law of conservation of linear momentum is a consequence of the *homogeneity* of space, i.e., *translational symmetry* of space. This is possible only in the absence of external forces. If there is an external force then the point at which it acts is a special point and it is not physically identical with other points. Thus homogeneity of space ensures the absence of external forces and, along with the law of inertia, establishes the law of conservation of linear momentum.

Knowledge of conservation laws is very important for studying any system or solving physical problems. Hence the study of symmetries of the system is equally important. We define symmetry thus:

If a physical system undergoes certain transformations (e.g., translations, rotations), and if the transformed system looks identical (on the basis of physical observables) to the untransformed one, then those transformations will be called symmetry transformations and the system will be said to possess those symmetries.

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Symmetries are of two types: continuous and discrete. Continuous symmetry transformations are labelled by parameters each of which can take any value in a given range. On the other hand, discrete symmetry transformations are labelled by a set of integers or discrete numbers. The translational symmetry of empty space is a continuous symmetry because translation by any amount leaves the space unchanged. Rotation of a circle in its plane is also a continuous symmetry. Rotation of a square is a discrete symmetry as only rotations by $n \times 90°$ for all integer n, leave the square unchanged.

In this article we shall be concerned with symmetries of the laws that describe and govern the interactions of *elementary particle physics* (see *Box* 1). We will be dealing with the implications of certain *bilateral* symmetries (see next section) of these interactions and their possible violations.

Bilateral Symmetries

Keywords
Discrete symmetries, parity violation.

Those discrete symmetry transformations whose double operation is the same as no operation are called bilateral

Box 1. History of Elementary Particle Physics

It is very difficult to say exactly when elementary particle physics (EPP) came into being. The first elementary particle to be discovered was the *electron* by J J Thomson in 1896. Radioactivity was discovered in 1896 by Becquerel, which is considered as the beginning of nuclear physics and EPP was a subset of it in early years. It might be fair to say that EPP separated from nuclear physics around 1930's.

Since the beginning of the last century the experimentalists started probing the atom and in 1911 Rutherford found it to be composed of electrons and a positively charged *nucleus* and the nucleus of hydrogen atom was identified as the *proton*. Then in 1932 Chadwick discovered the *neutron* and now the nucleus is understood to be a bound state of protons and neutrons. Study of unstable nucleii hinted at the existence of a massless chargeless particle, called the *neutrino*, which was postulated by Pauli in 1931 and experimentally observed by Reines and Cowan in 1956. The stability of nucleii against Coulomb repulsion was explained by Yukawa in 1935 by introducing π-mesons as mediators of nuclear interaction and which were first observed by Powell in 1947. After that a large number of mesons were discovered. The existence of anti-particles was predicted by Dirac in 1932 and the *positron*, the anti-particle of the electron was discovered by Anderson in 1932. The heavier cousin of the electron, the muon was discovered by Neddermeyer and Anderson in 1937.

By mid 1950's a big list of *baryons*, the heavy particles, *mesons*, the medium mass particles and *leptons*, the light particles, which was then categorised based on their mass, spin, electric charge, intrinsic parity, etc. faced the theorists. The quantum numbers of particles were found to have a pattern in the categorised lists and hinted that all baryons and mesons must have further constituents called *quarks*. The first quark model talked about only three quarks, namely, up, down and strange but later this was extended to six quarks, where the sixth quark, the top quark was discovered as late as in 1995. In late 60's weak interactions were postulated to be caused by exchange of massive bosons, namely, $W^{\pm}$ and Z which were observed in collider experiments from 1983. Today observed matter is understood to be made up of six quarks, three leptons and three neutrinos interacting among themselves via exchange of photons, three massive bosons and eight gluons (carriers of strong interaction) along with one spin-0 massive boson called *higgs* which is not yet discovered.

symmetries. For example, mirror reflection is a bilateral transformation since mirror reflection of a mirror reflection is as good as no reflection. In 3-dimensions, if the mirror is kept parallel to xy-plane, then the reflection will reverse the direction of z axis while reflection of this reflected image brings the z-axis back to its initial configuration. If we denote the bilateral transformation operator which acts on the system S by B then we have

$$B(BS) = S,$$

which means for all bilateral operators, $B^2=$ Identity.

In the following we will talk about three kinds of bilateral symmetries namely, parity or spatial inversion (P), charge conjugation (C) and time reversal (T).

(a) Parity – The Left-Right Symmetry, P

Parity being a good symmetry of a physical system implies that the system is left-right symmetric.

Parity transformation refers to the inversion of spatial co-ordinates with respect to the origin, i.e.,

$$x \longrightarrow -x, \quad y \longrightarrow -y, \quad z \longrightarrow -z,$$

which is the same as $\vec{r} \rightarrow -\vec{r}$. From this definition, it is clear that parity is a bilateral transformation. In 3-dimensions, parity is also called left-right symmetry. If you align the thumb, forefinger and the middle finger of your right hand perpendicular to each other with thumb and forefinger in the plane of your palm, then this describes a right-handed co-ordinate system with x, y and z axes pointing along thumb, forefinger and middle finger, respectively. After inversion of co-ordinates, if you try to align your thumb and forefinger with x and y axes, then the middle finger will point opposite to z axis. But if you try the same with your left hand, you will find that all the three axes match with the fingers. This co-ordinate system is left-handed. Thus, parity being a good symmetry of a physical system implies that the system is left-right symmetric.

Under parity operation P, a function $f(\mathbf{r})$ transforms to $f(-\mathbf{r})$, and if these two functions are the same up to a sign then the function $f(\mathbf{r})$ will be said to have definite parity. For example,

$$\cos(x) \xrightarrow{P} \cos(-x) = \cos(x) \qquad \text{even parity}$$

$$\sin(x) \xrightarrow{P} \sin(-x) = -\sin(x) \qquad \text{odd parity.}$$

If $f(-\mathbf{r})$ and $f(\mathbf{r})$ are of different forms then the function does not have definite parity. The solutions of parity

Symmetry of a physical system under time reversal simply means that all the processes in the system are reversible.

symmetric physical equations may be of definite parity. In the context of elementary particle physics it becomes necessary to assign such parity *quantum numbers* to particle states (wave functions). The parity of the wave function of a single particle state is called its *intrinsic parity*.

(b) Charge Conjugation – C

Charge conjugation reverses the sign of electric charge of a particle along with all of its other internal quantum numbers, such as strangeness, baryon number, lepton number, and leaves all other quantum numbers unchanged. Symmetry under C means that interaction of two particles is independent of the sign of their internal quantum numbers and charge. In other words, this symmetry implies interaction of two particles is exactly identical to the interaction of the corresponding *anti-particles*, where we define anti-particles as the charge conjugate counterparts of the corresponding particles (see *Table* 1 for examples).

(c) Time Reversal – T

Time reversal means reversing the direction of the time co-ordinate, i.e.,

$$t \xrightarrow{T} -t.$$

Symmetry of a physical system under time reversal simply means that all the processes in the system are reversible.

Particle/ anti-particle	Electric charge	Baryon number	Lepton number	Strangeness
Electron	$-e$	0	1	0
Positron	e	0	−1	0
Proton	e	1	0	0
Anti-proton	$-e$	−1	0	0
K^+	e	0	0	1
K^-	$-e$	0	0	−1

Table 1. Particles and anti-particles.

Physical systems involving only strong and electromagnetic interactions are symmetric under all three bilateral transformations listed above. But in nature, other types of interactions, namely, weak and gravitational interactions, exist. Weak interactions are known to violate P as well as T We will discuss P and T violations later on in this article.

Invariance under the combined action of C, P and T is a consequence of relativistic invariance or *Lorentz invariance* of the laws of physics.

CPT Theorem

If we take the whole universe as one system, which involves all four kinds of interactions, then surely the system is not symmetric under P, C and T separately. In fact, the system violates all three symmetries. Then one may ask, "Is the system symmetric under certain combinations of these transformations?" to which the answer turns out to be "yes" Under the combined operation of all three transformations physical laws remain unchanged. More accurately, invariance under the combined action of C, P and T is a consequence of relativistic invariance or *Lorentz invariance* of the laws of physics. Certain consequences of this theorem are:

- the mass of a particle and its anti-particle are exactly the same,
- the total life-time, τ, of an unstable particle and its anti-particle are exactly the same,
- the magnetic moment is equal and opposite for particle and anti-particle.

For example, masses of electron and positron are exactly same, the life-time of K^+ is same as that of K^- etc. Till date all the tests for CPT violation have yielded negative results.

Parity Violation

Before 1950's, parity was assumed to be a good symmetry of natural forces. But in the early 50's the '$\tau - \theta$

puzzle' posed a question on parity symmetry. Two particles, then named as τ and θ, were found to be identical in almost every respect, such as their masses, life-times, charges, spins, except their weak decay into pions,

$$\theta \longrightarrow \pi^+\pi^0 \qquad P = +1$$

$$\tau \longrightarrow \pi^+\pi^+\pi^- \qquad P = -1.$$

Based on intrinsic parity of pions ($P_\pi = -1$), conservation of angular momentum and conservation of parity, it was inferred that θ is an even-parity particle and τ is an odd-parity particle. The puzzle was "How can two particles with otherwise identical kinematical properties have different parities?" This puzzle was solved by C N Yang and T D Lee, who proposed that the weak interaction does not conserve parity and that the τ and θ are the same particle, now renamed as K^+ Yang and Lee then suggested experiments to search for parity violation, later confirmed by C S Wu in β-decay of ^{60}Co nuclei. In the experiment the ^{60}Co atoms were located in a thin surface layer of a single crystal of Ce-Mg-nitrate, which was cooled to 0.003 K to reduce any thermal vibrations and the whole system was placed in a strong magnetic field to align the nuclear spins of ^{60}Co nuclei. If parity was a good symmetry then the emitted β-particles should emerge in a symmetric way with respect to the spin alignment of the nuclei. But it was observed that the β-particles are emitted preferentially in a direction opposite to that of the nuclear spin. Further study of β-decay of ^{60}Co indicated that parity is not only violated, but is violated maximally. Neutrinos produced in β-decay are found to be left-handed only, and left-handed anti-neutrino was not observed. This indicates that P is violated along with violation of C symmetry such that CP is conserved. These properties of the weak interactions have been tested at very high precision and at very low to very high energies for several decades. Nevertheless a certain effect has only been

Suggested Reading

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Box 2: The Nuclear Anapole Moment

Soon after the proposal that the weak interactions violate parity, and its experimental confirmation in the ^{60}Co system, Zel'dovich and Vaks proposed that the weak interaction should induce an observable nuclear 'anapole' moment, at a level that became possible to detect with technology that was available only as recently as 1998.

The first term in the multipole expansion of the potential due to an electric charge distribution, at a point outside the distribution is called the monopole moment. The same term is called anapole moment when the potential is expanded at a point inside the charge distribution. The anapole moment is zero if parity is a good symmetry of the interaction among the charged particles. But in the case of nuclei, the quarks interact among themselves via parity violating weak interaction along with parity conserving strong and electromagnetic interactions, and the anapole moment is non-zero and proportional to the nuclear spin I. Experimentally it is very difficult to measure the nuclear anapole moment (NAM) because it is caused by higher order weak interactions among the quarks. Further, its contribution to parity non-conserving (PNC) transitions in atoms goes to zero when the exchanged photon is real. A very high precision experiment (more than 1% accuracy) on PNC transitions is required to see the contribution from NAM. Other contributions to PNC transitions are independent of the nuclear spin while NAM contributions depend on I. Thus to measure the NAM one has to separate the I dependent part from the comparatively large I independent part, which became possible only as recently as 1998.

This example illustrates that while the electro-weak interactions have been tested to very great precision at accelerator experiments, there continue to be experimental challenges at the level of table top experiments.

recently experimentally observed (see *Box* 2) although it was predicted soon after the work of Yang and Lee.

CP, first thought to be conserved in weak interactions, was later found to be violated minutely in the neutral kaon system, and more recently in the neutral B-meson system. We will discuss CP violation and T violation in the second part of this article.

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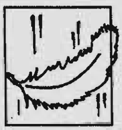

Symmetry, as wide or as narrow
as you may define its meaning,
is one idea by which man through
the ages has tried to comprehend and
create order, beauty, and perfection.

Hermann Weyl