CP violation

In particle physics, **CP violation** (CP standing for **charge parity**) is a violation of the postulated **CP-symmetry** (or **charge conjugation parity symmetry**): the combination of C-symmetry (charge conjugation symmetry) and P-symmetry (parity symmetry). CP-symmetry states that the laws of physics should be the same if a particle is interchanged with its antiparticle (C symmetry), and when its spatial coordinates are inverted ("mirror" or P symmetry). The discovery of CP violation in 1964 in the decays of neutral kaons resulted in the Nobel Prize in Physics in 1980 for its discoverers James Cronin and Val Fitch.

It plays an important role both in the attempts of cosmology to explain the dominance of matter over antimatter in the present Universe, and in the study of weak interactions in particle physics.

1 CP-symmetry

CP-symmetry, often called just *CP*, is the product of two symmetries: C for charge conjugation, which transforms a particle into its antiparticle, and P for parity, which creates the mirror image of a physical system. The strong interaction and electromagnetic interaction seem to be invariant under the combined CP transformation operation, but this symmetry is slightly violated during certain types of weak decay. Historically, CP-symmetry was proposed to restore order after the discovery of parity violation in the 1950s.

The idea behind parity symmetry is that the equations of particle physics are invariant under mirror inversion. This leads to the prediction that the mirror image of a reaction (such as a chemical reaction or radioactive decay) occurs at the same rate as the original reaction. Parity symmetry appears to be valid for all reactions involving electromagnetism and strong interactions. Until 1956, parity conservation was believed to be one of the fundamental geometric conservation laws (along with conservation of energy and conservation of momentum). However, in 1956 a careful critical review of the existing experimental data by theoretical physicists Tsung-Dao Lee and Chen Ning Yang revealed that while parity conservation had been verified in decays by the strong or electromagnetic interactions, it was untested in the weak interaction. They proposed several possible direct experimental tests. The first test based on beta decay of cobalt-60 nuclei was carried out in 1956 by a group led by Chien-Shiung Wu, and demonstrated conclusively that weak interactions violate the P symmetry or, as the analogy goes, some reactions did not occur as often as their mirror image.

Overall, the symmetry of a quantum mechanical system can be restored if another symmetry *S* can be found such that the combined symmetry *PS* remains unbroken. This rather subtle point about the structure of Hilbert space was realized shortly after the discovery of *P* violation, and it was proposed that charge conjugation was the desired symmetry to restore order.

Simply speaking, charge conjugation is a symmetry between particles and antiparticles, and so CP-symmetry was proposed in 1957 by Lev Landau as the true symmetry between matter and antimatter. In other words, a process in which all particles are exchanged with their antiparticles was assumed to be equivalent to the mirror image of the original process.

1.1 CP violation in the Standard Model

"Direct" CP violation is allowed in the Standard Model if a complex phase appears in the CKM matrix describing quark mixing, or the PMNS matrix describing neutrino mixing. A necessary condition for the appearance of the complex phase is the presence of at least three generations of quarks (if fewer generations are present, the complex phase parameter can be absorbed into redefinitions of the quark fields).

The reason why such a complex phase causes CP violation is not immediately obvious, but can be seen as follows. Consider any given particles (or sets of particles) a and b , and their antiparticles $\bar{a}$ and $\bar{b}$. Now consider the processes $a \to b$ and the corresponding antiparticle process $\bar{a} \to \bar{b}$, and denote their amplitudes M and $\bar{M}$ respectively. Before CP violation, these terms must be the *same* complex number. We can separate the magnitude and phase by writing $M = |M|e^{i\theta}$. If a phase term is introduced from (e.g.) the CKM matrix, denote it $e^{i\phi}$. Note that $\bar{M}$ contains the conjugate matrix to M , so it picks up a phase term $e^{-i\phi}$. Now we have:

$$M = |M|e^{i\theta}e^{i\phi}$$

$$\bar{M} = |M|e^{i\theta}e^{-i\phi}$$

Physically measurable reaction rates are proportional to $|M|^2$, thus so far nothing is different. However, consider that there are *two different routes* (e.g. intermediate states) for $a \to b$. Now we have:

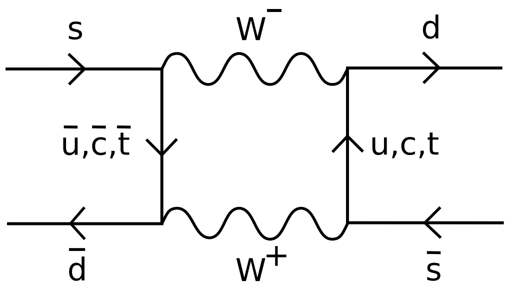
$$M = |M_1|e^{i\theta_1}e^{i\phi_1} + |M_2|e^{i\theta_2}e^{i\phi_2}$$

$$\bar{M} = |M_1|e^{i\theta_1}e^{-i\phi_1} + |M_2|e^{i\theta_2}e^{-i\phi_2}$$

Some further calculation gives:

$$|M|^2 - |\bar{M}|^2 = 4|M_1||M_2|\sin(\theta_1 - \theta_2)\sin(\phi_1 - \phi_2)$$

Thus, we see that a complex phase gives rise to processes that proceed at different rates for particles and antiparticles, and CP is violated.



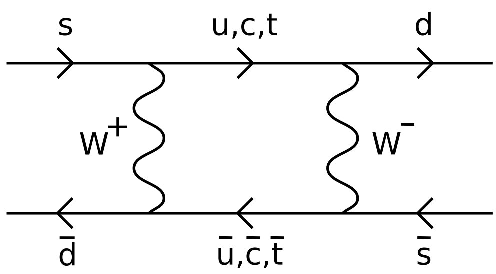
Kaon oscillation box diagram

2 Experimental status

2.1 Indirect CP violation

In 1964, James Cronin, Val Fitch and coworkers provided clear evidence (which was first announced at the 12th ICHEP conference in Dubna) that CP-symmetry could be broken. This work[1] won them the 1980 Nobel Prize. This discovery showed that weak interactions violate not only the charge-conjugation symmetry C between particles and antiparticles and the P or parity, but also their combination. The discovery shocked particle physics and opened the door to questions still at the core of particle physics and of cosmology today. The lack of an exact CP-symmetry, but also the fact that it is so nearly a symmetry, created a great puzzle.

Only a weaker version of the symmetry could be preserved by physical phenomena, which was CPT symmetry. Besides C and P, there is a third operation, time reversal (T), which corresponds to reversal of motion. Invariance under time reversal implies that whenever a motion is allowed by the laws of physics, the reversed motion is also an allowed one. The combination of CPT is thought to constitute an exact symmetry of all types of fundamental interactions. Because of the CPT symmetry, a violation of the CP-symmetry is equivalent to a violation of the T symmetry. CP violation implied nonconservation of T, provided that the long-held CPT theorem was valid. In this theorem, regarded as one of the basic principles of quantum field theory, charge conjugation, parity, and time reversal are applied together.



The two box diagrams above are the Feynman diagrams providing the leading contributions to the amplitude of K0-K0 oscillation

2.2 Direct CP violation

The kind of CP violation discovered in 1964 was linked to the fact that neutral kaons can transform into their antiparticles (in which each quark is replaced with the other's antiquark) and vice versa, but such transformation does not occur with exactly the same probability in both directions; this is called *indirect* CP violation. Despite many searches, no other manifestation of CP violation was discovered until the 1990s, when the NA31 experiment at CERN suggested evidence for CP violation in the decay process of the very same neutral kaons (*direct* CP violation). The observation was somewhat controversial, and final proof for it came in 1999 from the KTeV experiment at Fermilab[2] and the NA48 experiment at CERN.[3]

In 2001, a new generation of experiments, including the BaBar Experiment at the Stanford Linear Accelerator Center (SLAC)[4] and the Belle Experiment at the High Energy Accelerator Research Organisation (KEK)[5] in Japan, observed direct CP violation in a different system, namely in decays of the B mesons.[6] A large number of CP violation processes in B meson decays have now been discovered. Before these "B-factory" experiments, there was a logical possibility that all CP violation was confined to kaon physics. However, this raised the question of why it's *not* extended to the strong force, and furthermore, why this is not predicted in the unextended Standard Model, despite the model being undeniably accurate with "normal" phenomena.

In 2011, a hint of CP violation in decays of neutral D mesons was reported by the LHCb experiment at CERN using 0.6 fb^{-1} of Run 1 data.[7] However, the same measurement using the full 3.0 fb^{-1} Run 1 sample was consistent with CP symmetry.[8]

3 Strong CP problem

There is no experimentally known violation of the CP-symmetry in quantum chromodynamics. As there is no known reason for it to be conserved in QCD specifically, this is a "fine tuning" problem known as the strong CP problem.

QCD does not violate the CP-symmetry as easily as the electroweak theory; unlike the electroweak theory in which the gauge fields couple to chiral currents constructed from the fermionic fields, the gluons couple to vector currents. Experiments do not indicate any CP violation in the QCD sector. For example, a generic CP violation in the strongly interacting sector would create the electric dipole moment of the neutron which would be comparable to 10^{-18} e·m while the experimental upper bound is roughly one trillionth that size.

This is a problem because at the end, there are natural terms in the QCD Lagrangian that are able to break the CP-symmetry.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{n_f g^2\theta}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5})\psi$$

For a nonzero choice of the θ angle and the chiral phase of the quark mass θ′ one expects the CP-symmetry to be violated. One usually assumes that the chiral quark mass phase can be converted to a contribution to the total effective $\tilde{\theta}$ angle, but it remains to be explained why this angle is extremely small instead of being of order one; the particular value of the θ angle that must be very close to zero (in this case) is an example of a fine-tuning problem in physics, and is typically solved by physics beyond the Standard Model.

There are several proposed solutions to solve the strong CP problem. The most well-known is Peccei–Quinn theory, involving new scalar particles called axions. A newer, more radical approach not requiring the axion is a theory involving two time dimensions first proposed in 1998 by Bars, Deliduman, and Andreev.[9]

3.1 Little CP problem

The little CP problem is a term coined by Lisa Randall. It refers to an issue related to the enhanced new physics contributions to the electric dipole moment (EDM) of the neutron in flavor anarchic models.[10]

4 CP violation and the matter–antimatter imbalance

Main article: Baryogenesis

The universe is made chiefly of matter, rather than consisting of equal parts of matter and antimatter as might be expected. It can be demonstrated that, to create an imbalance in matter and antimatter from an initial condition of balance, the Sakharov conditions must be satisfied, one of which is the existence of CP violation during the extreme conditions of the first seconds after the Big Bang. Explanations which do not involve CP violation are less plausible, since they rely on the assumption that the matter–antimatter imbalance was present at the beginning, or on other admittedly exotic assumptions.

The Big Bang should have produced equal amounts of matter and antimatter if CP-symmetry was preserved; as such, there should have been total cancellation of both—protons should have cancelled with antiprotons, electrons with positrons, neutrons with antineutrons, and so on. This would have resulted in a sea of radiation in the universe with no matter. Since this is not the case, after the Big Bang, physical laws must have acted differently for matter and antimatter, i.e. violating CP-symmetry.

The Standard Model contains at least three sources of CP violation. The first of these, involving the Cabibbo–Kobayashi–Maskawa matrix in the quark sector, has been observed experimentally and can only account for a small portion of the CP violation required to explain the matter-antimatter asymmetry. The strong interaction should also violate CP, in principle, but the failure to observe the electric dipole moment of the neutron in experiments suggests that any CP violation in the strong sector is also too small to account for the necessary CP violation in the early universe. The third source of CP violation is the Pontecorvo–Maki–Nakagawa–Sakata matrix in the lepton sector. Current neutrino experiments are not yet sensitive enough to allow experimental observation of CP violation in the lepton sector, but the NOνA experiment currently under construction could observe some small fraction of possible CP violating phases and proposed neutrino experiments Hyper-Kamiokande and LBNE will be sensitive to a relatively large fraction of CP violating phases. Further into the future, a neutrino factory could be sensitive to nearly all possible CP violating phases. If neutrinos are Majorana fermions, the PMNS matrix could have two independent CP violating phases leading to a fourth source of CP violation within the Standard Model. The experimental evidence for Majorana neutrinos would be the observation of neutrinoless double-beta decay. As of September 2013, the best limits come from the GERDA experiment. CP violation in the lepton sector generates a matter-antimatter asymmetry through a process called leptogenesis. This could become the preferred explanation in the Standard Model for the matter-antimatter asymmetry of the universe once CP violation is experimentally confirmed in the lepton sector.

If CP violation in the lepton sector is experimentally determined to be too small to account for matter-antimatter asymmetry, some new physics beyond the Standard Model would be required to explain additional sources of CP violation. Fortunately, it is generally the case that adding new particles and/or interactions to the Standard Model introduces new sources of CP violation since CP is not a symmetry of nature.

5 See also

- B-factory
- LHCb
- BTeV experiment
- Cabibbo–Kobayashi–Maskawa matrix
- Penguin diagram
- Neutral particle oscillation

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7 Further reading

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8 External links

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