Broken CP Symmetry and the Physics Nobel Prize 2008

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Kobayashi and Maskawa shared half the Physics Nobel Prize for 2008 for their work which incorporated CP violation in the standard model using three generations of quarks. We give an elementary discussion of this work and its importance in our understanding of the fundamental physical laws of nature.

1. Introduction

Makoto Kobayashi and Toshihide Maskawa (see *Box* 1) shared the physics Nobel Prize for 2008 with Yoichiro Nambu "for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature".

In this article we will discuss, in simple language, the work of Kobayashi and Maskawa (KM) and its importance. We will explain (i) the meaning of broken symmetry, specifically the broken CP, (ii) the meaning of three families of quarks, (iii) how the ideas of broken CP led KM to suggest the existence of (at least) three families of quarks and (iv) how their ideas got verified which culminated in their getting the Nobel Prize.

2. Fundamental Laws and their Symmetries

Keywords
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The concept of symmetry is a familiar one. Objects that we see around us – squares, circles, plants, trees, animals, etc. – exhibit obvious symmetries. Things which may not look symmetric to our eyes may also be made of symmetric objects at the microscopic level. Various solids can be described in terms of fundamental units which display crystal symmetries. These symmetries

Box 1. The Nobel Laureates

Makoto Kobayashi (left) and Toshihide Maskawa (right) shared the 2008 Nobel prize in physics with Yoichiro Nambu. Both are Japanese citizens. This comes in quick succession in Japan. Just six years ago, another Japanese high energy physicist M Koshiba was awarded the Nobel Prize for the discovery of cosmic neutrinos.

Makoto Kobayashi was born in 1944 in Nagoya in Japan. He completed his PhD in 1972 at the Nagoya university. Presently, he is a Professor Emeritus at the Japanese laboratory KEK, the same laboratory which built the B factory and verified the theory of CP violation proposed by Kobayashi and Maskawa. Professor Kobayashi is also an executive director of the Japan Society for the Promotion of Science.

Toshihide Maskawa was born in 1940 and completed his PhD five years earlier than Kobayashi from the same university – Nagoya. He is presently a Professor at Kyoto Sangyo University in Kyoto and Professor Emeritus at Yukawa Institute of Theoretical Physics in Japan. Maskawa has a remarkable life. He does not speak English and according to newspaper reports he did not have a passport to travel when he got the news of the Nobel Prize. He did finally go out of Japan to receive the honor. In a speech at the Japanese Embassy in Sweden he said that he is like a statue of Buddha and just like the statue he has never left Japan. He said that he loved Japan, and now that he had ventured out, he loved Japan even more!

play an important role in determining the properties of solids made from these basic units.

Symmetries familiar to everyday human experience refer to symmetries of objects or of their constituents. In physics, we are more concerned with symmetries of fundamental physical laws. What are the fundamental physical laws and how does one define their symmetries? The complex world around us follows a few basic principles of physics. We call them fundamental physical laws. Familiar examples in classical mechanics are Newton's laws and Maxwell's equations. Mathematically, symmetries can be defined as transformations on a physical system or on basic equations governing the system. If they remain unchanged then the system or these equations are said to possess the specific symmetry. A simple example of a symmetry is translation in space. The outcome of an experiment does not depend on where the apparatus is placed as long as the surroundings are identical. Equivalently, Newton's and Maxwell's equations are invariant under the simple coordinate change $x \rightarrow x + a$. In 1918, a mathematician named Emmy Noether[1] discovered a curious fact: the existence of symmetries of equations describing dynamics implies that some physical quantity is conserved! Thus the fact that the results of experiments are independent of where the experiments are performed implies that momentum is conserved! In addition to momentum, we know that energy, angular momentum, electric charge and baryon number are also absolutely conserved quantities. Conservation of each of these quantities is related to the presence of some symmetry.

Not all symmetries found in nature are exact. There exist several symmetries which are broken. Symmetries can be broken in two distinct ways. It can happen that the underlying equation describing a phenomenon has a (possibly small) piece which violates the invariance associated with the main part. A familiar example of this is the Zeeman effect. If we place an atom in a (weak) magnetic field then its motion is governed by two parts of the Hamiltonian. The first part is invariant under the rotations made on the coordinates and spin while the second part containing the magnetic field is not rotationally invariant since the field is chosen in a specific direction. Symmetry can also be broken in a more subtle way. It may happen that the basic equations governing a system remain exactly symmetric under some specific set of transformations. But the state of the physical system described by these equations chooses one of many possibilities, each related by the symmetry transformations. This idea called 'spontaneous symmetry breaking' was the central point of Nambu's work for which he shared half the Nobel Prize with Kobayashi and Maskawa. We shall not discuss here the concept of spontaneously broken symmetry further. (This is separately discussed in the accompanying article [1]). We will consider in this article the first possibility, which is sometimes called the explicit symmetry breaking. The work of KM uses this way of breaking the 'CP symmetry', a term which we will explain as we go along.

Symmetries have played a fundamental role in the development of physics. Historically, one discovered the symmetries associated with classical Newton's and

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[1] *Resonance,* Vol.3, No.9, 1998.

Maxwell's equations after they were proposed. Development of several concepts in modern physics went the other way round. One employed the existing and new symmetries to formulate new fundamental laws! Einstein derived his equation of general relativity by appealing to a symmetry called the 'general coordinate invariance'. In particle physics, both the exact and partially broken symmetries have been exploited in successfully formulating the basic laws of strong and weak interactions. Kobayashi and Maskawa used the concept of broken 'CP symmetry' to suggest the existence of new quarks and to determine their weak interactions. In order to appreciate this work we first introduce the ideas of the standard model – and its basic constituents quarks and leptons.

3. Standard Model of Particle Physics

The world of elementary particle physics reveals itself at distances shorter than the nuclear radius $R_{\mathrm{N}} \approx 1\mathrm{Fermi} = 10^{-15}\mathrm{meter}$. One needs higher and higher energy to probe shorter and shorter distances. After the second world war, physicists were able to build machines with higher and higher energy. This led to the discovery of many new particles, and attempts to systematically classify and understand their behavior finally led to the birth of what is now called the standard model of elementary particle physics. The history of how various particles were detected and how our present-day knowledge of particle physics was arrived at, is an exciting one. Rather than going into all the details, we summarize what we know about particle physics and the basic properties of the standard model.

All the known objects in the world are made up of only three familiar particles, namely, protons, neutrons and electrons. Electrons and protons attract each other by the electromagnetic forces. Electric charge e is the fundamental parameter which determines electromagnetic forces. The force between two charged particles is determined by e^2 and one uses a dimensionless coupling $\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}$ to characterize the strength. Protons and neutrons also attract each other at a distance of the order of a Fermi. This attraction is due to an entirely different force called 'strong or nuclear force'. It is called so because the strength α_{s} analogous to α is about 25 times stronger. If these were the only forces and particles then all the matter on earth would be stable. This is not the case. We know that many nuclei are radioactive. One nucleus changes to another by changing its proton or neutron numbers. This phenomenon is caused by yet another force called the 'weak force'. One needs yet another coupling to describe this force. Fermi gave a quantitative description of weak interactions. According to his theory, weak interactions are characterized by a coupling G_F (analogous to the Newton coupling

G in gravitational force). G_F is much larger than G. The name 'weak interaction' arises from the fact that the 'weak force' between, say, two protons at the nuclear radius distance is much weaker than the strong or electromagnetic force. The existence of the weak force is not limited to particles in the nucleus but it also affects the electrons. In fact, electrons interact weakly with a neutral (almost) massless particle called 'neutrino'. Weak interactions affect almost everything. All the known particles except photons (and strongly interacting particles called 'gluons') experience weak forces.

Theoretical studies of the above forces at high energy require a formalism called 'quantum field theory'. This formalism allows one to include the effects of creation and destruction of particles which can occur at high energy. One of the interesting features associated with this desription is that the basic couplings α, $\alpha_{\rm s}$ and analogous weak coupling are not constant. Their values depend on the distance between particles interacting with each other. This feature is experimentally verified. It was found that the $\alpha_{\rm s}$ decreases with distance, i.e., with increase in energy. This resulted in the Nobel Prize in 2004 for Gross and Wilczek as well as Politzer who worked out a detailed theory for this before this behavior of $\alpha_{\rm s}$ was verified [2]. The behavior of weak and electromagnetic couplings is opposite to that of $\alpha_{\rm s}$. Their strengths increase with energy. Increase in the weak force is much faster than in the electromagnetic force with the result that there exists some energy at which the weak force has the same strength as the electromagnetic force. The electromagnetic and weak couplings become comparable at an energy 100 times the rest energy of the proton, $m_{\rm p}c^2$. (In particle physics terminology, energy is measured in terms of electron volt rather than Joule: 1eV$\approx 1.6 \times 10^{-19}$ Joule. The proton rest energy in this unit is approximately 10^9 eV=1 GeV.) The standard model is a unified description of the electromagnetic and weak forces. This is based on ideas developed by Nambu, Glashow, Weinberg and Salam. The last three shared the Physics Nobel Prize in 1979 and Nambu's work got recognized in 2008 with the Nobel Prize.

Historically, the basic forces were determined in studies of interactions of known particles like protons, neutrons and electrons. As more and more particles were discovered a simpler description became necessary. Gell-Mann and Neeman provided this description in terms of particles called quarks. All the known elementary strongly interacting particles prior to 1974 could be understood as bound states of three quarks called up (u), down (d) and strange (s) and their anti-particles called anti-quarks. A proton consists of two up quarks (each with $e = \frac{2}{3}$) and a down quark with $e = -\frac{1}{3}$. One also needed a replica of d quark called s

	Quarks	**Leptons**
First Generation	$\begin{pmatrix} u \\ d\cos\theta_C + s\sin\theta_C \end{pmatrix}$	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$
Second Generation	$\begin{pmatrix} c \\ s\cos\theta_C - d\sin\theta_C \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$

Table 1. Quarks and Leptons as in the Cabibbo theory with two generations.

quark to make up some elementary particles which were called strange particles. The bound states of three quarks are called Baryons and that of quark anti-quark are called mesons.

To start with, quarks were postulated as mere building blocks but as time progressed, they were found to play a more dynamical role. The quarks were assumed to provide basic 'currents' which resulted in the interactions among the protons, neutrons and other particles. In the standard model, one makes use of symmetries to determine the nature of electroweak interactions of quarks. We will not need the details of these symmetries, but let us summarize how the weak interactions affect quarks and leptons. The standard model symmetry acts on a pair of particles, either quarks or leptons. This pair is pictorially depicted as a column vector *(Table* 1).

There are two types of weak interactions. One converts upper members (say ν_e) to the lower (say e) and vice versa. These are called the charged weak interactions. The other acts between two upper or between two lower members in a given column. These are called the neutral weak interactions. Both types of weak interactions share a single coupling constant – a fact following from symmetries in the standard model. Identical weak interactions exist between any pair represented by a column in *Table* 1. Thus the charged weak interactions convert electrons to neutrinos and the neutral one can act between two neutrinos or two electrons. The pairs ν_e, e and u, d refer to completely different types of particles but weak interactions affect them in a universal way, i.e., strength of weak interactions between u and d is the same as that between ν_e and e. Actually, it turned out that these strengths are not quite the same: If some coupling g measures the strength of the ν_e-e interactions then the corresponding strength of the u-d interaction is $0.97g$! Why this small difference? Understanding of this small difference was the beginning which ultimately led to the formulation of the KM theory of CP violation.

4. Milestones in Particle Physics

Let us digress here and describe some historical milestones which led to the final KM theory. We discuss various findings in the language of the standard model. Some of the ideas were developed using a somewhat different terminology than used here.

- In 1934, Yukawa gave a theoretical formulation of the nuclear force. He postulated a particle – the π meson with mass around 100 MeV. Cosmic ray experiments discovered a similar particle. It soon turned out that this particle did not have anything to do with the nuclear forces. It was altogether a different particle with identical properties as the electron but with a different mass. This was called 'muon'.
- In 1962, the muon was shown to have its own neutrino called ν_μ. This was proved elegantly by Lederman, Schwartz and Steinberger. They showed that anti-neutrinos, from the energetic muon decays, interacting with a proton always produced muons and not electrons, showing that these are different from the electron (anti-)neutrinos.
- ν_e, e and ν_μ, μ provide two weakly interacting pairs shown in $Table$ 1. Weak interactions do not distinguish between them and the basic strength of interactions between them is a universal coupling g. These particles are called leptons and two replicas are termed as two families or generations in the particle physics terminology.
- The charged weak interactions of leptons are described in terms of a single coupling constant g. Originally, u and d quarks were assumed to pair up in a column like ν_e, e. This turned out to be not quite correct. As already mentioned the strength of the u-d weak interaction is more precisely $.97g$. This discrepancy was found through the beta decay of oxygen. More importantly, strange particles were found to decay to the ordinary particles consisting of the up and down quarks, e.g., K mesons (bound states of strange and anti-d or u quarks) were known to decay into pions. The existence of these decays showed that there exist weak interactions in which a strange quark changes to an up quark. The symmetry of the SM model dictates that weak interactions act only between members of the same generation. Thus if u and d are paired then u can convert to d only. In 1963, Cabibbo systematically looked at the available information on all the strange decays

and formulated an elegant theory to describe these decays along with the ordinary beta decays involving the u-d transitions. The final proposal was very simple and universal. He suggested that it is not the d quark but a combination of the d and s given by $d\cos\theta_{\rm C} + s\sin\theta_{\rm C}$ that pairs up with the up quark and makes a family. Thus the u-d interactions occur with an amplitude $g\cos\theta_{\rm C}$ and the u-s with an amplitude $g\sin\theta_{\rm C}$. The sum of probabilities for conversion of u to d and s is still given by the universal constant g^2. The $\theta_{\rm C}$ is called the Cabibbo angle whose magnitude was determined by Cabibbo to be $\sim 12^0$. Thus the u-d weak interactions are given by gcos$\theta_{\rm C} \approx 0.97g$ and not g as was found earlier. An explanation similar to Cabibbo's was suggested earlier by Gell-Mann and Levy to explain the reduced strength of the beta decay of oxygen.

- Cabibbo theory described the existing weak interactions very well. However, its inclusion into the standard model led to a problem. If $d\cos\theta_{\rm C} + s\sin\theta_{\rm C}$ occurred as a lower member of the quark doublet, then there should be neutral weak interactions connecting two such lower members. This led to the neutral interactions causing d-s transitions, with the same strength as the d-d transitions. No such transitions were known to exist. In 1970, Glashow, Illiopoulos and Maiani (GIM) came out with an ingenious idea. They suggested that a fourth quark analogous to u exists. They named it as charm quark and paired it with $-d\sin\theta_{\rm C} + s\cos\theta_{\rm C}$, a combination orthogonal to the one entering with the up quark, see (*Table* 1). This was shown to remove the unwanted d-s weak interactions. This remarkable result was the theoretical discovery of charm quark. Finally, mesons containing the charm quarks were discovered in 1974. Thus by 1974, the existence of two generations of quarks u, d and c, s was firmly established. In 1975, a heavy electron called τ was discovered by Martin Perl. This too has its own neutrino called ν_τ. The existence of ν_τ was experimentally proved in 2000. Together with e and μ, this completes three generations of leptons.

- One did not have at that time any convincing reason to believe that there exists a third generation of quarks as well. In 1977, a meson (which is now called Υ) around 11 times more massive than the proton was discovered at Fermilab in Chicago. This could be interpreted as a bound state of yet another quark which was called b (bottom). The existence of the b quark led to theoretical speculations that a top quark analogous to u and c must also exist. This quark was finally discovered at FermiLab in 1995.

5. P, CP and their Breakdown

Starting with the cosmic ray discovery of muons in 1937, one finally ended up with the experimental discovery of all members of three generations of quarks and leptons by 2000. Theoretical 'discoveries' did not follow this simple chronological order! Kobayashi and Maskawa [3] wrote their paper in 1973. At that time the only quarks known were u, d and s. GIM paper was written before the KM paper. Thus the theoretical existence of the charm quark was possibly known to them. However there was no indication of the existence of the third generation of leptons or of quarks. Their theoretical argument about the existence of the third generation was based purely on the observed phenomenon of CP violation which we now describe.

The catalog of the exact symmetries prior to 1956 included a symmetry corresponding to a mirror reflection. It was thought that the mirror image of a physical system should obviously also be a perfectly realizable physical system, i.e., laws of physics should be invariant under mirror reflection. When we look in the mirror, our left hand becomes the right hand of our image. Thus mirror symmetry is also referred to as the left right symmetry. The corresponding conserved quantity is called parity. Parity is exactly conserved in strong as well as electromagnetic processes. The first hint of parity violation by weak interactions came around 1954. A strange particle was found decaying into three pions. This was called τ-particle (different from the τ lepton discovered in 1975). An identical particle called θ with the same charge, spin and mass was also found to decay to two pions. A simple-minded interpretation would be to assume that τ and θ represent the same particle which sometimes decays to two and sometimes to three pions. This caused a problem. It turns out that two and three pion states found in the above decays have different parities. If parity was conserved then the initial and final states should have the same parity. In this case the τ and θ should represent different particles with opposite parities. Why should their other properties be identical? This puzzle can be solved if one assumes that parity is not conserved in weak decays. Lee and Yang systematically looked at all the available results on beta decays and found that the parity conservation was not tested in weak interactions. Following their suggestion, Wu did an experiment with the beta decay of Cobalt and found that electrons emitted in their decay preferentially moved parallel to the spin of the Cobalt nuclei. The mirror image of this would correspond to electrons moving anti-parallel to spin. But no such events were seen. This established parity violation. Parity violation was soon discovered in other processes: π decays, polarized μ decays, strange particles decays.

All the weak decays involving neutrinos are found to have a curious property. Neutrinos emitted in any weak decay are always left-handed, i.e., their spins are directed opposite to their momenta. Now the mirror image of such a neutrino would be a right-handed neutrino for which the spin is in the same direction as the motion. If parity was conserved then one should have found equal numbers of the left and right handed neutrinos. The situation here can be compared with chemical reactions. Organic molecules (sugar for example) have definite handedness. However, if one produces sugar in the laboratory one finds equal numbers of molecules with both handedness. Neutrinos produced in beta decays on the other hand are always left-handed! Experimental proof of the non-conservation of parity led to the formulation of an elegant theory of weak interactions which finally led to the standard model.

Parity was not the only symmetry to be violated by weak interactions. It also violated another symmetry called the charge conjugation C. Charge conjugation reverses the roles of particles and anti-particles. Electromagnetic and strong interactions respect this symmetry. Electromagnetic repulsion between two electrons is the same as that between two positrons. Anti-hydrogen made up of antiproton and positron would have the same set of energy levels as hydrogen. Weak interactions were found to violate the charge conjugation symmetry. Muons are found to decay to an electron, a muon neutrino and an electron anti-neutrino. It was found that the polarized muons emitted electrons mainly in a direction opposite to its polarization. The corresponding charge conjugate state would be the one in which polarized anti-muons would emit positrons in a direction opposite to the muon polarization! In reality, positrons emitted in the polarized anti-muon decays preferred to come in the direction of the anti-muon polarization! This shows two things. First, the charge conjugation like parity is violated in weak interactions. Second, if we make a combined operation of C and P then CP remains a good symmetry of weak interactions. This was a triumph for the then existing theory of weak interactions. It successfully described maximal violation of C and P and invariance under the combined operation CP.

In 1963, Christenson, Cronin, Fitch and Turlay were the first to show that CP is violated. This evidence came through the studies of strange particles called K mesons. A neutral K^0 meson is made up of an anti-s and a d quark. Its anti-particle $\bar{K}^0$ contains an s and $\bar{d}$. Now the charged weak interactions can convert an $\bar{s}$ to $\bar{d}$ through the chain $\bar{s} \to \bar{u}, \bar{c}, \bar{t} \to \bar{d}$. Similarly, d can get converted to s with the result that K^0 converts itself to $\bar{K}^0$. This phenomenon is known as the K–$\bar{K}$ mixing. What should one call a propagating K–K^0 or $\bar{K}^0$? Neither.

One constructs two equivalent states from these two K mesons known as K-long and K-short. They are so called because the K-long decaying into three pions lives longer than the K-short which decays to two pions. These states have the property that one can assign definite CP values to them. K-long are CP odd and K-short are CP even. If CP was exactly conserved than K-long should decay only to three pions and K-short only to two pions. It was found by the above experimenters that one K-long in about 1000 actually decayed to two pions. This was the first proof of CP violation. The next conclusive proof of CP violation had to wait for more than 30 years!

What could be the origin of CP violation? Unlike the P and C violation, CP violation was found to be tiny. One possible theory of CP violation assumed that the basic equation of weak interactions has a small piece which violates CP. This piece was called super-weak to distinguish it from the weak interactions which conserved CP. The Kobayashi Maskawa proposal does not invent additional 'super weak' interactions. They realized that the standard weak interactions are enough to generate the CP violation. The standard model is characterized by particles, interactions among them and basic couplings like $\alpha, \alpha_{\mathrm{s}}, g, \cos\theta_{\mathrm{C}}$. All these couplings are real numbers. It turns out that CP is violated in a theory if it contains some couplings which are necessarily complex numbers with non-zero phases. Not all phases in quantum mechanics are physical. If it so happens that some of the couplings remain complex after removing all the unphysical phases from the theory then one gets CP violation. Kobayashi and Maskawa realized that the four quark model of Cabibbo and GIM has no room for any complex phases. They looked at various ways of adding a physical phase to the theory. One of the alternatives they suggested amounted to adding two new quarks, now called top and bottom. This was a radical suggestion since at that time only four leptons and three quarks were known and now they proposed three more! As we have already discussed all three missing quarks (and leptons) were discovered one by one, c in 1974, b in 1977 and t in 1995. With six quarks and six leptons one now has a picture of basic building blocks which is believed to be complete by many. *Table* 2 shows how weak interactions connect different quarks according to the KM picture. This contains three angles analogous to the Cabibbo angle θ_{C} and a phase δ called the Cabibbo–Kobayashi–Maskawa (CKM) phase. Now each of the charge $\frac{2}{3}$ quark pairs with a combination of three charge $-\frac{1}{3}$ quarks. Note that the KM picture reduces to the Cabibbo picture and CP violation disappears if the angle θ_3 is zero. This angle has been measured. It is not zero but quite small: $\sin\theta_3 \sim 0.005$. This is the reason why CP violation as measured in the K meson system is small.

	Quarks	**Leptons**
First Generation	$\begin{pmatrix} u \\ c_1c_3d + s_1c_3s + s_3e^{-i\delta} \end{pmatrix}$	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}$
Second Generation	$\begin{pmatrix} c \\ -(s_1c_2 + c_1s_2s_3e^{i\delta})d + (c_1c_2 - s_1s_2s_3e^{i\delta})s + s_2c_3b \end{pmatrix}$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$
Third Generation	$\begin{pmatrix} t \\ (s_1s_2 - c_1c_2s_3e^{i\delta})d - (c_1s_2 + s_1c_2s_3e^{i\delta})s + c_2c_3b \end{pmatrix}$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

Table 2. Presently accepted complete picture of three generations of quarks and leptons. Description of the quark family involves three angles called the CKM angles $\theta_i = 1,2,3$ with $s_i = \sin\theta_i$ and $c_i = \cos\theta_i$ and a phase δ. The analogous angles (not shown here) enter the leptonic generations also.

The Kobayashi–Maskawa paper remained practically unnoticed for almost three years. In 1975, Pakvasa and Sugawara [4] confronted the KM model with the observed CP violation in the K mesons. They showed that one could indeed obtain the observed CP violation. Maiani also reached the same conclusion independently and detailed investigations were performed later by Ellis Gaillard and Nanopoulos. All these showed that the KM picture is adequate for explaining the K-meson CP violation. But is this the only alternative? Indeed there were alternative suggestions which added some pieces to the standard model to incorporate complex couplings and these too could account for the K-meson CP violation. One needed to conclusively show that the only experimentally-successful path to CP violation was through the CKM picture. This became feasible after the advent of particle physics machines called B-factories.

6. *B*-Factories and Proof of the CKM Picture

Existence of three generations was crucial in the CKM picture and its viability was crucially dependent on observing the right amount of CP violation in particles counting the third generation quarks. By 1995, all six quarks making three generations were known. It remained to prove that they interact exactly in the way KM proposed.

Around 1981, Bigi, Carter and Sanda looked at signatures of CP violation in mesons containing the b quarks. They identified definite decays involving these particles which can be used to test the CKM picture of CP violation. It became clear that one would need more than a million B mesons to look at their CP violating decays. This became possible through experiments involving the B mesons in the late nineties.

The existence of b quark allows one to have new sets of mesons analogous to π and K mesons. For example, an anti b quark forms a bound state with d to form B_d^0 meson. The $\bar{B}_d^0 \equiv b\bar{d}$ would be its anti-particle. One also has $B_s^0 \equiv \bar{b}s$ and its anti-particle. As we already discussed, there also exist states (called Υ) which are bound states of the b and anti b in different angular momentum states. The Υ decays to a pair of B mesons. B factories are machines which produce Υ particles in large amounts. These are produced in machines called colliders. These machines collide energetic electrons with positrons. There are two such colliders which studied the B meson decays and observed CP violation in these decays. One was in USA at the Stanford Linear Accelerator (SLAC) in California. The other was at the KEK laboratory near Tokyo in Japan. The SLAC collider detected B meson decays in a detector called BABAR. The analogous detector at KEK is called BELLE. Both colliders used the same basic principle to produce B mesons. Electrons and positrons are accelerated and are then made to collide with each other. These being particle antiparticle pairs, they annihilate and produce energy in the form of elementary particles. Their energies are tuned in such a way that one has maximum probability of producing Υ particles which decay to B mesons. These colliders are similar to the LEP collider built at CERN [5] in Geneva but they operate at much lower energy. Moreover, one needs B and anti B mesons to travel some distance before their decays. This is made possible if electrons and positrons carry different energies. B mesons produced in this way are not at rest and travel before decaying in the detector.

How does one observe CP violation in them? In principle, the way is simple. One looks at the decay pattern of B^0 into some definite set of particles and then compares it with the corresponding pattern of the anti-B^0 decays. If they show different behaviors then one concludes that CP is violated. In practice this process gets complicated since both B^0 and $\bar{B}^0$ are simultaneously produced and one needs to know whether one is looking at B^0 or its anti-particle. Moreover, just like K^0, the B^0 meson converts itself into its antiparticle and vice versa as it moves. The BABAR and BELLE detectors devised ingenious methods to look at specific decays of B^0 and $\bar{B}^0$, could compare their rates and observed CP violation exactly as predicted in the theory of Kobayashi and Maskawa. In fact, these experiments have measured several independent CP violating quantities and the conclusion that has emerged from this is that if at all there exist alternative theories of CP violation, their contributions to observed CP violation are quite small.

7. What Lies Ahead?

Understanding basic forces and nature of particles which experience them has remained an important problem in particle physics. It is remarkable that many times the concept of symmetries has shown us the right directions in this pursuit. Often one symmetry has led to another. CP invariance is a good example of this. The existence of only four quarks and the basic symmetry of the standard model automatically implied that CP is conserved. Similarly, the conservation of Baryon and Lepton numbers is also an automatic consequence of the standard model symmetries and content. The desire to break CP invariance led Kobayashi and Maskawa to propose a six-quark model which is now firmly established. However, one cannot still rule out small deviations from their basic picture. The Large Hadron Collider (LHC) built at CERN in Geneva will be one of the experiments which will try to test the CKM picture. The future may throw new surprises, maybe new symmetries and/or new particles! Time will tell.

Violation of CP symmetry is also crucial in another respect. We know that our universe is dominated by what we call matter and not anti-matter. It is unlikely that the universe started in that way. If our universe started with equal amounts of matter and anti-matter then what forces caused the asymmetry that we see today? While we do not know the basic forces, we do know that violation of CP symmetry is required as an essential ingredient. Connection between the CKM picture of CP violation and generation of matter anti-matter asymmetry, if at all it exists, is far from clear at this stage. But it is gratifying to see the experimental proof that CP is indeed violated at the fundamental level. Maybe someday one will find a definite link between cosmic and the CKM CP violation. Time will once again tell!

Suggested Reading

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