CP violation and Kobayashi–Maskawa mechanism

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The universe as we see today is matter dominated and there is no trace of anti-matter within a distance of about ten billion light years and perhaps in the whole visible universe. From combined microwave background and large scale structure the baryon asymmetry parameter is now known to be $\eta = (n_B - n_{\bar{B}}/n_\gamma = (6.21 \pm 0.16) \times 10^{-10}$, where n_B, $n_{\bar{B}}$ and n_γ are baryon, antibaryon and photon densities respectively. This dominance of matter over anti-matter is termed as Baryon Asymmetry of Universe (BAU). It is believed that there were equal amount of matter and anti-matter when the universe was created. So the question arises what happened to the anti-matter. The phenomenon of CP violation is considered to be one of the key ingredients to this great mystery of nature and for the very existence of us.

In 1967 Andrei Sakharov pointed out that the baryon asymmetry of the universe can actually arise dynamically during the evolution of the universe from an initial matter–antimatter symmetric state (that is a state with net baryon number equal to zero) if these following conditions are satisfied: (i) baryon number (B) violation, (ii) C and CP violation, (iii) departure from thermal equilibrium. We have not seen any B violating process at the currently accessible energy scale. Fortunately, we have observed CP violation in the flavour sector. There are various beyond the standard model scenarios in which the baryon asymmetry can be understood. The future experiments at Large Hadron Collider (LHC) will shed more light in this regard.

The combined operation of CP (where C stands for charge conjugation operator which changes particle to anti-particle and P for parity which is related to mirror symmetry) was believed to be sacred even though separately C and P were found to be violated in weak interaction. In 1964, CP violation was observed in the neutral kaon (particle containing a strange quark or anti-quark) system and in fact the CP symmetry was found to be broken only at the level of one in about 500 events (Noble prize was awarded to J. W. Cronin and V. L. Fitch in 1980 for the discovery of CP violation).

Let us now outline the developments leading to the Kobayashi–Maskawa (KM) mechanism. In order to account for the reduced strength of strangeness changing ($\Delta S = 1$, where S is the strangeness quantum number) transitions in comparison to the strangeness conserving ($\Delta S = 0$) ones, Cabibbo in 1963 advocated that the 'down' and 'strange' quarks participating in the weak interaction were not pure flavour states but rather mixed ones. The mixing angle θ_c is called the Cabibbo angle. Later on it was noticed that the absence of $\Delta S = 1$ neutral current (as in the case of strange quark to down quark transition) in Cabibbo model was hard to explain. In 1970 Glashow, Iliopoulos and Maiani (GIM) pointed out that if another quark with same charge as that of the 'up' quark existed, the discrepancy could be successfully explained in the Cabibbo framework. The fourth quark was named 'charm' (and the charm quark was discovered in 1974).

Unfortunately, the observed CP violation in the Kaon sector could not be explained in the two family or four quark model. In 1973 Kobayashi and Maskawa[1] (generalizing the Cabibbo–GIM idea[2]) predicted that there should be at least three families of quarks (or 6 quarks) to account for the observed CP violation. These quarks are now known as up (u), down (d), charm (c), strange (s), top (t) (discovered in 1995), bottom (b) (discovered in 1977). These quarks along with the six leptons (electron (e), muon (μ), tau (τ) and their corresponding neutrinos: electron neutrino (ν_e), muon neutrino (ν_μ) and tau neutrino (ν_τ)) and the mediating gauge bosons are believed to be the basic building blocks of nature. It should be mentioned here that we will restrict ourselves to the framework of the standard model (SM) (which is successful in explaining almost all the data obtained so far with the exception of neutrino oscillations).

In the KM mechanism the three down type quarks (d, s and b) are in fact mixed rather than being pure ones (in analogy with that of the Cabibbo prescription). The mixed (say, d', s', b') and unmixed down (d, s, b) type quarks are related by a 3 × 3 matrix known as the KM matrix (which is also called CKM matrix). The KM matrix (V_{KM}) in unitary ($V^\dagger V = 1$) and the elements of the V represent the couplings of various charged current weak interactions taking place involving the six quarks mentioned in the SM framework. The 3 × 3 KM matrix can be parameterized in terms of four independent parameters (namely, three Cabibbo type rotation angles and a phase (denoted by δ_{KM}) in the so-called standard parametrization). The complex phase δ_{KM} is the only source of CP violation in the framework of the SM. Note that in case of two families of quarks we have only one parameter which is the rotation angle θ_c whereas in case of three families of quarks we have three rotation angles and one complex phase (δ_{KM}). In the case of four families of quarks there are three phases for the CP violation but here we will discuss the scenario with three families of quarks as in case of the SM. So the measurement of this KM phase (δ_{KM}) is of utmost importance in order to confirm the KM mechanism.

There are three types of CP violation that can occur: (i) The direct CP violation (which are associated with the decay amplitudes and charged mesons exhibit only this type of CP violation), (ii) CP violation in mixing (associated with the neutral meson mixing), and (iii) CP violation in the interference of decay amplitudes with and without mixing. The last two categories are called indirect CP violation. CP violation in B-system has been confirmed in 2001 at the B factories at SLAC, USA and KEK, Japan. Within the Standard Model, CP violation is characterized by the unitarity triangle (the geometrical representation of the unitarity of KM 3 × 3 quark mixing matrix). There are essentially two important parameters in the so-called unitarity triangle which are to be measured. The unitarity triangle has three angles, named, alpha (α), beta (β), gamma (γ) and the measurement of any two angles would suffice as only two angles are independent. The angle β has been measured, as suggested by I. Bigi and A. Sanda[3] and is in accordance with the standard model expectation (a nice review on CP violation and other technical details can be found in the book by I.

Bigi and A. Sanda). The angle α is notoriously difficult to measure because of some problem called penguin pollution and we do not know how to disentangle the penguin contamination and therefore considered to be not clean from theoretical point of view (although efforts are on to directly determine the same). So we are left with the option to measure the KM angle γ and there are many methods proposed to measure the same in the last two decades.

Before proceeding further let us emphasize the significance of KM angle γ. In the so-called Wolfenstein parameterization (which is a suitable one adopted by the high energy physics community to analyse the b-systems) the weak phase γ is associated with the $b \to u$ transitions and is the only angle (phase) associated with tree decay processes. This weak phase is also responsible for direct CP violation in B systems. Comparing the standard and Wolfenstein parameterizations it can be seen that the all important phase δ_{KM} is indeed the weak KM phase γ (the argument of $\rho + \mathrm{i}\eta$) of the Wolfenstein parameterization that describes the CP violation in the SM.

For the first time, the KM angle γ has been measured by BELLE (KEK, Japan) and BABAR (SLAC, USA) B-factory experiments[4] based on the article written by A. Giri, Y. Grossman, A. Soffer and J. Zupan (GGSZ)[5], which is in agreement with the SM expectation and vindicates the KM phenomenon. There are other two competing methods for the determination of the KM angle γ. These are the method by M. Gronau, D. London and D. Wyler (GLW)[6] and another one by D. Atwood, I. Dunietz and A. Soni (ADS)[7]. The details of the methods are highly technical and beyond the scope of this article. But let us briefly outline why GGSZ method became successful ahead of other plausible ones. In GGSZ, we used the interference of two Cabibbo allowed decay amplitudes (against the common wisdom that the interference must be with Cabibbo allowed and doubly Cabibbo suppressed ones or among two singly Cabibbo suppressed amplitudes), where we considered the multi-body final state common to both D^0 and $\bar{D}^0$. Also the final decay products are charged particles which are easy to detect from the experimental point of view and moreover the multi-body final states can proceed through resonances which can provide us the crucial strong phase information. All the methods mentioned above are being employed now and also will be taken up at the LHC B-experiment along with some other methods[8].

CP violation observed in 1964 in the kaon system and the measurement of large sin 2β, which confirmed the large CP violation in B system, are examples of indirect CP violation. After strenuous effort finally direct CP violation in the K system was established almost a decade ago by various Kaon experiments and first direct CP violation in B system (namely, in $B \to K\pi$ process) was observed only recently, which ruled out the super-weak model of CP violation. The KM phase is now measured, unitarity triangle has been constructed (area of the unitarity triangle is also a measure of the CP violation) out of the various measurements available and they are according to the SM expectations. Measurement of large KM phase, the evidence of direct CP violation in the B system along with results from K system have now firmly established the KM mechanism of CP violation in the SM. M. Kobayashi and T. Maskawa have been awarded the Nobel prize in Physics in 2008 for their work on CP violation.

Note added: The interested readers may refer to a similar article[9] which appeared in the previous issue of *Current Science*.

1. Kobayashi, M. and Maskawa, T., *Progr. Theor. Phys*., 1973, **49**, 652–657.
2. Cabibbo, N., *Phys. Rev. Lett*., 1963, **10**, 531–532.
3. Bigi, I. and Sanda, A., *Nucl. Phys. B*, 1981, **193**, 85–108; *CP Violation, Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology*, Cambridge University Press, Cambridge, England, 2000.
4. Abe, K. *et al.* (BELLE Collaboration), BELLE-CONF-0343, 2003, arxiv: hep-ex/0308043 (1–525); Aubert, B. *et al.* (BABAR Collaboration). *Phys. Rev. Lett*., 2005, **95**, 121802 (1–7); Poluektov, A. *et al.* (BELLE Collaboration), *Phys. Rev. D*, 2004, **70**, 072003 (1–14).
5. Giri, A., Grossman, Y., Soffer, A. and Zupan, J., *Phys. Rev. D*, 2003, **68**, 054018 (1–9).
6. Gronau, M. and London, D., *Phys. Lett. B*, 1991, **253**, 483–488; Gronau, M. and Wyler, D., *Phys. Lett. B*, 1991, **265**, 172–176.
7. Atwood, D., Dunietz, I. and Soni, A., *Phys. Rev. Lett*., 1997, **78**, 3257–3260; *Phys. Rev. D*, 2001, **63**, 036005 (1–17).
8. Aleksan, R., Dunietz, I. and Kayser, B., *Z. Phys. C*, 1992, **54**, 653–660; Giri, A. K., Khanna, M. P. and Mohanta, R., *Phys. Rev. D*, 2002, **65**, 034016 (1–6); Fleischer, R., *Phys. Lett. B*, 1996, **365**, 399–406.
9. Pakvasa, S., *Curr. Sci*., 2009, **96**, 186–187.

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Genome sequencing of cells that live inside glass cages reveals their past history

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One-quarter of the total primary production on earth is contributed by diatoms[1]. These are photosynthetic, unicellular algae with ornamented silica shells found in all aquatic and moist environments. They form the base of energy-efficient food webs that support all aquatic life forms. More than 250 genera of living diatoms, with as many as 100,000 species are known[2]. Fossil diatoms are known as early as the Cretaceous, 144–65 m.y. ago[3]. In India, deposits of diatoms occur in Rajasthan and are known as 'multani mitti'. Multani mitti or Indian Fuller's earth or diatomaceous earth as it is called in the West, is applied as a paste on the surface of the skin for 15–20 min and then washed-off. This leaves the skin feeling smooth, soft, moist and rejuvenated. Diatomaceous earth is now being used in the formulation of soaps, cleansing products, face powders and skincare preparations. Diatomaceous earth is a mineral material consisting mainly of