Recent advances in the study of B-meson systems

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A recent publication from the Belle experiment at the KEK B-factory in Japan in *Nature*[1] reports the observation of a significant difference in the measurements of the 'direct charge-parity (CP) violation between charged and neutral B meson decays'. The experiment looks at the relative difference in the rates from the decays $B^{\pm} \rightarrow K^{\pm}\pi^{0}$ and the corresponding rates from their neutral counterparts. Although these differences are expected to be similar, the experiment finds them to be significantly different. Somewhat earlier, the BaBar experiment at the Stanford Linear Accelerator Center (SLAC) B-factory, USA also carried out significant related studies[2,3]. The same issue of *Nature* carries an article by the well-known theorist, Michael E. Peskin[4], which explains the significance of this measurement and presents a detailed discussion on its implications to theory as well as experiment.

The measurements here pertain to a phenomenon known as 'direct' CP violation in the B-meson system, where C stands for charge conjugation, a symmetry that exchanges particles for their anti-particles and vice versa, and P for parity, or mirror symmetry. CP violation is of central importance in the field of elementary particle physics and also in cosmology. For instance, the famous Russian physicist, Andrei Sakharov proposed that CP violation is one of the three required phenomena which underpin our understanding as to why there is an excess of matter over antimatter in the universe (with a net baryon number), if the universe began from an initial state where it was matter–antimatter symmetric (with zero baryon number). The other two phenomena are baryon number-violating interactions (not yet observed) and departure from thermal equilibrium. Baryon number-violating interactions occur naturally in grand unified models of elementary particle interactions, into which the 'standard model', viz. the theory of electroweak and strong interactions, can be embedded. The standard model as we understand it today, itself has the seeds of CP violation, although these may be insufficient to generate the observed baryon number asymmetry. A prior publication in this journal[5] gives a lucid introduction to these ideas. In the following, we explain why the newly observed differences in the direct CP violation of charged and neutral B mesons, may be of importance.

We recall here that mesons are composite particles made up of a quark and an anti-quark, which could be of different 'flavours'. Quarks, which are believed to be elementary particles with strong interactions, come in six different flavours, namely *u*-, *d*-, *s*-, *c*-, *b*- and *t*. *u*-, *c*- and *t*-quarks have electric charge 2/3 and *d*-, *s*- and *b*-quarks have electric charge –1/3, in units of proton charge. Of the B-mesons observed by BELLE, charged ones are made up of the flavours $B^{+}(= bu)$ and $B^{-}(= \bar{u}b)$ and the neutral ones are of flavours $B^{0}(\bar{b}d)$ and $\bar{B}^{0}(\bar{d}b)$. If in these, the *b*-quark were to be replaced by the *s*-quark, it would represent the K-meson system. In the six-quark model, there is a subtle phenomenon that occurs: *d*-, *s*- and *b*-quarks (all of which have the same electric charge) that would be stable in the absence of weak interactions, get 'mixed' amongst one another in accordance with the laws of quantum mechanics, when the weak interactions are present. Such mixing would be governed by the action of a most general 3×3 unitary matrix with complex entries. However, simple redefinitions of phases of the fields that describe each of the quark flavours can make most of the entries in this matrix real. It was shown by Kobayashi and Maskawa[6] that the resulting matrix, after phase redefinitions, would be parametrized by three angles that would enter the matrix through sines and cosines, and one parameter that would enter the matrix as a 'phase' $e^{i\delta}$. This latter, which represents the unalterable complex nature of the quark mixing, would lead to CP violation. The bold prediction of Kobayashi and Maskawa is that every instance of CP violation can be consistently fitted to the value of this unique parameter δ. The ideas of Kobayashi and Maskawa were remarkably prescient as they were presented when the three heaviest quark flavours were actually undiscovered. However, it showed that the presence of heavy quarks was somehow needed to account for CP violation. They also predicted that CP violation is expected to be more dominant in the B-meson system than in the K-meson system.

Indeed, the Nobel Prize-winning discovery of CP violation in 1964 was in the neutral K-meson system through the so called 'indirect' CP violation which proceeds through 'mixing' of a neutral K-meson $(\bar{s}d)$ with its anti-particle $s\bar{d}$ (a neutral particle is not its own anti-particle, if it has 'charges' other than electric charge). This mixing, whose origin can be traced to the 'mixing' of the quarks of the same charge mentioned above, leads to the production of one long-lived (K_{L}) and one short-lived (K_{S}) state. CP conservation would have implied that K_{L} would never decay into two-pions. The fact that it does, is the hallmark of CP violation in this indirect manifestation. The discovery of 'direct' CP violation even in the K-meson system had to wait until 1999, as it is a very fine effect in this system. This comes from the observation of a difference in the rates for the decay of K_{L} into $\pi^{+}\pi^{-}$ and $\pi^{0}\pi^{0}$ pairs by the KTeV and NA48 experiments. For a highly accessible review of these results, see Kleinknecht and Wahl[7].

In order to pursue the goal of discovering CP violation the B-meson systems, two B-factories, one at KEK and another at SLAC, have been built. We recall here that these factories collide electrons and positrons of differing energies, which are tuned to produce a 'resonance' known as $\Upsilon(4S)$, which is a bound state of the $b - \bar{b}$ system. This resonance decays rapidly into a B^{+}–B^{-} pair or $B^{0}-\bar{B}^{0}$ pair. Due to the unequal energies of the colliding particles, the $\Upsilon(4S)$ resonance and its decay products are boosted in the laboratory frame. Because of the relativistic time dilation, the lifetimes of these boosted B-mesons are larger than their natural lifetimes. Thus the time of the decay of each meson could be accurately determined. This time information plays a crucial role in making many of the observations possible. With the present-day luminosities achieved by these accelerators, today there exists a dataset consisting of more than a billion B-meson pairs which are being studied thoroughly by the detectors Belle and BaBar, at these facilities.

As in the case of the K-meson system, CP violation in the B-meson system was first discovered via indirect CP violation in 2002. This discovery was reviewed in this journal[5] and in *Nature*[8]. Direct CP violation was discovered later[9].

The Belle collaboration reports the results obtained from studying a sample of 535 million B-meson pairs, and looks at a final state containing one K-meson and one pion, as well as a final state containing two pions. These result from the change of the flavour of the B-meson, which decays into two lighter mesons. These decays can be represented in terms of 'Feynman diagrams', where the *b*-quark which is confined inside a meson, decays through the emission of one of the force carriers of the weak interaction, namely the W boson. The decay 'amplitude', the mathematical expression that governs the strength of the probability of such a transition, also receives quantum mechanical contributions through virtual quanta that run around in 'loops' which can, for a process of this sort, be comparable in magnitude to the direct decay amplitude. Such diagrams have come to be known as 'penguin diagrams'. It is the quantum mechanical interference of these diagrams that leads to the decay rate of $B^+ \to K^+\pi^0$ being different from that of $B^- \to K^-\pi^0$ and similarly, for the decays $B^+ \to K^+\pi^-$ and $\overline{B}^0 \to K^-\pi^+$. This difference is the signature of direct CP violation and is parametrized in terms of a dimensionless number known as 'CP-asymmetry'. Such asymmetries are expected to be comparable for those arising from the neutral B-mesons and for the charged B-mesons. The discovery that is being reported by Belle as well as BaBar is that there is a significant mismatch between these asymmetries. This is expressed as 7% and –10% by Belle. For a discussion on these points, see Peskin[4].

Since there are always 'strong interaction' effects which are difficult to estimate, as the quarks are confined within the mesons, it could be that contributions in the standard model which are expected to be small are actually not so. Furthermore, the penguins referred to earlier come in several varieties, of which only one, namely the gluon penguin is expected to be dominant. It could so happen that sub-dominant ones may be enhanced due to: (a) our poor understanding of the dynamics, or (b) could be receiving contributions from hitherto undiscovered physics. This latter possibility is particularly exciting because it points to a possible new source of CP violation (other than the phase δ introduced by Kobayashi and Maskawa). This has been eloquently referred to as the 'song of the electro-weak penguin' by Peskin.

We now turn to other interesting data on B-mesons from other experiments. The Fermilab experiments CDF and DØ, in USA have recently reported important observations concerning properties of so-called B_s mesons. These are a pair of neutral mesons with quark content $B_s = \overline{b}s$ and $\overline{B}_s = b\overline{s}$. In a previous publication[10], oscillation phenomena in the $B_s - \overline{B}_s$ system at these Fermilab experiments soon after their discovery were reviewed. We now turn to some of the properties of the B_s meson system that have been measured subsequently.

The CDF experiment[11] and the DØ experiment[12] considered the particular final state $J/\psi\phi$. In Figure 1 we show how the decays of both B_s as well as $\overline{B}_s$ can lead to this final state. We recall that J/ψ is a bound state of a charm and anti-charm (viz. it is a 'charmonium' resonance) and ϕ is a corresponding resonance with *s*-quark and its anti-quark. J/ψ is detected through its decay into $\mu^+\mu^-$, and ϕ through its decay into K^+K^-. All these particles are relatively long-lived and hence it is straightforward to measure their momenta and energies. Thus a full reconstruction of the $B_s/\overline{B}_s$ along with the determination of the CP properties of the final states is possible. The difference in the rates $B_s \to J/\psi\phi$ and $\overline{B}_s \to J/\psi\phi$ is a measure of the CP violation in the B_s system. This is predicted to be small in the Kobayashi–Maskawa model and the experimental results are in accordance. The difference in the rates between decays into CP-even and CP-odd final states gives the lifetime difference between the two B_s mesons. This is predicted to be measurably large. The measured value from untagged decays is $\Delta\Gamma = 0.076 \pm 0.060$ ps^{-1}, which is consistent with zero (for a review see Kuhr[13]). However, the present tagged experiments now yield the number[12] for this quantity $\Delta\Gamma = 0.19 \pm 0.07$ ps^{-1} from DØ. A useful review of all these experimental results is Di Giovanni[14]. On the theoretical front, a case for the possibility of discovery of new physics based on this data is the analysis of Bona *et al.*[15].

To summarize, we have reviewed some interesting experimental developments in the sector involving B-mesons and B_s mesons at a variety of experiments at e^+e^- colliders and at the Tevatraon, the proton–antiproton collider. Having entered an era of precision studies in this sector, it is clear that many interesting and exciting developments lie ahead, both experimentally and theoretically, as a possible window to physics beyond what the standard model may open up in these systems.

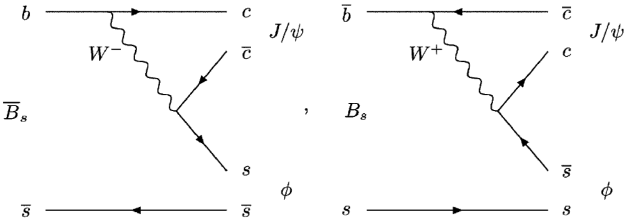

Figure 1. Decay of B_s mesons into $J/\psi\phi$.

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