

## Novel discoveries at B meson factories

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Important measurements and observations continue to emerge from the two presently operating 'B-factories' at the Stanford Linear Accelerator Centre, Stanford, USA and at the KEK, the High Energy Accelerator Research Organization, Tsukuba, Japan. See ref. 1 for a discussion of some important discoveries in 2008. The two experiments at these locations are BABAR at the PEP-II collider and BELLE at the KEK-B collider. BABAR has recently announced the observation of the ground state of the 'bottomonium system'<sup>2</sup> something which was predicted several decades ago, and which defied observation until now despite the observation of a tower of excited states (resonances) of this system. BELLE has announced the observation of a couple of resonances in the 'charmonium' system recently<sup>3</sup>, and has also observed certain important purely leptonic decays of B-mesons<sup>4</sup> as well as the observation of an important 'strangeness changing neutral current' process and measurements of differential branching fractions and forward-backward asymmetries<sup>5</sup>. Each of these observations represents a triumph of experiment and serves as a precision test for the predictions of the standard model of elementary particle physics, as described here.

Recall that the standard model is the theory of interactions of elementary particles of the leptonic type, which includes the well-known electron and its neutrino, the heavier counterparts of the electron, namely the muon and the  $\tau$  lepton and their neutrinos, the familiar u and d quarks that are constituents of protons and neutrons, their heavier cousins, the s, c, b and top quarks. The heavy quarks are all unstable due to the ubiquitous presence of the weak interactions, indeed as are the heavy charged leptons. B-factories are dedicated machines that probe the properties of B-mesons (in general meson is a bound state of a quark and an anti-quark; a meson which is a bound state of a c quark and an anti-c quark is known as 'charmonium' and a corresponding meson with c replaced by b is known as 'bottomonium'). As a result of the enormous statistics available at these machines, it has been possible to

establish such diverse phenomena as CP violation and flavour physics at an unprecedented level. Indeed, the 2008 Nobel prize has been awarded to M. Kobayashi and T. Maskawa as many of the predictions of their theory have now been borne out. See ref. 6 for a review.

We begin by reviewing the details of observation of ground state of the bottomonium system by BABAR collaboration. The ground state is denoted by the symbol  $\eta_b$  (ref. 2). As mentioned earlier, a bottomonium state is one which is made up of a b quark and antiquark of b. This system behaves pretty much as an atomic system and can therefore have radial excitations as well as excitations associated with spin and orbital angular momentum. The crucial difference is that the energies associated with the excitations are themselves similar in magnitude to the masses of the quarks themselves as the underlying force in this case is the strong interaction, in contrast to the underlying force in atomic systems, which is the significantly weaker electromagnetic interaction. Many of the excited states, alternatively resonances or bottomonia states have been observed from the earliest days following the discovery of the first bottomonium resonance  $\Upsilon$  in 1976 by Leon Lederman's group at Fermilab. These are called resonances as they are typically associated with sharp increases in their production cross-section in collisions and correspond to the production of shortlived bound states of their constituents and associated with them are definite quantum numbers of mass, lifetime and angular momenta. The bottomonia are made up of a b-quark and b-antiquark pair, each of which is a spin-half fermion, and could therefore have a variety of possibilities associated with the relative orientations of the spins. It may also be recalled that these orientations are associated with magnetic energy counterpart of the strong interactions. The ground state is that in which the quantum numbers make it a spin-singlet. The higher excitations are typically spin-triplets and therefore more energetic.

The recent experimental breakthrough of BABAR is in its observation of the  $\eta_b$

in an electromagnetic decay of the excited state known as the  $\Upsilon(3S)$  by searching for a monochromatic photon emission from the decay, and by carefully eliminating backgrounds associated with a cascade of decays in the excitation spectrum. One of the reasons for the long delay in the discovery is the presence of another state known as the  $\Upsilon(1S)$ , whose energy is higher than that of  $\eta_b$  by as little as 71 MeV. As a result, an unambiguous detection of the decay products of the  $\eta_b$ , required for its reconstruction was very difficult. This energy splitting has a well-known analogue in atomic physics known as the hyper-fine splitting, due to the spin-spin interactions of the constituent quark and antiquark. Over 100 million  $\Upsilon(3S)$  events provided the sample from which 19,000  $\eta_b$  candidates have been identified. These candidates have been identified by the search for a peak in the photon energy distribution peaked at 921.2 MeV, which is interpreted as a monochromatic emission of photons in the radiative transition of the  $\Upsilon(3S)$ . The mass of the  $\eta_b$  has been determined at around 9.39 GeV within small errors. This observation will now challenge theory as regards the computation of its mass in effective models of the strong interactions, and for instance computations on the lattice.

We now turn to the discovery of certain charmonium resonances at BELLE in certain decays<sup>3</sup>. In the strong interaction sector with both light as well as heavy quarks, the subject of identifying the states of these systems from experiment remains an outstanding challenge. Once identified as specific resonances, i.e. as states of definite mass, angular momentum and lifetimes, there arises a theoretical challenge of understanding the precise content of the states. In other words, are they merely a quark and antiquark pair, or could it be that these contain more than one such pair? Since it has not been possible so far to actually solve the strong interaction theory to obtain its spectrum, such experimental determinations and checks remain crucial to our understanding of the subject. The present resonances are identified from

657 million B meson pairs recorded by BELLE and have masses of 4051 and 4248 MeV. It appears that these could be containing such tetraquark configurations.

One of the most familiar mesons is the charged pion, which has the preferred decay mode into a muon and its anti-neutrino. B-meson is after all a very heavy counterpart of the pion, and the  $\tau$  lepton is a very heavy counterpart of the muon. As a result, the decay  $B \rightarrow \tau \bar{\nu}_\tau$  is not an entirely unexpected decay mode. The BELLE collaboration has recently used a new tagging technique to study this decay<sup>4</sup>. It confirms the observations using more traditional hadronic tagging techniques. Furthermore, it offers a sensitive measurement of the element of the Cabibbo–Kobayashi–Maskawa matrix element denoted by  $V_{ub}$ .

The last observations reviewed here is the one associated with the decay  $B \rightarrow K^* l^+ l^-$ , where  $K^*$  is a vector meson (carrying a spin 1 in units of  $\hbar$ ) containing an s-quark and  $l$  denotes a lepton<sup>5</sup>. This is sensitive to the transition  $b \rightarrow s$ , which is a very rare transition in the standard model, occurring only at higher orders in the weak interactions. Therefore, it is a sensitive window to non-standard effects. By measuring the differential branching fraction and forward–backward asymmetry, the BELLE collaboration affords a new sensitive test of the standard model. It is the interference of the standard model effects with those from possible non-standard physics that would lead to a signal in the forward–backward asymmetry of the leptons. There is some evidence of deviation from the standard model expectation.

All the discoveries and observations discussed above suggest that there is lot to be done at the frontier in B factories. Indeed, there are proposals for the con-

struction of so-called Super-B factories. The Super-B, with a luminosity of  $10^{36} \text{ cm}^{-2} \text{ s}^{-1}$  can provide a unique window to the flavour structure of the standard model and also as a sensitive probe of new physics in the flavour sector. The study of new physics effects in the heavy quark and heavy lepton sectors requires data samples two orders of magnitude larger than the ones provided by present B-factories. The Super-B will enable more accurate measurement of the CKM parameters  $V_{ub}/V_{cb}$  and  $V_{td}/V_{ts}$ . The Super-B besides producing B mesons, will also produce charmed hadrons and tau leptons in huge amounts. One striking thing about the study of charmed hadrons is that the D meson (which contains a c-quark) mixing will allow sensitive search for CP violation which, if found would be a clear indication of new physics. The study of tau leptons that are produced will also help in testing the lepton number violation from rare tau decays.

The idea of a Super-B factory becomes realistic with the upgradation of the luminosity of the operational B factories at SLAC and KEK (a notable milestone achieved by KEK in the recent past is the world record in luminosity which reads  $2.11 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ). They will be extrapolations of the existing ones with improved parameters such as increased current and improved beam bunches, inside the colliders. In constructing a Super-B, however, one has to do away with the problematic power consumption and background issues associated with it. These, if solved, would be a breakthrough even in collider design.

On the other hand, it is entirely likely that a brand new facility can be built, based on e.g. the new so-called crabbed-waist technology<sup>7</sup> developed at the INFN Frascati National Lab in Italy. The gain

in luminosity could be utilized in a corresponding Super-B design. This technology has been tested successfully by an international team at the Dafne collider in 2008.

In this article, we have reviewed four important experimental observations at B-factories, and have pointed out that the future holds exciting prospects, especially if super-B factories are to be built based on recent breakthroughs in accelerator techniques.

1. Abbas, G., Ananthanarayan, B., Ashok, K. and Uma Sankar, S., *Curr. Sci.*, 2008, **95**, 827–828.
2. Aubert, B. *et al.*, *Phys. Rev. Lett.*, 2008, **101**, 1–7; *Erratum: ibid*, 2009, **102**, 1–2.
3. Mizuk, R. *et al.*, *Phys. Rev.*, 2008, **D78**, 1–14.
4. Adachi, I. *et al.*, Belle Collaboration, Measurement of  $B^- \rightarrow \tau \bar{\nu}_\tau$  decay with a semileptonic tagging method; arXiv:0809.3834 [hep-ex].
5. Adachi, I. *et al.*, Belle Collaboration, Measurement of the differential branching fraction and forward–backward asymmetry for  $B \rightarrow K^* l^+ l^-$ ; arXiv:0810.0335 [hep-ex].
6. Pakvasa, S., *Curr. Sci.*, 2009, **96**, 186.
7. Milardi, C. *et al.*, In Proceedings of 11th European Particle Accelerator Conference (EPAC 08), Magazzini del Cotone, Genoa, Italy, 23–27 June 2008, pp. WEPP036.

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