Tetraquark sighting at Belle?

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At the Japanese KEKB electron–positron collider the Belle experiment (for a review of exciting recent results from here see, Ananthanarayan *et al.*[1]) recently reported anomalously large rates for the production of certain particles in the final state $\Upsilon(2S)\pi^+\pi^-$ and $\Upsilon(1S)\pi^+\pi^-$. Here the symbol Υ stands for 'resonances' containing *b*-quarks and *b*-antiquarks, and $\pi^{\pm}$ are the traditional pions first introduced by Hideki Yukawa to explain the inter-nucleon force. The reaction is studied[2] at an energy which is in the vicinity of another resonance $\Upsilon(5S)$.

The experimental effort includes an energy scan where the centre-of-mass energy of the electron–positron system runs over the range 10.83–11.02 GeV. Such high energies are required as the mass of the *b*-quark is about 4.5 GeV/c^2 (to fix the scale, the mass of the proton is about 0.940 GeV/c^2). The symbols *nS*, where $n = 1, 2, \ldots$ describe the radial excitations of well-known bound states of *b*-quarks and *b*-antiquarks that form each of these resonances, and fall into regular families with masses and lifetimes that can be deduced from experimental information and can be accommodated in models of which quarks are the building blocks.

Theorists have now proposed that these anomalously large rates are due to the formation in the electron–positron collision of an elusive and short-lived particle belonging to a family known as tetraquarks in the *b* quark–antiquark system[3]. This is because if indeed the reaction was

$$e^+e^- \rightarrow \Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-,$$

then the rate would have had to be two orders of magnitude smaller than the observed one when inferred from the corresponding reactions at lower energies from the formation of $\Upsilon(4S)$. The implications of the tetraquark hypothesis for this system are explained in the following after introducing the necessary background.

Quantum chromodynamics, the microscopic theory of the strong interactions is a theory of quarks of different 'flavour', which interact amongst themselves via the exchange of gluons and has the property of 'confining' quarks and gluons in 'hadronic matter'. The flavours are denoted by *u*, *d*, *s*, *c*, *b* and *t*. Familiar matter such as protons and neutrons is made up of *u* and *d* quarks, while matter made up of the heavier flavours is unstable as the weak interactions, which are responsible for, among other things, the β decay of nuclei and free neutrons, lead to their spontaneous conversion to lighter flavours with the emission of lighter particles in accordance with Einstein's special theory of relativity, that is to say, additional binding energy can be converted into particles. The mathematics that underpins this theory explains why protons and neutrons (baryons) are made up of three constituent quarks, and particles such as pions (mesons) are made up of quark–antiquark pairs. The theory does not forbid configurations such as with four quarks and an antiquark (pentaquarks), and two quarks and two antiquarks (tetraquarks). Such states of matter would be unstable and would decay into the more common particles with emission of mesons. Nevertheless, there has been no definitive evidence for the existence of such states, although some years ago there were signals for exotic particles[4,5]. Now the new Belle data suggest the existence of tetraquarks in a system with a *b*-quark and *b*-antiquark[3].

The work of the theorists is based on a model for a new state[6] denoted by $Y_b(10890)$ that is quite different from any of the Υ resonances[7,8]. It has a mass 10890 MeV/c^2 (here and elsewhere in this report, numbers appearing in parenthesis denote the mass of the associated state in MeV/c^2 units) and lifetime of about 10^{-23} s, typical of particles that decay through the strong interactions. This state is also consistent with the findings of the other B-factory, the BABAR collaboration[9] PEP-II storage ring at Stanford Linear Accelerator Centre, USA. Ali *et al.*[3] propose that this state is an example of a tetraquark, which is actually a diquark–diantiquark ($[bq][\bar{b}\bar{q}]$, where *q* can stand either for *u* or for *d*) system. In the context of tetraquarks it should be mentioned that their existence would imply fairly strong forces binding the diquark to the diantiquark, in contrast to a situation where there could be a weak 'molecular' bond between two mesons. Also of interest are 'hybrids' where a meson could have active gluonic degrees of freedom, which are also allowed by the mathematical structure of the strong interaction theory.

The model describes how the constituent quarks sitting inside the tetraquark can effectively and efficiently produce two pions in the final state, which would not be possible without the assumption of the tetraquark nature of the $Y_b(10890)$. The scheme employed in Ali *et al.*[3] utilizes conservation laws involving angular momentum (*J*), parity (*P*) and charge conjugation (*C*). The initial state $Y_b(10890)$ has $J^{PC} = 1^{--}$. In the final state $\Upsilon(1S)\pi^+\pi^-$ or $\Upsilon(2S)\pi^+\pi^-$, $\Upsilon(nS)$ has $J^{PC} = 1^{--}$. Due to the conservation laws above, the remainder of the final states and intermediate states can have quantum numbers either 0^{++} or 2^{++}. From the Particle Data Group, the three lowest lying states which have the required quantum numbers are chosen, viz. $f_0(600)$, $f_0(980)$ and $f_2(1270)$ (the subscript denotes *J*). These are unflavoured mesons and belong to the light quark sector. Kinematically, only the following decays are allowed; $Y_b \rightarrow \Upsilon(nS)\pi^+\pi^-$, $n = 1, 2$, which is non-resonant as it does not involve the *f* states. The possible resonant decays are $Y_b \rightarrow \Upsilon(1S)[f_0(600)$ or $f_0(980)]$, $Y_b \rightarrow \Upsilon(2S)f_0(600)$ and $Y_b \rightarrow \Upsilon(1S)f_2(1270) \rightarrow \Upsilon(1S)\pi^+\pi^-$. Here, $f_2(1270)$ is an intermediate, while $f_0(600)$ and $f_0(980)$ are final states, all three of which subsequently decay to pions. In order to use this to fit the observed data, amplitudes for each of the above processes are calculated and added. The striking feature of this work is that it reproduces the mass distributions and the angular distributions of the final state pions for both the $\Upsilon(1S)$ as well as $\Upsilon(2S)$ final states. In this manner, the tetraquark interpretation of $Y_b(10890)$ has been put forward.

It is worth recalling here that in the decade that is now coming to a close a large body of information has been gathered at the two B-factories, indeed at the Tevatron in Fermilab, Batavia, USA and CLEO experiment at Cornell University and the BES experiment in Beijing. Of note are the discoveries of states

labelled *X*, *Y* and *Z* in the sector containing 'charm' quarks, lighter counter parts of the *b* quarks. Of special note is a state known as *Y*(4260), which appears to the charm counterpart of our $Y_b(10890)$. In fact, the existence of the latter had been predicted on the basis of the existence of the former[10]. Despite accurate studies of the properties of this charm state, it is not yet clear whether it is a molecule[11] or a tetraquark[12]. This once again underscores the difficulty of establishing the true properties of states in the hadronic sector. As mentioned earlier analogous states ought to exist in the sector involving *s* quarks as well. Indeed this is the case and a candidate designated $Y_s(2175)$ was discovered by BABAR and BES-II; for a discussion see Olsen[7].

In the pure light quark sector theoretical approaches such as solving the strong interactions on the computer known as lattice gauge theory have also provided some evidence for the existence of tetraquarks; for a recent report see Prelovsek *et al.*[13].

In conclusion, we have reported here the interpretation of anomalously large rates for the production of $\Upsilon(nS)\pi^+\pi^-$ in terms of the process

$$e^+e^- \rightarrow Y_b(10890) \rightarrow \Upsilon(nS)\pi^+\pi^-$$

recently seen by the Belle collaboration. A dynamical model that interprets $Y_b(10890)$ as a tetraquark reproduces the rates as well as the angular and mass distributions of the final state pions. Thus a signal has been found in the *b* quark system for states that are theoretically permitted by QCD for the first time.

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Structure of an enzyme revealed 80 years after it was crystallized – differential functional behaviour of plant and microbial ureases uncovered

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It is indeed a proud moment for Indian structural biologists, in particular to the Madras University crystallography group who have recently made a contribution of historical significance, by determining the three-dimensional structure of the Jack bean urease (JBU). JBU is not only the first enzyme ever to have been crystallized way back in 1926, but also one that has demonstrated that enzymes are proteinaceous. James B. Sumner shared the Nobel Prize in chemistry with John Northrop and Wendell Standley in 1946 for this work. Surprisingly, JBU had to wait for more than 80 years for its structural revelation! It may be recalled that it is at the University of Madras, that structural biology research began in this country, under the eminent leadership of G. N. Ramachandran, with the discovery of the triple helical coiled-coil structure for collagen during 1954–55. Also, V. R. Sarma[1], a Madras University crystallographer was involved in the first ever crystal structure determination of the enzyme, lysozyme in UK by David Phillips and co-workers in 1965 and, also the first protein crystal structure, also an enzyme, ribonuclease A, determined in the US by Gopinath Kartha, J. Bello and D. Harker[2] in 1967. It is gratifying to note that the first protein ever to be crystallized has its structure unravelled eventually by Madras University crystallographers. They deserve to be congratulated upon this achievement.

JBU was also the first enzyme that provided the specific biological role for nickel. JBU along with other ureases forms a class of nickel-dependent metallo-enzymes synthesized by plants, some bacteria and fungi. They provide ammonia required for growth by catalysing the hydrolysis of urea into ammonia and carbon dioxide. Although the amino acid sequences of plant and bacterial ureases are closely related, some biological activities differ significantly. Plant ureases, but not bacterial ureases, possess insecticidal properties independent of their ureolytic activity. These contrasting biological properties and the fact that there was no structural information of plant ureases motivated Ponnuraj[3] and his group at the Centre of Advanced Study in Crystallography and Biophysics, University of Madras to take up the