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Convener Report of the session Heavy Quark Spectroscopy

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Heavy Quark Spectroscopy is a very active field, as demonstrated by the results presented at this Conference. There are many open questions, with plenty of opportunities for theoreticians and experimentalists. This short note highlights some of the interesting issues.

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The discovery of the $X(3872)$ state in 2003, by BELLE [1], opened a new era in heavy quark spectroscopy. This was an unexpected gift from the B-factories. In the following years there was a proliferation of new "exotic" states, the XYZ, whose interpretation has been challenging both theoreticians and experimentalists. Excellent and comprehensive reviews can be found in [2, 3, 4, 5, 6].

All XYZ states have masses above the $D\bar{D}$ threshold. A common feature of these states is that they decay into final states containing a $c\bar{c}$ pair. The $c\bar{c}$ states with mass bellow the $D\bar{D}$ threshold are very well described by models based on QCD-inspired potentials. As a matter of fact, the $c\bar{c}$ mesons bellow the $D\bar{D}$ threshold are one of the most well understood systems in particle physics. But above the $D\bar{D}$ threshold, the new states don't quite fit into the predicted charmonium spectrum. The latter is tightly constrained by theory and by the already observed states. That's why the XYZ states are so interesting. They may be the first compeling evidence of new forms of aggregation of quarks and gluons.

There is no demonstration that configurations other than the regular $q\bar{q}$ and qqq states from the Constituent Quark Model must exist, but there is a general belief that the low energy strong dynamics is so rich that these unconventional configuration will eventually be found, since they are allowed by QCD. The search for these new types of hadrons has been performed for quite a long time, but so far none of these unconventional particles have been clearly identified. In the light quark sector, for instance, the lightest scalar glueball is expected to have mass around 1.5 GeV/c^2. It may be mixed with the regular $q\bar{q}$ mesons, yielding the triplet $f_0(1710)$, $f_0(1500)$ and $f_0(1370)$. Since the scalar mesons are tipically broad, overlapping states, decaying isotropically, the identification of exotic states is a very hard task. The XYZ states, on the other hand, are narrow, in most cases, and, therefore, much easier to detect.

The most popular among the possible configurations are the tetraquarks and molecules, as illustrated in Fig. 1 of ref. [4]. Another important possibility are the hybrids ($c\bar{c}g$). One interesting aspect is that the whole set of new states cannot be described by only one of the above possibilities. Moreover, the new states may involve a mixing of different configurations.

The determination of the quantum numbers of the new states is a crucial point. States that are produced via ISR ($e^+ e^- \to \gamma X$), like the $Y(4260)$, $Y(4360)$, and $Y(4660)$, have well defined quantum numbers, $J^{PC} = 1^{--}$, constrained by the production mechanism. The Y fammily is often identified with the hybrid hypothesis. But for the other states the J^{PC} assignment is rather uncertain, and information from different decay channels is necessary. The $X(3872)$, for instance, decays to $J\psi\pi^+\pi^-$ – the discovery mode. Belle, BaBar, CDF and D0 data the $\pi^+\pi^-$ is consistent with being originated from the $\rho \to \pi^+\pi^-$. In addition, the decay $X(3872) \to \gamma J/\psi$ has been also seen, and this means the $X(3872)$ has a positive C-parity. The analysis of the lineshape of the $\pi^+\pi^-\pi^0$ spectrum from the decay $X(3872) \to J/\psi\omega$ [7] indicates that the $J^{PC} = 2^{-+}$ assignment is favored compared to $J^{PC} = 1^{++}$, although the latter cannot be ruled out. One possible interpretation of this state is an admixture of a $D\overline{D}^*$ and the χ'_{c1}, but one can find a rather extensive literature on this subject, with different interpretations.

The $Z^+(4330)$ is a key state. Being a charged state, its minimal quark content would be $c\bar{c}u\bar{d}$. It was found in 2007 by Belle [8] in the decay $B \to K\pi^+\psi'$ and appears as a narrow peak in the $\pi^+\psi'$ mass distribution. Its mass is close to the $D^*(2010)\overline{D_1}(2420)$. A full Dalitz plot analysis was performed on the same data [9] confirming the results of Belle's original paper. This state,

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however, has not been found by BaBar, and this opened a lively debate. Would this state be actually an interference effect with the $K\pi$ system? Another possible explanation was given by Rosner [10], according to which the $Z^+(4330)$ is an S-wave threshold enhancement due to the $D\overline{D}$ rescattering. The existence of this state could be confirmed by LHCb, but this will take at least one year of data taking, unfortunately.

A natural question is whether there are corresponding states in the $s\bar{s}$ and $b\bar{b}$ quark sectors. The $f_0(980)$ and the $a_0(980)$ have been proposed as candidates for $K\overline{K}$ molecules. The $f_0(980)$ meson, however, couples strongly to charm decays, and this may be seen as an evidence of an $s\bar{s}$ content in its wave function. In 2008 Belle found an anomalously large production of for $\Upsilon(nS)\pi^+\pi^-$ $(n = 1,2)$ around the $\Upsilon(5S)$ mass [11]. This would be the equivalent to the $\psi(ns)\pi^+\pi^-$ channels in the charm sector. The di-pion transition to $\Upsilon(1S)$ and $\Upsilon(2S)$, if attributed entirely to the $\Upsilon(5S)$ would result in partial widths that are 2 orders of magnitude larger that those from the $\Upsilon(4S)$ and $\Upsilon(3S)$. A combined fit of the $\sigma(e^+e^- \to \pi^+\pi^-\Upsilon(nS))$, $(n = 1,2,3)$, is consistent with a resonance with mass 10888.4 ± 3 MeV/c^2 and width 30.7 ± 8.9 MeV/c^2. This state would be the counterpart of the $Y(4260)$ in the $b\bar{b}$ sector. This region of the spectrum will be explored by the LHC experiments, in particular by LHCb, given its very good mass resolution.

Heavy quark spectroscopy is a field plenty of opportunities for experimentalists and theoreticians. The experimental evidence for the unconventional quarkonium-like and bottomonium-like states are summarized in Table 9 of ref. [6]. There are 12 states that still need confirmation. In addition, the determination of masses, widths, production and decay rates, as well as the quantum numbers, are the necessary information in order to identify the nature of these states. This is a challenging programme for the experimentalists.

The effective field theories (EFTs) of heavy quarkonium have reached a mature and very sophisticated state. This was nicely reported by N. Brambilla in her opening talk. In her words, "the identification of the appropriate degrees of freedom for an EFT for the new states remains an open question". An EFT for the new states needs to be constructed.

The new hadrons are by no means the only interesting issue in Heavy Quark Spectroscopy. There is still a long list of missing regular states: heavy quarkonia above $D\bar{D}$ and $B\bar{B}$ thresholds, many open charm and open beauty excited states, excited charmed and beauty baryons, doubly charmed baryons, etc. An example is the observation by BaBar of the bottomonium ground state, $\eta_b(1S)$ [12]. BaBar found a peak in the inclusive photon energy spectrum, which was inetrpreted as evidence for the radiative transition $\Upsilon(3S) \to \gamma\eta_b$. Under the bottomonium interpretation, the mass splitting between the $\Upsilon(1S)$ and the η_b is larger than the predictions based on potential models, but compatible with lattice calculations. This is a clear instance were more data is highly desirable.

The observation of B_c mesons and their excitations is another instance of measurements that should be performed at the LHC and at the Tevatron. CDF showed at this meeting interesting results on beauty and charm baryons, whereas BaBar reported on the observation of four new resonances decaying to $D\pi$ and $D^*\pi$ [13]. The four states were denoted $D(2550)^0$, $D^*(2600)^0$, $D(2750)^0$ and $D^*(2760)^0$. Once again, this is a subject to be furtherexplored by the LHC experiments and by the Tevatron.

Nice examples were given by the CDF and BaBar presentations at the Spectroscopy Session. A complete picture of the hadron spectrum is still far away, and this justify the ambitious programme of future experiments.

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