Exotic and conventional quarkonium physics prospects at Belle II

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Abstract. The Belle II experiment belongs to a new generation of B-factories, and it is located at the SuperKEKB collider. Its goal is to collect an integrated luminosity of 50 ab$^{-1}$, corresponding to a data sample that is 50 times larger than the one collected by its predecessor Belle. From February to July 2018, the machine has completed a commissioning run, achieving a peak luminosity of $5.5 \times 10^{33}$ cm$^{-2}$ s$^{-1}$, and a data sample of about 0.5 fb$^{-1}$ has been recorded. Belle II is capable of studying the so-called XYZ states with unprecedented precision: heavy exotic hadrons consisting of more than three quarks. First discovered by Belle, these now number in the dozens, and represent the emergence of a new category within quantum chromodynamics. In this paper, a general introduction to the experiment is presented, together with the perspectives for studies of conventional and exotic quarkonium-like states.

1. Introduction

The beginning of the 21st Century marked a turning point in the field of QCD. The $X(3872)$, unexpectedly discovered in 2003 by the Belle collaboration [1], was only the first in a large family of states. Currently, more than 20 such states have been found. These are referred to as the XYZ states, and cannot be explained in simple terms of quark-antiquark pairs. Instead, they call for more complex models involving at least 4 valence quarks. These exotic, 4-quark states were predicted already at the dawn of the quark model. However, the rigorous searches in the light quark sector were inconclusive. The heavy meson sector turned out to be a more fruitful searching ground, since the intrinsic non-relativistic nature of heavy $Q \bar{Q}$ pairs generates a spectrum of well separated states. However, more studies are required in order to resolve the role of the light degrees of freedom, which appear to be important players also in the heavy meson spectroscopy.

2. The Belle II experiment at SuperKEKB

Belle II is a multipurpose detector operating at the SuperKEKB $e^+ e^-$ asymmetric collider [2]. The accelerator is situated in Tsukuba, Japan, and it is an upgrade of KEKB [3]. The latter represents, together with PEPII at the SLAC National Accelerator Laboratory (California, USA) [4], the first generation of B-factories, i.e. asymmetric electron-positron colliders optimized at center of mass energies close to the mass of the $\Upsilon(4S)$ resonance. These factories produce large samples of $B \bar{B}$ mesons pairs, and have played a leading role in the field of particle physics in the last decades. The mass of the $\Upsilon(4S)$ resonance ($m_{\Upsilon(4S)} = 10.58$ GeV) is nearly the
same as that of the $B\bar{B}$ pair. As a consequence, the mesons are coherently produced nearly at rest in the $e^+e^-$ center of mass frame. Furthermore, the branching fraction for the $\Upsilon$ decay into a pair of $B$ mesons is $>96\%$. The asymmetry in the beam energies boosts the $B$ pair in the lab frame, allowing for measurements of time dependent CP-violation \[7\]. The next-generation B-factory, represented by SuperKEKB, will perform a wide number of high-precision measurements, aiming for the search for new physics. There are many differences between SuperKEKB and its predecessor, but the most important are the larger beam current ($\times2$) and the reduced beam spot size ($1/20$). These differences will allow for a peak luminosity of $8\times10^{35}$ cm$^{-2}$ s$^{-1}$, about 40 times higher than the one reached by KEKB. Another difference worth to mention is the sizable reduction in the beam energy asymmetry. This has tangible benefits, like an increased detector hermeticity, but also the drawback that it reduces the flight length of the $B$ meson pair and, as a consequence, it requires better precision in the reconstructed vertex position. A schematic view of SuperKEKB is shown on the left in Fig. 1. A detailed description of the SuperKEKB facility can be found in Ref. \[2\]. The Belle II detector is an upgrade of its predecessor Belle \[8\]. Belle II has to deal with a higher interaction rate and a larger background, hence an overall improvement of the performance is required. Starting from the part closer to the interaction point and proceeding outward, the Belle II detector is composed of the following elements:

- **Vertex detector (VXD),**
  comprised of two devices:
  - 2 layers of PiXel vertex Detector (PXD)
  - 4 layers of Silicon Vertex Detector (SVD)
- **Central Drift Chamber (CDC)**
- **Particle Identification system,**
  comprised of two detectors, covering different space regions:
  - Time Of Propagation (TOP) counter in the barrel region
  - Proximity focusing Aerogel Ring-Imaging Cherenkov (ARICH) in the forward endcap
- **Calorimeter (ECL)**
- **$K_L$ and Muon detector (KLM)**
Table 1. Summary of the existing data samples collected at \( \Upsilon(nS) \) resonances, together with the plans for the upcoming experiment. The numbers represent luminosities in \( \text{fb}^{-1} \); the corresponding number in millions for bottomonium decays is reported in brackets. The data sample fraction collected at non-\( \Upsilon(4S) \) resonances with respect to the \( \Upsilon(4S) \) is given in the last column. The table is reproduced from Ref. [9].

| Experiment | \( \Upsilon(1S) \) | \( \Upsilon(2S) \) | \( \Upsilon(3S) \) | \( \Upsilon(4S) \) | \( \Upsilon(5S) \) | \( \Upsilon(6S) \) | \( \Upsilon(nS) \) fraction |
|------------|------------------|------------------|------------------|------------------|------------------|------------------|-----------------------------|
| CLEO       | 1.2(21)          | 1.2(10)          | 1.2(5)           | 16(17.1)         | 0.1(0.4)         | -                | 23%                         |
| BaBar      | -                | 14(99)           | 30(122)          | 433(471)         | \( R_b \) scan  | \( R_b \) scan  | 11%                         |
| Belle      | 6(102)           | 25(158)          | 3(12)            | 711(772)         | 121(36)          | 5.5              | 23%                         |
| Belle II   | -                | -                | 300(1200)        | \( 5 \times 10^4(5.4 \times 10^4) \) | 1000(300)        | 100+400(scan) | 3.6%                        |

A schematic view of the Belle II detector is shown in the right panel of Fig. 1. A more detailed description can be found in Ref. [2].

3. Quarkonium-like physics

In addition to the main goal of Belle II, i.e. the search for new physics signatures in \( B \) meson decays, the physics program of the experiment also includes a wide scope of other topics. One example is the extensive physics program for quarkonium decays, that has great potential [10]. Quarkonium is a bound state of a heavy quark and a heavy antiquark (\( c\bar{c} \), \( b\bar{b} \) and \( bc \)). The term “quarkonium-like” is here used to include in the classification also the exotic XYZ states (not \( Q\bar{Q} \)) that have been observed. The bound state of two heavy quarks is non-relativistic, since the velocity of an individual quark is very small, hence \( v/c \ll 1 \) for \( c\bar{c} \), \( (v/c)^2 \sim 0.3 \) for \( b\bar{b} \).

This allows to introduce a hierarchy of energy scales: the hard scale \( m \) typical of the annihilation processes, the soft scale \( p \sim mv \), and the ultra-soft scale \( E \sim mv^2 \), which is similar to the binding energy. This hierarchy is usually expressed as

\[
 m \gg p \sim 1/r \sim mv \gg E \sim mv^2,
\]

where \( r \) represents the distance between the two components in the heavy quark-antiquark pair. It is indeed this peculiar hierarchy of energy scales that makes heavy quarkonium an ideal environment to study the interplay between perturbative and non-perturbative QCD. At present, there are more than 20 quarkonium-like states that cannot be interpreted as pure \( Q\bar{Q} \) states, a clear indication that they have an exotic structure. Several theoretical interpretations exist but the structures of the XYZ states remain undetermined. Therefore, further experimental efforts are crucial for a better understanding of their nature. An extensive review on the argument can be found in Refs. [11, 12]. A fraction of the Belle II data will be collected at other energies than the mass of the \( \Upsilon(4S) \) resonance, collecting unprecedented samples at the \( \Upsilon(3S, 5S, 6S) \) resonances. These data will be of fundamental importance in providing a deeper understanding of bottomonium-like states. Table 1 presents a summary of the existing data samples collected at \( \Upsilon(nS) \) resonances, together with the plans for the Belle II experiment.

3.1. Bottomonium-like sector

As already mentioned, part of the data taking of the experiment will be devoted at energies different from the \( \Upsilon(4S) \) resonance. Thanks to the upgrade in instantaneous luminosity, a limited amount of time will be required to increase the existing data samples collected at non-\( \Upsilon(4S) \) by one order of magnitude.
3.1.1. Sample above the Υ(4S) mass: To this date, five states containing $b\bar{b}$ pairs have been observed above the $B\bar{B}$ threshold:

- Three vector states with isospin 0, i.e. Υ(10580), Υ(10860), Υ(11020), also known as Υ(4S), Υ(5S), Υ(6S), respectively;
- Two axial states with isospin 1, $Z_b(10610)$ and $Z_b(10650)$.

For the latter group, the interpretation as a pure $b\bar{b}$ state fails completely to explain their properties, while for the former one, models which include a non-$b\bar{b}$ component have been proposed. Different alternative interpretations exist, but none of them has been confirmed yet. An energy scan above the $B\bar{B}$ threshold would therefore make a major contribution to the field [13]. The two axial states have masses very close to the $B\bar{B}^*$ and $B^*\bar{B}$ threshold, respectively. Up to now, their measured masses are above these thresholds, but not significantly [14, 15]. Collecting more data is crucial to address this problem, and to try to establish the true nature of the axial states. Another interesting question is to compare hadronic transitions from Υ(10860) and Υ(11020). Since the mass difference between these two states is relatively small, possible discrepancies in hadronic transitions should be related to the differences in their structure [16].

3.1.2. Sample below the Υ(4S) mass: Part of the Belle II physics program involves narrow resonances. In the energy region of Belle II, there are three different ways to access $b\bar{b}$ states below the $B\bar{B}$ threshold: via Initial State Radiation (ISR), via decays of higher-mass states, or via direct production, operating the accelerator at a lower center of mass energy. The gluon fragmentation in $\Upsilon(nS) \to ggg$ annihilation (with $n = 1,2,3$) provides a fertile ground for low energy QCD topics and for rare hadronic transitions. During the data taking, some data will be collected at the $\Upsilon(3S)$ resonance, resulting in a data sample $\sim 10$ times larger than the currently existing one. The studies performed by the BaBar collaboration [17] on $\Upsilon(3S)$ transitions left several open questions, like the unexpected evidence for the isospin-violating transition $\Upsilon(3S) \to \pi^0 h_b(1P)$ [18]. Furthermore, additional opportunities will be given by the study of the $\Upsilon(3S)$ annihilations. Having quantum numbers $J^{PC} = 1^{--}$ and being located below the $B\bar{B}$ threshold, this resonance has a large partial width for annihilation into three gluons, with a very high initial partonic density. This is due to the relatively small $\Upsilon$ radius. In a significantly different scenario compared to final states containing $B$-mesons, the production of multi-quark states and hadrons is favored, thus opening the possibility to study channels with implications in fields like astrophysics and dark matter searches. The understanding of the antideuteron ($\bar{d}$) production mechanism in annihilations, already performed by previous $e^+e^-$ experiments [19, 20], is possible with an unprecedented precision with the Belle II experiment. This knowledge is essential for the interpretation of the future results on the anti-matter content in the cosmic rays [21], expected by the AMS-02 [22] and GAPS [23] collaborations. Finally, the large hyperon production rate in annihilations, resulting from the enhancement of strangeness production [24], will allow to study hyperon-hyperon correlations. One of the Belle II goals is to deepen the study about the existence of the $\mathcal{H}$ dibaryon performed by Belle [25] and to extend it to the search for long-lived or stable dibaryons [26]. All these questions can be addressed by Belle II, especially thanks to the dedicated runs with center of mass energy below the $B\bar{B}$ threshold.

3.2. Charmonium-like sector

In the charmonium-like sector, there are different production methods that can be exploited: $B$ decays, two-photon collisions, ISR and double charmonium production. Each of these processes offers the possibility to access states of different spin-parity:
$B$ decays: It is possible to produce charmonium-like states in $B$ meson decays in association with a kaon ($B \to K X_{cc}$). The branching fractions for such processes are relatively large. Furthermore, useful properties are associated with these states when produced at $\Upsilon(4S)$: the charmonium-like states are produced polarized. The absolute branching fractions of these decays are poorly known but can be measured with Belle II requiring a full reconstruction of the second $B$ meson.

Two-photon collisions: With electron-positron colliders it is also possible to study two-photon interactions through the process $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-R$. Exploiting the two-photon physics, all the data at any energy point can be used to investigate the lower invariant mass region. Thanks to a smaller boost, the efficiency in the process should be higher with respect to Belle, and promising results are expected from some process, like $\gamma\gamma \to \phi J/\psi$, to name but one.

Initial state radiation: At $e^+e^-$ accelerators, there is the possibility to explore mass regions below the nominal center of mass energy exploiting the ISR technique, and to study states with $J^{PC} = 1^{--}$. The cross sections for ISR processes are in general very small, but the very large data samples foreseen with Belle II will compensate for this. The full Belle II data sample foreseen corresponds to about 2,000-2,300 pb$^{-1}$ data for every 10 MeV from 4-5 GeV, and will result in a similar amount of data as BESIII [27] for modes like $e^+e^- \to \pi^+\pi^- J/\Psi$.

Double charmonium production: The Belle collaboration was the first to report about the existence of double charmonium production processes in $e^+e^-$ annihilation [28]. This production mechanism offers a powerful tool in the charmonium sector, giving the possibility to search for possible new states, as well as to verify the charmonium production models.

4. Summary
The Belle II experiment is ready to start where the first generation B-factory ended, and to give an outstanding contribution to the quarkonium field. It offers unique opportunities in both charmonium- and bottomonium-like sectors, and it will provide key results to wide our knowledge of the basic constituents of matter.

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