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Physics prospects of exotic and conventional bottomonia at Belle II

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Abstract The Belle II experiment, being constructed at the KEK laboratory in Japan, is a substantial upgrade of the Belle detector. The construction of the SuperKEKB accelerator, which is the upgrade of the KEKB accelerator, has been just completed. It aims to collect 50 times more data than the existing B-Factory samples beginning in 2018. Belle II is uniquely positioned to study the so-called XYZ particles: heavy exotic hadrons consisting of more than three quarks. First discovered by Belle, the number of these particles is in the dozens now, which implies the emergence of a new category within quantum chromodynamics. This talk will present the capabilities of Belle II to explore exotic and conventional bottomonium physics. There will be a particular focus on the physics reach of the first data, where opportunities exist to make an immediate impact in the field.

Keywords Belle II · Bottomonia · Exotic

1 Introduction

The two asymmetric flavor factories, KEK-B, in Tsukuba, Japan and PEP-II, at SLAC, California, USA and their companion detectors, Belle [1] and BaBar [2] have produced several landmark results in flavor physics results, providing stringent tests of the standard model (SM). Belle and BaBar are the first generation B-factories, operating at centre-of-mass energies equal to the mass of the $\Upsilon(nS)$, mainly at $m_{\Upsilon(4S)} = 10.58 GeV$, and also at off-resonance energies, collecting an integrated luminosity of about 0.5 and 1 fb^{-1}, respectively. KEKB reached the world highest instantaneous luminosity of about $2 \times 10^{34} cm^{-2} s^{-1}$. B-factories (Belle, BaBar) reaped rich physics harvest in just one decade, namely CKM matrix elements, unitary triangle parameters

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through discovery of charge-parity violation (CPV) in the B meson system [3, 4], charm mixing [5], first observation of exotic X(3872) [6] and the tetra-quark candidate $Z(4430)^+$ [7]. One of the major achievements of B-factories was the experimental confirmation of the CKM mechanism, which paved the way to the Nobel Prize in Physics in 2008 awarded to M. Kobayashi and T. Maskawa [8]. Belle has made rich contribution to quarkonium spectroscopy. However, still few unsolved mysteries remain such as hierarchy in SM, large matter anti-matter asymmetry in nature. Hence, the hunt is on in the intensity/precision frontier at SuperKEKB, the successor of KEKB. Thus, a second generation of B-factories has a lot of physics potential. Keeping this in mind, KEKB and Belle are being upgraded to SuperKEKB and Belle II respectively at KEK, Japan.

2 SuperKEKB and Belle II

2.1 SuperKEKB

SuperKEKB, located at KEK (High Energy Accelerator Research Organization) in Tsukuba, Japan is a major upgrade to the KEKB accelerator. It consists of two 3 km rings equipped with radio-frequency (RF) systems which accelerate e^- and e^+ beams to 4 and 8 GeV, respectively, and make them collide at the center of the Belle II detector. There are several changes with respect to the predecessor, KEKB accelerator, namely, longer dipoles and redesigned magnet lattice to squeeze the emittance, and additional (or modified) RF systems for higher ($\times 2$) beam currents. SuperKEKB reduces ($\times 20$) the beam spot size using a nano-beam scheme achieved with new superconducting final focusing quadrupole magnets near the interaction region. The upgraded collider will deliver an integrated luminosity of 50 ab^{-1} and reach a peak luminosity of $8 \times 10^{35} cm^{-2} s^{-1}$, about 50 and 40 times KEKB, respectively, meaning about 10^{10} $B\bar{B}$ or $\tau\bar{\tau}$ pairs per year. The schematic diagram of SuperKEKB collider is shown in Fig. 1.

2.2 Belle II

The Belle II detector [9] consists of several sub-detectors that, with respect to Belle, were either upgraded or replaced for improved detection performance at higher luminosity environment. The schematic diagram of Belle II detector is shown in Fig. 1. A larger tracker improves the impact parameter and secondary vertex resolutions, increases the K_s^0 and pion efficiencies, and provides better flavor tagging. A smaller beryllium double-wall beam pipe ($r = 1.5 \rightarrow 1.0$ cm), combined with an innermost silicon pixel layer much closer to the interaction region ($r = 1.4$ cm), improve the impact parameter resolution along the beam line ($\sigma d_z \sim 60 \rightarrow 20$ m). An upgraded time-of-propagation (TOP) counter and ring-imaging Cherenkov counters with aerogel radiator (A-RICH), together

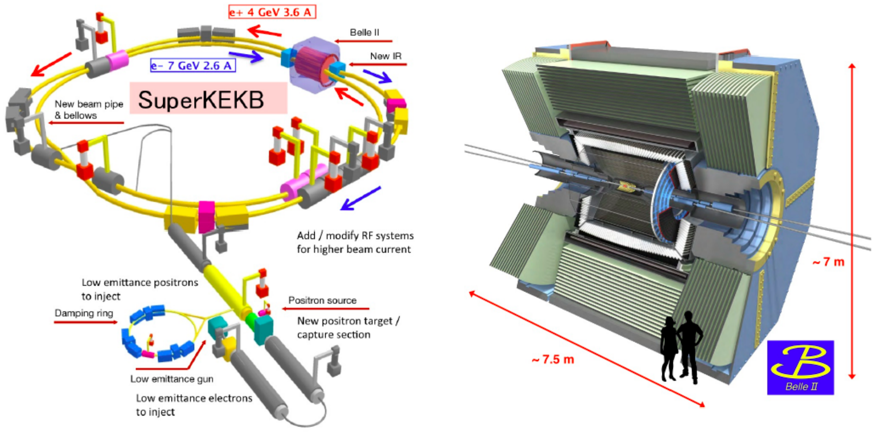

Fig. 1 SuperKEKB collider (left), Belle II detector (right)

with a faster and more hermetic K_L^0 and μ (KLM) detector, allow a better particle identification and further enhance the flavor tagging and background rejection. Belle II will have faster and more reliable trigger and data acquisition (DAQ) systems in order to operate at a much higher event rate.

3 Physics prospects of exotic and conventional bottomonia at Belle II

3.1 Conventional and Exotic states

Although the Standard Model (SM) allows any color-neutral combinations, conventional hadrons exist as bound states of either three quarks, qqq (baryon) or a quark and an anti-quark, $q\bar{q}$ (meson). The exotic color-neutral combinations, that are also allowed in SM as proposed by Gell-Mann [10] and Zweig [11], include tetra-quarks ($q\bar{q}q\bar{q}$), penta-quarks ($qqqq\bar{q}$), glue-balls (gg), and so on. The first exotic appeared in the charmonium sector in 2003 , and since then, several exotics have been discovered.

3.2 Search for Bottomonia states

There are generally three ways in which to access bottomonia below the $B\bar{B}$ threshold [12]: via decays of higher mass states (e.g. $\Upsilon(4S, 5S, 6S)$, production of 1^{--} states via initial-state radiation, or by direct production via operation at a lower centre-of-mass energy. Below the $\Upsilon(4S)$ threshold, there are several predicted bottomonium states that have yet to be positively identified, separation of the $\chi_b(3P)$ triplet, the $\Upsilon(2D_3)$ and so on.

Although much progress has been made on understanding of the $\Upsilon(1^3D_J)$ triplet by CLEO [13], BaBar [14] and Belle [15], isolation and identification of the individual $\Upsilon(1^3D_J)$ states still remains elusive. From $\Upsilon(3S)$, two decay pathways have been employed: the four-photon radiative decay cascade [41], and radiative decays to $\Upsilon(1^3D_J)$ followed by a dipion decay to $\Upsilon(1S)$ [199]. Since the branching fraction of these decays is small, a large $\Upsilon(3S)$ dataset is required to perform these analyses.

In order to access bottomonium-like states above $B\bar{B}$ threshold, we need energy scan and data at $\Upsilon(5S)$, $\Upsilon(6S)$, and higher peaks, if they are found in the energy scan. Using data collected at $\Upsilon(6S)$, several searches can be performed. Search for transitions into ordinary bottomonia and light hadrons, such as $\Upsilon(nS)\pi^+\pi^-$, $\Upsilon(nS)\eta$ transitions could be performed using this data. Further, search for missing bottomonium levels such as $2D$, $1F$ multiplets, and states other than $Z_b(10610)$ and $Z_b(10650)$ bottomonium-like states can also be performed.

At Belle II, the following golden modes will be investigated [12]:

- Search for hadronic transitions from $\Upsilon(6S)$ to study its structure
- Search for missing bottomonia below $B\bar{B}$ threshold, e.g. spin-singlet member of the 1D multiplet, all members of the 2D and 1F multiplets
- Search for molecular states, partners of Z_b using radiative and transitions
- Scan near and above $\Upsilon(6S)$, to clarify structure of $\Upsilon(6S)$ state (decomposition of R_b), to search for vector bottomonium-like states

3.3 $Z_b(10610)$ and $Z_b(10650)$ states

Z_b states are responsible for large rates of production of $h_b(1P, 2P)$ states seen in $\Upsilon(5S)$ decays. Charged $Z_b(10610)$ and $Z_b(10650)$ were discovered in $\Upsilon(nS)\pi^\pm$ and $h_b(mP)\pi^\pm$ at $\Upsilon(5S)$ [18]. Neutral $Z_b(10610)$ was discovered in $\Upsilon(nS)\pi^0$ at Y(5S) [19]. Charged Z_b (10610) to B^*B decays and $Z_b(10650) \to B^*B^*$ decays observed at Y(5S) [20]. In 2016, Belle reported the first observations of the three-body processes with a statistical significance above 8σ.

The typical analysis procedure for such analyses is shown in one of the Golden Modes, $\Upsilon(6S) \to \pi Z_b(\pi h_b(nP))$. The missing mass ($M_{miss}$) can be computed for the two pion system and for each pion individually. One of the pions missing mass must be within $10.55\ GeV < M_{miss}(\pi) < 10.70\ GeV$ to select the pion created in the $\Upsilon(6S) \to \pi Z_b$ transition. The missing mass of this pion can be used to deduce the Z_b properties. Additional requirements are employed to suppress background, namely high particle identification confidence for pion hypothesis, ensuring pions originated at the interaction point. Finally, the M_{miss} distribution is fitted. These states have a minimum four quark content. Recent observations are consistent with expectations for molecular state [21]. Proximity to $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds and their being dominant decay modes has been observed.

These Z_b states are produced in both $\Upsilon(5S)$, $\Upsilon(6S)$ decays, and it is important to study production from both resonances in Belle II. We expect $20 fb^{-1}$

of $\Upsilon(6S)$ in Phase 2 or early Phase 3 and much more later and hope to collect at some point a large $\Upsilon(5S)$ sample, increasing its statistics up to $\sim 5\ ab^{-1}$. Further analysis is required to understand the properties of these states. At Belle II, we aim to improve the understanding of the $Z_b(10610)$ and $Z_b(10650)$ states and their branching fractions.

4 Models

$Z_b(10610)^+$ and $Z_b(10650)^+$ [22,23] decay predominantly into $\bar{B}B^*$ and $\bar{B^*}B^*$ [24], respectively, although all of them were discovered in decay modes with a heavy quarkonium and a pion. This suggests that the states are close relatives and their interactions connected via heavy quark flavor symmetry. A molecular interpretation for the bottomonium states was proposed shortly after the discovery of the Z_b^+ states [25]. However, their properties also appear to be consistent with tetraquark structures [26]. The primary tool for theoretical predictions is Lattice QCD, which is a reliable non-perturbative method to study hadron properties based directly on QCD, that relies on numerical path integration in Euclidean discretized and finite space-time. The above searches require more high quality data for various decay channels and therefore, Belle II can contribute significantly in this important field of research.

5 Early physics program at Belle II

The Belle II experiment is scheduled to begin its first physics run in late 2018. As a prelude to this, there are two commissioning periods known as Phase 1 (early 2016) and Phase 2 (late 2017- early 2018) where a varied collection of smaller detectors are deployed for measuring background rates and operating conditions. The first physics run (Phase 3) in late 2018 will involve the entire Belle II detector, with the machine operating with an instantaneous luminosity of at least $1 \times 10^{35} cm^{-2}s^{-1}$. Based on the expected operating conditions and physics prospects, collecting data above the $\Upsilon(4S)$ offers the best physics opportunities (6S) during Phase 2. The (6S) energy region ($\sim 11020 MeV$) is particularly interesting, both because only $< 5.6\ fb^{-1}$ of data have been collected there previously, and also because of the discoveries of multi-quark Z_b states in its midst [27].

6 Summary and outlook

There have been precise predictions of bottomonia spectra below open flavor and are in reasonable agreement with experiment. From the scattering matrix extracted on the lattice, information on the states above or slightly below threshold can be inferred. The states that can decay hadronically into two different two-meson final states are challenging, but manageable. Recently, the scattering matrix for the two-coupled channels has been extracted for the first time using the Luscher-tye method [28]. So, the analogous results relevant to quarkonium (like) spectroscopy at Belle II can be expected by the time it starts operating. Belle II will aim also the quarkonium and quarkonium-like states that are located above multiple thresholds, for example Z_b and $Z^+(4430)$. To conclude, the potential of physics searches in the bottomonia spectroscopy is immense and thus, Belle II measurements in this field would be quite interesting.

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