Snowmass 2021 Letter of Interest: Hadron Spectroscopy at Belle II

on behalf of the U.S. Belle II Collaboration

D. M. Asner[1], Sw. Banerjee[2], J. V. Bennett[3], G. Bonvicini[4], R. A. Briere[5], T. E. Browder[6], D. N. Brown[2], C. Chen[7], D. Cinabro[4], J. Cochran[7], L. M. Cremaldi[3], A. Di Canto[1], K. Flood[6], B. G. Fulsom[8], R. Godang[9], W. W. Jacobs[10], D. E. Jaffe[1], K. Kinoshita[11], R. Kroeger[3], R. Kulasiri[12], P. J. Laycock[1], K. A. Nishimura[6], T. K. Pedlar[13], L. E. Piilonen[14], S. Prell[7], C. Rosenfeld[15], D. A. Sanders[3], V. Savinov[16], A. J. Schwartz[11], J. Strube[8], D. J. Summers[3], S. E. Vahsen[6], G. S. Varner[6], A. Vossen[17], L. Wood[8], and J. Yelton[18]

[1]*Brookhaven National Laboratory, Upton, New York 11973*
[2]*University of Louisville, Louisville, Kentucky 40292*
[3]*University of Mississippi, University, Mississippi 38677*
[4]*Wayne State University, Detroit, Michigan 48202*
[5]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[6]*University of Hawaii, Honolulu, Hawaii 96822*
[7]*Iowa State University, Ames, Iowa 50011*
[8]*Pacific Northwest National Laboratory, Richland, Washington 99352*
[9]*University of South Alabama, Mobile, Alabama 36688*
[10]*Indiana University, Bloomington, Indiana 47408*
[11]*University of Cincinnati, Cincinnati, Ohio 45221*
[12]*Kennesaw State University, Kennesaw, Georgia 30144*
[13]*Luther College, Decorah, Iowa 52101*
[14]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[15]*University of South Carolina, Columbia, South Carolina 29208*
[16]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[17]*Duke University, Durham, North Carolina 27708*
[18]*University of Florida, Gainesville, Florida 32611*

Corresponding Author:

B. G. Fulsom (Pacific Northwest National Laboratory), bryan.fulsom@pnnl.gov

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Abstract:

The Belle II experiment at the SuperKEKB energy-asymmetric e^+e^- collider is a substantial upgrade of the B factory facility at KEK in Tsukuba, Japan. It aims to record a factor of 50 times more data than its predecessor, to be collected over the course of the next 10 years. Belle II is uniquely capable of studying topics in hadronic spectroscopy, including conventional mesons, baryons, quarkonia, and so-called "XYZ" particles: heavy exotic hadrons consisting of more than three quarks. This Letter of Interest briefly summarizes the capabilities of the Belle II experiment in this area.

Quantum Chromodynamics (QCD) is the elementary theory that describes strong interactions between quarks and gluons in the Standard Model. A consequence of this theory is the prediction that quarks and antiquarks bind to form mesons, while three-quark combinations form baryons. In recent years, experiments have discovered several exotic manifestations of QCD, such as weakly-bound meson molecules, quark-gluon hybrids, and tetraquarks and pentaquarks. The experimental study of hadronic spectroscopy is important to uncover the nature of these newly discovered states of matter, and for furthering our fundamental understanding of the strong force. The Belle II Experiment presents several unique opportunities in this domain as it collects $\sim 50\text{ab}^{-1}$ of data at the SuperKEKB e^+e^- collider over the course of the next ten years.

The light hadron spectrum, despite many years of study, remains relatively poorly understood. The lightest expected glueball states mix with conventional states so careful study and comparison of light meson spectra are necessary to elucidate their nature. Studies of high statistics samples from two-photon production at Belle II will provide important, complementary information to light hadron spectra from other experiments, such as BESIII. A comprehensive study of many final states, including those with neutral particles in the final state, is important to account for complicated rescattering effects and identify states with high glueball content.

Quarkonium is the bound state of heavy quark-antiquark pairs ($c\bar{c}$, $b\bar{b}$). Study of the quarkonium system has been the gateway for the discovery of nearly all new multiquark states, via decays to and from conventional quarkonia particles. The $X(3872)$[1] was the first of a growing alphabet of charmonium-like particles (i.e. $X(3872)$, $Y_c(4260)$[2], $Z_c^{\pm}(3900)$[3], and several others) that do not fit the well-established theoretical framework[4]. Analogous discoveries containing bottom quarks (e.g. $\Upsilon(5S)$ decays to $Z_b^{\pm}(10610/50)$[5]) indicate that a similar family of particles may exist in the bottomonium sector. An extensive quarkonium physics program is planned to study both conventional and exotic states at Belle II. Several mechanisms exist to produce quarkonium(-like) states, including B meson decays, initial state radiation (ISR), double $c\bar{c}$ processes, two-photon processes, and direct production by changing collider center-of-mass energy[6].

Belle II expects approximately a factor of fifty increase in statistics for B decays compared to the previous generation Belle experiment. Belle II holds advantages for final states including neutral particles. This should allow confirmation of evidence for previously discovered $Z_c^{\pm}$ states and the search for neutral partners, measurement of the absolute $B \to X(3872)K$ branching fraction, and confirmation of $X(3872)$ width measurements using the $D^0\overline{D}^0\pi^0$ final state. ISR production of charmonium and exotic states can be exploited to cover a wide mass range, complementary to, *e.g.*, the BESIII experiment operating at specific center-of-mass energies. One of the unique aspects of Belle II is the ability to study Z states in both B meson decays and in direct production via ISR, which appear to produce two distinct sets of Z states. At 10 (50) ab^{-1} Belle II is estimated to have an equivalent on-peak luminosity between $300 - 500$ $(1500 - 2500)$ pb^{-1}/10 MeV over a range of $3 - 5$ GeV, allowing detailed study of Y_c states, decays to various $Z_c^{\pm}$ states, and reaching the threshold for $\Sigma_c\overline{\Sigma}_c$ production. Double-charmonium production of $J/\psi(1S)$ with an accompanying charmonium(-like) state[7] will also be improved by increased statistics, and searches for new states recoiling against charmonium of other quantum numbers (*e.g.* η_c and χ_{cJ}) become a possibility. Similarly, two-photon interactions with greater statistics can be used to probe exotics such as controversial four-quark $c\bar{c}s\bar{s}$ states decaying to $\phi J/\psi(1S)$[8].

Belle II and SuperKEKB have the unique opportunity to explore bottomonium(-like) states by scanning over or operating at center-of-mass energies near the $\Upsilon(4S)$ resonance, where a relatively small amount of data have been collected ($\mathcal{O}(10)$ fb^{-1} at $\Upsilon(1S, 2S, 3S, 6S)$, $\mathcal{O}(100)$ fb^{-1} at $\Upsilon(5S)$, and typically < 1 fb^{-1} at intermediate points). Efforts by previous experiments spanning the range from $\Upsilon(1S)$ up to $\Upsilon(6S)$ ($\sim$11 GeV) led to the discovery of several bottomonia ($\eta_b(1S, 2S)$, $h_b(1P, 2P)$, and $\Upsilon(1D_2)$), and four-quark states ($Z_b^{\pm}(10610, 10650)$, $Y_b(10750)$)[9;10]. Energies above these points, to cover the $\Lambda_b\overline{\Lambda_b}$ threshold and to potentially search for other new Y_b states, are possible with future accelerator upgrades. Operating points below the $\Upsilon(4S)$ open the possibility to test predictions of physics beyond the Standard Model in Υ decays to invisible or lepton flavour violating final states. Belle II is actively pursuing all of these options as part of its hadronic spectroscopy program.

Electron-positron colliders have historically made the majority of discoveries in the rich spectroscopy of charmed baryons. In recent years, that mantle has been taken by LHCb who have an advantage in statistics. However Belle II will still have certain advantages over the hadronic environment, in particular their detection of electromagnetic transitions and long-lived hyperons (Σ^+, Ξ^-, Ξ^0, Ω^-, *etc.*). For instance, the structure of the excited Ω_c baryons discovered by LHCb will be greatly clarified by detection of their decays through Ξ'_c, and their narrow widths imply that direct electromagnetic decays to Ω_c^0 may well be detected. In addition, the large production of charmed baryons can be reconstructed by Belle II in a vast array of different decay modes, leading to a better understanding of the weak decay processes and making a laboratory for the investigation of the many resonances produced. Charmed baryon decays can thus address the many open questions in the light and strange baryon spectra, which contain several exotic candidate states, such as the $\Xi(1620)$. While it is more complicated, the baryon spectrum presents potential studies of exotic states even in the first excited states, such as the $\Lambda(1405)$ and $N(1440)$, for which the inner quark structure identification remains controversial.

The field of hadronic spectroscopy is currently one of renewed vibrancy and continual discovery. The Belle II experiment is an essential contributor in this area, and is poised to expand upon the past successes of B Factories to provide a deeper understanding of QCD over the course of the coming decade.

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