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Hyperon pair production at BESIII

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Hyperons provide a unique avenue to study the strong interaction. Due to their limited lifetime, the hyperon production in e^+e^- collisions is a new viable way to obtain information to understand the hyperon structure and internal dynamics, and even insight into the nature of the charmonium(-like) states. With the unique data sets obtained by the BESIII experiment, the recent results for the hyperon pair production in e^+e^- collisions are presented, such as observation of $\psi(3686) \to \Xi(1530)^-\bar{\Xi}(1530)^+$, determination of the Ω^- spin, observation of the Ξ hyperon polarization, study of threshold effect in the sector of Ξ hyperon, search for $Y(4230/4260) \to \Xi^-\bar{\Xi}^+$ and so on.

Keywords: Hyperon pair production; charmonium decay; e^+e^- annihilations; cross section; form factor.

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1. Introduction

Study of the hyperon pair ($H\bar{H}$) production in e^+e^- annihilations and charmonium(-like) decays provides a favorable and rich laboratory to probe pQCD and the hyperon properties, as well as to understand internal structure of hadron [1–8]. Figure 1 shows the lowest-order Feynman diagram for the $H\bar{H}$ production in e^+e^- annihilations and charmonium(-like) decays.

In 1974, the first member of charmonium(-like) states J/ψ was discovered [9], which was subsequently proposed a nonrelativistic $c\bar{c}$ bound state by Appelquist and Politer [10]. After that, more and more charmonium(-like) states were found by modern particle colliders, where the J/ψ, $\psi(2S)$, $\psi(3773)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$, *etc.*, are called charmonium states since the experimental information of these states is in good agreement with the prediction of the lattice QCD and potential models [11–16], while for other states, such as $X(3872)$, $Y(4260)$, $Y(4360)$ $Y(4660)$, etc., the theoretical models can not favor well the experimental information [17, 18], which are so-called charmonium-like states. Hyperon is one of baryon that consists of the qqs quarks configuration with the zero total color charge. The knowledge of charmonium(-like) states coupling to the $H\bar{H}$ final states in e^+e^- collisions could offer valuable insights into the nature of these states and even help us understand the hyperon structure and internal dynamics well.

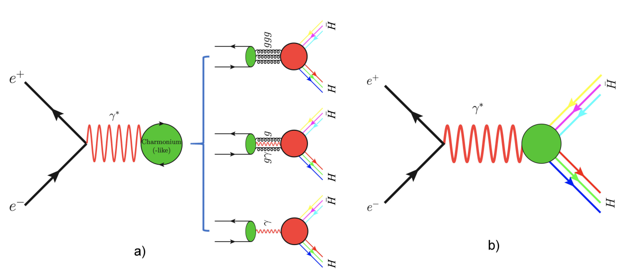

FIGURE 1. a) Hyperon pair production in charmonium(-like) decays via three gluons, the mixed two gluons plus one virtual photon, and one virtual photon. b) Hyperon pair production in e^+e^- annihilations via one photon exchange.

2. BESIII experiment

BESIII at BEPCII accelerator is an experiment designed for the study of hadron physics at τ-charm physics region [19, 20]. The BEPCII by far has achieved a peak luminosity of 10^{33} cm^{-2}s^{-1} at center-of-mass (c.m.) energy of 3.78 GeV [21]. BESIII detector, as shown in Fig. 2, has collected large data samples at c.m. energies from 2.0 to 4.9 GeV [22–25]. The BESIII Collaboration consists of more than 500 members from 76 institutions in 16 countries, including both engineers and physicists.

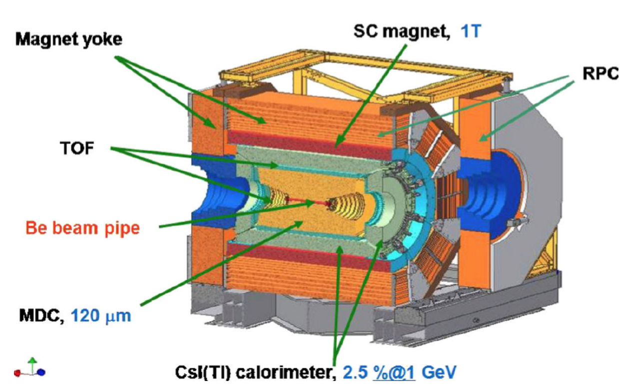

FIGURE 2. The BESIII detector [19] with its components.

TABLE I. Numerical results for angular distribution parameter α_ψ, polarization parameter $\Delta\Phi$, the Λ/Ξ decay parameters, $\alpha_{\Lambda/\bar{\Lambda}}$, $\alpha_{\Xi/\bar{\Xi}}$, $\phi_{\Xi/\bar{\Xi}}$, the strong and weak phase difference $\xi_P - \xi_S$, $\delta_P - \delta_S$ and CP asymmetries $A^{\Xi}_{\rm CP}$, $A^{\Lambda}_{\rm CP}$, $\Delta\phi^{\Xi}_{\rm CP}$, and the average $\langle\phi_\Xi\rangle$.

Parameter	This work	Previous works [9, 30, 31]
α_ψ	$0.586 \pm 0.012 \pm 0.010$	0.58 ± 0.09
$\Delta\Phi$ (rad)	$1.213 \pm 0.046 \pm 0.016$	–
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010
$\alpha_{\bar{\Xi}}$	$0.371 \pm 0.007 \pm 0.002$	–
ϕ_Ξ (rad)	$0.011 \pm 0.019 \pm 0.009$	-0.037 ± 0.014
$\phi_{\bar{\Xi}}$ (rad)	$-0.021 \pm 0.019 \pm 0.007$	–
α_Λ	$-0.757 \pm 0.011 \pm 0.008$	-0.750 ± 0.010
$\alpha_{\bar{\Lambda}}$	$-0.763 \pm 0.011 \pm 0.007$	-0.758 ± 0.012
$\xi_P - \xi_S$ ($\times 10^{-2}$ rad)	$1.2 \pm 3.4 \pm 0.8$	–
$\delta_P - \delta_S$ ($\times 10^{-2}$ rad)	$-4.0 \pm 3.3 \pm 1.7$	-10.2 ± 3.9
$A^{\Xi}_{\rm CP}$ ($\times 10^{-3}$)	$-6 \pm 13 \pm 6$	–
$A^{\Lambda}_{\rm CP}$ ($\times 10^{-3}$)	$-4 \pm 12 \pm 9$	–
$\Delta\phi^{\Xi}_{\rm CP}$ ($\times 10^{-3}$ rad)	$-5 \pm 14 \pm 3$	–
$\langle\phi_\Xi\rangle$ ($\times 10^{-3}$ rad)	$16 \pm 14 \pm 7$	

3. Recent results

3.1. Hyperon pair production in charmonium decays

3.1.1. $J/\psi \to \Xi^-\bar{\Xi}^+$

One of key puzzles in the Standard Model (SM) of particle physics is why the matter is much more than antimatter in the Universe. The violation of the charge-conjugation and parity (CP) symmetry could be responsible for this big question, which is accommodated by the CKM mechanism [26, 27]. However, the predicted amount of the CKM mechanism and even experimental information for the CP-violation are not sufficient to explain that our Universe is dominated by matter and other sources of CP-violation are desired and expected to exist [9,28]. Two-body decays of $H\bar{H}$ pairs provide a new laboratory to probe and test the CP-violation. Based on the 1310 million J/ψ events, BESIII experiment performs a test of CP-violation and measurement of the spin polarization of doubly-strange hyperon by exploiting their spin entanglement between the Ξ^- hyperon and its antihyperon $\bar{\Xi}^+$ in the $e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$ process [29]. Figure 3 shows the distribution of the polarization signal as a function of $\cos\theta$. Table I summarizes the numerical results. The angular distribution α_ψ, the decay parameters of Λ and Ξ^-, $\alpha_{\Lambda/\bar{\Lambda}}$, $\alpha_{\Xi/\bar{\Xi}}$, $\phi_{\Xi/\bar{\Xi}}$, strong phase difference $\delta_P - \delta_S$ and $A^{\Lambda}_{\rm CP}$ are measured to be consistent with the previous results and a little high precision. Other parameters, including the polarization $\Delta\Phi$, $A^{\Xi}_{\rm CP}$ and $\Delta\Phi^{\Xi}_{CP}$, are determined for the first time. These results provide a most precise test for CP violation in doubly-strange hyperon sector.

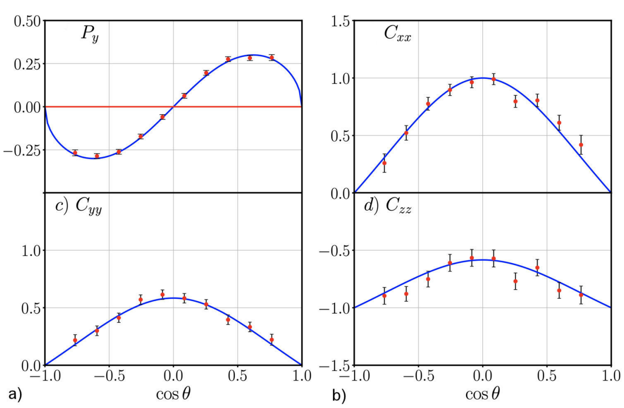

FIGURE 3. Distributions of moments P_y, C_{xx}, C_{yy} and C_{zz} in the $e^+e^- \to J/\psi \to \Xi^-\bar{\Xi}^+$ process as functions of $\cos\theta$. Dots with error bar are for data. The blue curves are for the phase space (PHSP) MC corrected shape from global fit. The red line shown on P_y is for PHSP MC.

3.1.2. $\psi(3686) \to \Xi(1530)^-\bar{\Xi}(1530)^+$

Based on 448 million $\psi(3686)$ events collected with the BESIII detector at the BEPCII collider, the $\Xi(1530)^-\bar{\Xi}(1530)^+$ and $\Xi(1530)^-\bar{\Xi}^+$ pair production in $\psi(3686)$ decays are observed by means of single-baryon tagging technique and the significances are estimated to be larger than 10σ and 5σ for both processes including the systematic uncertainties [32]. Figure 4 shows the fit to the recoil mass spectra of $\pi\Xi$. Clear $\Xi(1530)^-$ and Ξ^- signals can be seen. The branching fractions for both processes are measured to be $\mathcal{B}[\psi(3686) \to \Xi(1530)^-\bar{\Xi}(1530)^+] = (11.45 \pm 0.40 \pm 0.59) \times 10^{-5}$ and $\mathcal{B}[\psi(3686) \to \Xi(1530)^-\bar{\Xi}^+ \text{or c.c.}] = (0.70 \pm 0.11 \pm 0.04) \times 10^{-5}$, where non-zero branching fraction for $\psi(3686) \to \Xi(1530)^-\bar{\Xi}^+$ further validates the generality of SU(3) flavor

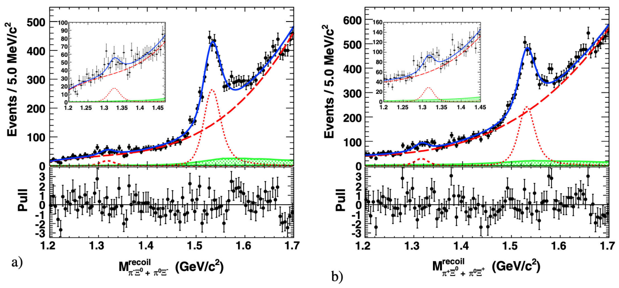

FIGURE 4. Distributions of $M^{\rm recoil}_{\pi\Xi}$ in the fit from the $\Xi(1530)^-$ tag a) and $\bar{\Xi}(1530)^+$ tag b). Dots with error bar are for real data. The red short-dashed lines represent the signal. The red long-dashed lines represent the smooth background and the green hatched histogram stands for the wrong combination background.

symmetry broken. In addition, angular distribution parameter for the $\psi(3686) \to \Xi(1530)^-\bar{\Xi}(1530)^+$ process is determined to be $\alpha = 0.40 \pm 0.24 \pm 0.06$, which is consistent with the theoretical predictions (0.31 and 0.18) from electromagnetic effect and quark mass [33, 34] within the uncertainty of 1σ.

3.1.3. $\psi(3686) \to \Omega^-\bar{\Omega}^+$

The discovery of Ω^- hyperon is a milestone for understanding the eightfold way model of particle physics, which further validates the postulate of color charge [9, 35, 36]. According to the prediction of quark model and eightfold way model, the Ω^- hyperon has a spin of $J = 3/2$, but it has never be confirmed unambiguously by experiment. In 2006, BaBar experiment performed a model-dependent measurement of the spin for the Ω^- hyperon with the assumption of a spin of $1/2$ for the Ξ_c^0 baryon [37]. Recently, BESIII experiment performed a mode-independent measurement for the spin of Ω^- hyperon and its polarization alignment based on 4035 $\Omega^-\bar{\Omega}^+$ pair production events survived in $\psi(3686)$ decays. The spin of Ω^- hyperon was determined to be $J = 3/2$ with a significance of 14σ larger than the one with a spin of $J = 1/2$. It is clear that the t value obtained from the real data favors the hypothesis of $J = 3/2$ as shown in Fig. 5a), where the test statistic $t = S^{J=1/2} - S^{J=3/2}$ is performed based on the MC

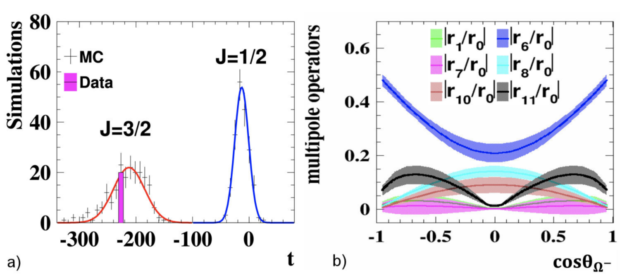

FIGURE 5. a) Distribution of the t value, where the lines stand for the fit with Gaussian function to the simulated MC events and the vertical bar indicates the t value obtained from the real data. b)The dependence of the multipolar polarization operators as a function of $\cos\theta_{\Omega^-}$. The solid lines stand for the central values with 1σ shaded areas.

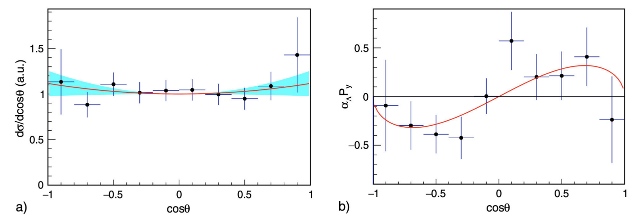

FIGURE 6. Distributions of the acceptance corrected Λ scatter angle a) and the products of $\alpha_\Lambda P_y$ b) as a function of $\cos\theta$. Dots with error bar are for data, the red line represents the polarization signal from MC simulation corrected by measured parameters of polarization and weak decay of Λ hyperon. The shaded area stands for the one standard deviation.

simulation, which used to discriminate both spins hypothesis [38]. By performing the analysis of angular distribution combined with the measured helicity amplitudes $e^+e^- \to \psi(3686) \to \Omega^-\bar{\Omega}^+$ and the weak decay parameters of Ω^- hyperon, the multipolar polarization operators for $\cos\theta_{\Omega^-}$-dependence are measured as shown in Fig. 5b). In addition, the branching fraction for $\psi(3686) \to \Omega^-\bar{\Omega}^+$ is measured to be $(5.85 \pm 0.12 \pm 0.25) \times 10^{-5}$ with high precision, in agreement with the previous measurement [9].

3.2. Hyperon pair production in e^+e^- annihilations

3.2.1. $e^+e^- \to \Lambda\bar{\Lambda}$

Hyperon pair production in e^+e^- annihilations offers a viable way to obtain fundamental information on the hyperon structure and internal dynamics by measuring their electromagnetic form factors (EMFFs). Using 66.9 pb^{-1} data collected at 2.396 GeV by BESIII detector, the Λ spin polarization observed in J/ψ decay [41] is further confirmed and the relative phase is measured to be $\Delta\Phi = \Phi_E - \Phi_M = (37 \pm 12 \pm 6)^\circ$ [40], which agrees with the results reported in J/ψ, $\psi(3770) \to \Lambda\bar{\Lambda}$ process [41, 42]. Figure 6 shows the distributions of the acceptance corrected Λ scatter angle and the products of $\alpha_\Lambda P_y$. Besides, the Born cross section, effective form factor (EFF) and EMFFs ratio for the $e^+e^- \to \Lambda\bar{\Lambda}$ reaction are measured. These information provides important and useful experiment evidence for understanding the production mechanism of $\Lambda\bar{\Lambda}$ pair.

3.2.2. $e^+e^- \to \Sigma^\pm\bar{\Sigma}^\mp$

The $\Sigma^\pm$ is one of hyperons configured by the uus/dds quarks, which is equivalent to replace the proton's down quark or neutron's up quark with a strange quark. Thus the EMFFs ratio for Σ^+ and Σ^- hyperons could provide useful information to insight into the internal structure of nucleons and $\Sigma^\pm$ hyperons. Using 330 pb^{-1} data collected at c.m. energies between 2.3864 and 2.9884 GeV by BESIII detector, the Born cross sections and EFFs for the $e^+e^- \to \Sigma^\pm\bar{\Sigma}^\mp$ processes are determined for the first time in the off-resonance region [43]. Figure 7a) shows the fit to the Born cross sections of $e^+e^- \to \Sigma^\pm\bar{\Sigma}^\mp$ with a pQCD function,

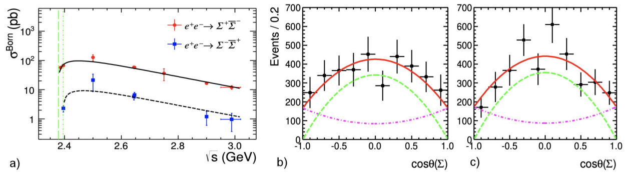

FIGURE 7. a) Fit to Born cross sections of $e^+e^- \to \Sigma^\pm\bar{\Sigma}^\mp$ in the c.m. energies between 2.4 and 2.9 GeV. b), c) Fit to angular distribution for categories A and B at $\sqrt{s} = 2.396$ GeV.

where no obvious threshold enhancements are observed for both processes. Born cross sections near threshold are not equal to zero, and even the Born cross sections for both processes are not in agreement with each other within the sector of isospin conservation. In addition, the EMFFs ratio of Σ^+ is determined based on angular distribution study at three high-statistics energy points (2.396, 2.64 and 2.9 GeV). Figure 7b), c) shows the fit to angular distribution at $\sqrt{s} = 2.396$ GeV for categories A and B. These measurements in the off-resonance region provide a precise input to understand the internal structure of $\Sigma^\pm$ hyperon.

3.2.3. $e^+e^- \to \Xi^0\bar{\Xi}^0$ and $\Xi^-\bar{\Xi}^+$

The previous studies observed a few surprising behaviors near threshold region for the production cross section of nucleon (p and n) and hyperon (Λ, Λ_c^+, etc.) pairs in e^+e^- collisions [9], which has attracted and driven many theoretical studies [44–47]. Recently, the BESIII experiment performed a study of possible threshold enhancement based on the Ξ^0 and Ξ^- hyperon pair production in e^+e^- annihilations using 500 pb^{-1} data collected at c.m. energies between 2.664 and 3.8 GeV [48, 49]. The measured Born cross sections of $e^+e^- \to \Xi^-\bar{\Xi}^+$ and $\Xi^0\bar{\Xi}^0$, as shown in Fig. 8, are basically described by a pQCD-driven energy power function [50], and tend to zero near threshold, while it does not exhibit obvious threshold enhancements due to the limited statistics. A ratio of the measured Born cross section between the charged mode and the neutral mode is calculated to be consistent with the expectation of the sector of isospin conservation. These results provide more information for insight into the mechanism of hyperon pair production in e^+e^- annihilation near threshold.

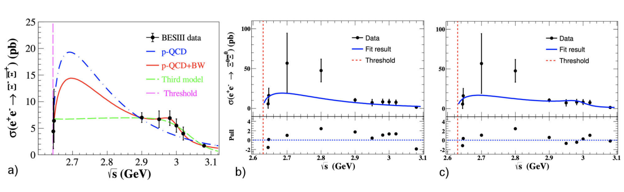

FIGURE 8. Fit to Born cross sections of $e^+e^- \to \Xi^-\bar{\Xi}^+$ (a) and $\Xi^0\bar{\Xi}^0$ (b, c) at c.m. energies between 2.4 and 3.08 GeV. Dots with error bar are the measured Born cross section including both statistical and systematic uncertainties. The solid lines represent the fit results with different assumptions and the vertical dashed lines stand for the production thresholds.

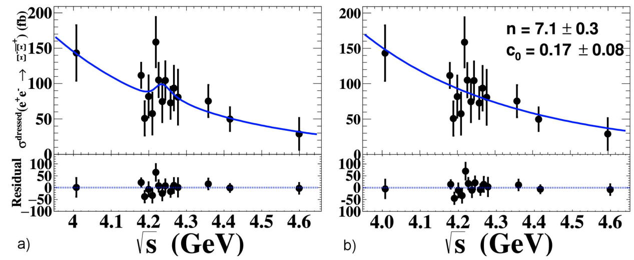

FIGURE 9. Fit to Born cross section of $e^+e^- \to \Xi^-\bar{\Xi}^+$ at c.m. energies between 4.0 and 4.6 GeV. Dots with error bar are the measured Born cross section including both statistical and systematic uncertainties. The solid lines represent the fit results with and without the resonance $Y(4230/4260)$ assumption.

The study of the hyperon pair production above the open charm threshold in e^+e^- annihilations provides important experimental information to validate the charmonium-like states and even probe the excited hyperon states. In particular, charmless decays of charmonium-like states are expected by the hybrid candidate [51]. Using 11 fb^{-1} e^+e^- data collected at c.m. energies between 4.0 and 4.6 GeV [52], the Born cross sections and EFFs of $e^+e^- \to \Xi^-\bar{\Xi}^+$ are measured for the first time by means of a single tag strategy. A fit to the dressed cross section with the assumption of the resonance $Y(4230/4260)$ plus power law function is performed as shown in Fig. 9. No obvious significance for $Y(4230/4260) \to \Xi^-\bar{\Xi}^+$ is observed. Thus, the upper limit on products of branching fraction of $Y(4230/4260) \to \Xi^-\bar{\Xi}^+$ and two electronic partial width are provided to be 0.33×10^{-3} eV and 0.27×10^{-3} eV at 90% confidence level. Besides, an excited hyperon state with the mass of $(1825.5\pm4.7\pm4.7)$ MeV/c^2 and a width of $(17.0\pm15.0\pm7.9)$ MeV is observed with a significance larger than 6σ, which is consistent with the mass and width of $\Xi(1820)$ from PDG value within 1σ uncertainty. These results offer useful and more information for insight into the nature of charmonium-like states, and even probe the structure of strange hyperon resonances.

4. Summary and outlook

BESIII is successfully operating since 2009 and has collected large data samples in τ-charm physical region. A lot of results for the hyperon pair production in e^+e^- annihilations and charmonium(-like) decays are achieved, which include the observation of $\psi(3686) \to \Xi(1530)^-\bar{\Xi}(1530)^+$, the determination of a spin of $J = 3/2$ for Ω^- hyperon, the observation of Ξ^- hyperon spin polarization, precise measurements of the Ξ^- decay parameter, CP test in Ξ^- hyperon decay, the confirmation of Λ hyperon spin polarization at 2.396 GeV, more studies for hyperon pair production near threshold, the measurement of EMFFs and EFFs, the observation of new excited hyperon state at 1.8 GeV and so on. These experimental information offers a unique avenue to validate the strong interaction and probe the hyperon structure. The

BESIII experiment will continue to take data in coming years and more excited results are on the way.

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