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PERSPECTIVE

Prospects for rare and forbidden hyperon decays at BESIII

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The study of hyperon decays at the Beijing Electron Spectrometer III (BESIII) is proposed to investigate the events of J/ψ decay into hyperon pairs, which provide a pristine experimental environment at the Beijing Electron–Positron Collider II. About 10^6–10^8 hyperons, i.e., $\mathit{\Lambda}$, $\mathit{\Sigma}$, $\mathit{\Xi}$, and $\mathit{\Omega}$, will be produced in the J/ψ and $\psi(2S)$ decays with the proposed data samples at BESIII. Based on these samples, the measurement sensitivity of the branching fractions of the hyperon decays is in the range of 10^{-5}–10^{-8}. In addition, with the known center-of-mass energy and "tag technique", rare decays and decays with invisible final states can be probed.

Keywords BESIII, J/ψ decay, hyperon, rare decay, FCNC, lepton flavor violation

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Contents

1 Introduction

In this paper, the hyperon physics program at the Beijing Electron Spectrometer III/Beijing Electron–Positron Collider II (BESIII/BEPCII) and prospects of its upgradation were surveyed. Even with the designed luminosity of the BEPCII, $\sim 10^{10}$ J/ψ and $\psi(2S)$ events can be collected with a running period of one year. The inclusive hyperon production rate can reach a few percent in the J/ψ decays, while the hyperon-pair production rate is $\sim 10^{-3}$. With these data, the decay properties of the spin-1/2 baryon octet can be revisited and the decay parameters with the coherent production of hyperon pairs in $J/\psi \to B\bar{B}$ decays (where the spin-1/2 hyperon pairs are in the 1^{--} state) can be probed. This survey will focus on hyperon decays that can be studied at BESIII and rare decays, for which the search has not yet begun.

2 Status of BESIII

The BESIII detector consists mainly of a cylindrical main draft chamber (MDC) with momentum resolution $\sigma_{p_t}/p_t \sim 0.5\%$ for charged particles with momentum at 1.0 GeV, a time-of-flight (TOF) system with two layers of plastic scintillator counters located outside of the MDC, and a highly hermetic electromagnetic calorimeter (EMC) with an energy resolution of $\sigma_E/E = 2.5\%/\sqrt{E(\mathrm{GeV})}$ [1]. The MDC has its first sensitive layer at a radius of 6.0 cm from the interaction point (IP), and the MDC combined with a magnetic field of 1.0 T provides precise momentum measurements of charged particles with transverse momentum >50 MeV.

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BESIII has so far acquired ∼5×10^8 and ∼13×10^8 events on the $\psi(2S)$ and J/ψ peaks, respectively. In the next few years, by the end of 2018, ∼10^{10} events on the J/ψ peak are going to be collected, and subsequently ∼3×10^9 events on the $\psi(2S)$ peak will be taken. The expected data samples collected at BESIII/BEPCII per year are summarized in Table 1 [2]. In this paper, the sensitivity studies are based on 5 fb^{-1} luminosity at the J/ψ or $\psi(2S)$ peaks for probing hyperon decays.

As indicated in Table 2, the branching fractions for the J/ψ decays into hyperon pairs are on the order of 10^{-3}, and ∼10^7 hyperon pairs can be produced in the J/ψ decays per year. The Ω^- can be only produced in the $\psi(2S)$ decays owing to the allowed phase space, and ∼10^4–10^5 $\Omega^-\bar{\Omega}^+$ pairs will be produced per year at BESIII. Since there is always a neutron or a neutrino produced from the Σ^- hadronic decays or semileptonic decays, one has to use a "tag technique" to look for the Σ^- decays. In Table 3, the three-body decays of $J/\psi \to \bar{\Lambda}\Sigma^-\pi^+$ + c.c. can be used to study the Σ^- decays by looking at the recoiling mass of the $\bar{\Lambda}\pi^+$.

Table 1 τ-charm production at BEPCII in one-year run (10^7 s).

Data sample	Central-of-mass (MeV)	#Events per year
J/ψ	3097	10×10^9
$\tau^+\tau^-$	3670	12×10^6
$\psi(2S)$	3686	3.0×10^9
$D^0\bar{D}^0$	3770	18×10^6
D^+D^-	3770	14×10^6
$D_s^+D_s^-$	4030	1.0×10^6
$D_s^+D_s^-$	4170	2.0×10^6

Table 2 Hyperon production from the J/ψ or $\psi(2S)$ two-body decays with 10^{10} events on the J/ψ peak and 3×10^9 events on the $\psi(2S)$ peak. N_B is the number of the expected hyperon events. Data are from the Particle Data Group (PDG2016) [3].

Decay mode	$\mathcal{B}(\times 10^{-3})$	N_B $(\times 10^6)$
$J/\psi \to \Lambda\bar{\Lambda}$	1.61 ± 0.15	16.1 ± 1.5
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.29 ± 0.09	12.9 ± 0.9
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.50 ± 0.24	15.0 ± 2.4
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}^+$ (or c.c.)	0.31 ± 0.05	3.1 ± 0.5
$J/\psi \to \Sigma(1385)^-\bar{\Sigma}(1385)^+$ (or c.c.)	1.10 ± 0.12	11.0 ± 1.2
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.20 ± 0.24	12.0 ± 2.4
$J/\psi \to \Xi^-\bar{\Xi}^+$	0.86 ± 0.11	8.6 ± 1.0
$J/\psi \to \Xi(1530)^0\bar{\Xi}^0$	0.32 ± 0.14	3.2 ± 1.4
$J/\psi \to \Xi(1530)^-\bar{\Xi}^+$	0.59 ± 0.15	5.9 ± 1.5
$\psi(2S) \to \Omega^-\bar{\Omega}^+$	0.05 ± 0.01	0.15 ± 0.03

Table 3 Hyperon production from the J/ψ three-body decays with 10^{10} events on the J/ψ peak and 3×10^9 events on the $\psi(2S)$ peak. N_B is the number of the expected hyperon events. Data are from PDG2016 [3].

Decay mode	$\mathcal{B}(\times 10^{-4})$	N_B $(\times 10^6)$
$J/\psi \to pK^-\bar{\Lambda}$	8.9 ± 1.6	8.9 ± 1.6
$J/\psi \to \Lambda\bar{\Lambda}\pi^+\pi^-$	43 ± 10	43 ± 10
$J/\psi \to pK^-\bar{\Sigma}^0$	2.9 ± 0.8	2.9 ± 0.8
$J/\psi \to \Lambda\bar{\Sigma}^-\pi^+$ (or c.c.)	8.3 ± 0.7	8.3 ± 0.7
$J/\psi \to \Lambda\bar{\Sigma}^+\pi^{-*}$ (or c.c.)	8.3 ± 0.7	8.3 ± 0.7
$J/\psi \to pK^-\bar{\Sigma}(1385)^0$	5.1 ± 3.2	5.1 ± 3.2

*Estimated from isospin symmetry.

3 Semileptonic hyperon decays

The Cabibbo–Kobayashi–Maskawa matrix elements $|V_{ud}|$ and $|V_{us}|$ characterize quark mixings in $d \to ue^-\bar{\nu}_e$ and $s \to ue^-\bar{\nu}_e$ processes [4, 5] in the Standard Model (SM). So far the most precise determinations of $|V_{ud}|$ and $|V_{us}|$ have been obtained, respectively, from superallowed Fermi transitions together with pion decays and from leptonic and semileptonic kaon decays [6–8]. However, hyperon semileptonic decays can also provide independent constraints on $|V_{ud}|$ and $|V_{us}|$ [9, 10].

In addition one can test the V–A structure [11] of the charged currents in the semileptonic hyperon decays [10, 12]. The semileptonic hyperon decays provide essential information on the structures of the nucleon and low-lying hyperons. The data for the semileptonic hyperon decays reveal experimentally the pattern of flavor $SU(3)$ symmetry breaking [13]. In exact flavor $SU(3)$ symmetry, the ratios of the axial-vector and vector constants g_1/f_1 are expressed only by the two constants F and D. Similarly, those of the vector constants f_2/f_1 are written in terms of the anomalous magnetic moments of the proton and the neutron with flavor $SU(3)$ symmetry assumed [9]. Details of the semileptonic hyperon decay constants can be found in a review paper [9], and recent developments are described elsewhere [14–18]. However, the experimental data for the semileptonic hyperon decays show that the flavor $SU(3)$ symmetry may be manifestly broken [14], and further precision data are needed, especially for the decays of Ξ^0, Ξ^-, and Ω^- as listed in Table 4. The current measured values for the form-factor ratio $g_1(0)/f_1(0)$ in the Cabibbo model [19] are also listed in Table 4.

The decays of $\Sigma^- \to \Sigma^0 e^-\bar{\nu}_e$ and $\Xi^- \to \Xi^0 e^-\bar{\nu}_e$ have not been observed yet. As the lepton pairs $(e^-\bar{\nu}_e)$ are too soft to be detected by the BESIII detector, to study $\Sigma^- \to \Sigma^0 e^-\bar{\nu}_e$ in the $J/\psi \to \bar{\Lambda}\Sigma^-\pi^+$ decay, $\bar{\Lambda}\pi^+$ can

Table 4 Allowed baryon transitions $B_i \to B_f e\nu$ between members of the $J^P = \frac{1}{2}^+$ $SU(3)$ baryon octet. The present status of branching fractions for the semileptonic hyperon decays from PDG2016 [3] and data for the form-factor ratio $g_1(0)/f_1(0)$ in the Cabibbo model [19] are also shown. "–" indicates "not available".

Decay mode	$\mathcal{B}$ ($\times 10^{-4}$)	$\lvert\Delta S\rvert$	$g_1(0)/f_1(0)$
$\Lambda \to pe^-\bar{\nu}_e$	8.32 ± 0.14	1	0.718 ± 0.015
$\Sigma^+ \to \Lambda e^+\nu_e$	0.20 ± 0.05	0	–
$\Sigma^- \to ne^-\bar{\nu}_e$	10.17 ± 0.34	1	-0.340 ± 0.017
$\Sigma^- \to \Lambda e^-\bar{\nu}_e$	0.573 ± 0.027	0	–
$\Sigma^- \to \Sigma^0 e^-\bar{\nu}_e$	–	0	–
$\Xi^0 \to \Sigma^+ e^-\bar{\nu}_e$	2.52 ± 0.08	1	1.210 ± 0.050
$\Xi^- \to \Lambda e^-\bar{\nu}_e$	5.63 ± 0.31	1	0.250 ± 0.050
$\Xi^- \to \Sigma^0 e^-\bar{\nu}_e$	0.87 ± 0.17	1	–
$\Xi^- \to \Xi^0 e^-\bar{\nu}_e$	< 23 (90% C.L.)	0	–
$\Omega^- \to \Xi^0 e^-\bar{\nu}_e$	56 ± 28	1	–

be fully reconstructed as the "tag side", following an examination of the recoiling mass of the $\bar{\Lambda}\pi^+$ to clearly define the Σ^- signal region; therefore, one can finally reconstruct a Σ^0 in the rest of the event to represent the $\Sigma^- \to \Sigma^0 e^-\bar{\nu}_e$ signal; namely, the lepton pairs can be missed and reconstructed by examining the tagged signals. To study $\Xi^- \to \Xi^0 e^-\bar{\nu}_e$ in $J/\psi \to \Xi^-\bar{\Xi}^+$ decay, one can reconstruct the $\bar{\Xi}^+$ with $\bar{\Xi}^+ \to \bar{\Lambda}\pi^+$ decay as a "tag", then look at the Ξ^- signal on the recoiling mass of the fully reconstructed $\bar{\Xi}^+$, and finally reconstruct a Ξ^0 (with a $\Xi^0 \to \Lambda\pi^0$ mode) to represent the signals. All these analyses will be benefit from the well-known center-of-mass energy of the initial e^+e^- collision at BESIII/BEPCII. The expected sensitivity on the branching fractions will be in the range of 10^{-5}–10^{-6}.

For the rare and forbidden semileptonic hyperon decays with $\Delta S = -\Delta Q$ or $\Delta S = 2$, examples are listed in Table 5, with available data from the PDG [3], which were from experiments conducted nearly forty years ago. Most of these upper limits can be improved with data from BESIII, and the expected sensitivity ranges from 10^{-6} to 10^{-5} on these branching fraction measurements.

Table 5 Present status of branching fractions ($\mathcal{B}$) for the $\Delta S = -\Delta Q$ or $\Delta S = 2$ rare semileptonic hyperon decays from PDG2016 [3]. "–" indicates "not available".

Decay mode	$\mathcal{B}$ ($\times 10^{-6}$) @90% C.L.	ΔS
$\Sigma^+ \to ne^+\nu_e{}^*$	< 5	1
$\Xi^0 \to \Sigma^- e^+\nu_e{}^*$	< 900	1
$\Xi^0 \to pe^-\bar{\nu}_e$	< 1300	2
$\Xi^- \to ne^-\bar{\nu}_e$	< 3200	2
$\Omega^- \to \Lambda e^-\bar{\nu}_e$	–	2
$\Omega^- \to \Sigma^0 e^-\bar{\nu}_e$	–	2

$^*\Delta S = -\Delta Q$ process.

4 Radiative hyperon decays

Since the discovery of hyperons, the nature of (weak) radiative decays still remains an open question [20, 21]. Study of weak radiative hyperon decays provides an important tool for investigating the interplay of the electromagnetic, weak, and strong interactions. The description of these processes in terms of well-understood electroweak forces is complicated by the presence of strong interactions [22, 23]. The hyperons in the baryon octet provide us with multiple reactions of this class with varying quark content of the initial and final state baryons. These decays are listed in Table 6.

The transition matrix element T for a general radiative decay of a hyperon B_i of momentum p to a baryon B_f of momentum p' and a photon momentum q,

$$B_i(p) \to B_f(p') + \gamma(q), \tag{1}$$

is given by [24]

$$T = G_F \frac{e}{\sqrt{4\pi}} \epsilon_\nu \bar{u}(p')(\boldsymbol{A} + \boldsymbol{B}\gamma_5)\sigma_{\mu\nu} q_\mu u(p), \tag{2}$$

where $\bar{u}(p')$ and $u(p)$ are the spinor wave functions of the baryon and hyperon, respectively, ϵ_ν is the polarization vector of the photon, $\boldsymbol{A}$ and $\boldsymbol{B}$ are the parity-conserving (M1) and parity-violating (E1) amplitudes, $\sigma_{\mu\nu}$ and γ_5 are the combinations of the Dirac gamma matrices, G_F is the Fermi constant, and e is the electron charge. The

Table 6 Present status of branching fractions ($\mathcal{B}$) and asymmetry parameters (α_γ) for the radiative hyperon decays from PDG2016 [3]. Neither the branching fraction nor the asymmetry parameter for $\Sigma^0 \to n\gamma$ has been measured owing to its huge electromagnetic partial width. "–" indicates "not available".

$B_i \to B_f\gamma$	$\mathcal{B}$ ($\times 10^{-3}$)	α_γ
$\Lambda \to n\gamma$	1.75 ± 0.15	–
$\Sigma^+ \to p\gamma$	1.23 ± 0.05	-0.76 ± 0.08
$\Sigma^0 \to n\gamma$	–	–
$\Xi^0 \to \Lambda\gamma$	1.17 ± 0.07	-0.70 ± 0.07
$\Xi^0 \to \Sigma^0\gamma$	3.33 ± 0.10	-0.69 ± 0.06
$\Xi^- \to \Sigma^-\gamma$	1.27 ± 0.23	1.0 ± 1.3
$\Omega^- \to \Xi^-\gamma$	< 0.46 (90% C.L.)	–

asymmetry parameter is [25]

$$\alpha_\gamma = \frac{2\mathrm{Re}(\boldsymbol{A}^*\boldsymbol{B})}{|\boldsymbol{A}|^2 + |\boldsymbol{B}|^2}. \tag{3}$$

One needs both nonzero $\boldsymbol{A}$ and $\boldsymbol{B}$ amplitudes to get nonzero asymmetry.

For a polarized spin-1/2 hyperon decaying radiatively via a $\Delta Q = 0$, $\Delta S = 1$ transition, which is a flavor-changing-neutral-current (FCNC) process, the angular distribution of the direction $\hat{\boldsymbol{p}}$ of the final spin-1/2 baryon in the hyperon rest frame is

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega} = \frac{N^0}{4\pi}(1 + \alpha_\gamma \boldsymbol{P}_i \cdot \hat{\boldsymbol{p}}), \tag{4}$$

where $\boldsymbol{P}_i$ is the polarization of the decaying hyperon. If the decaying hyperon is unpolarized, the decay baryon has a longitudinal polarization given by $P_f = -\alpha_\gamma$ [26].

There is an old theorem by Hara [27–30] regarding the vanishing of the parity-violating $\boldsymbol{B}$ amplitudes for weak radiative hyperon decays. According to Hara's theorem, the relevant parity-violating amplitude should vanish in the $SU(3)$ limit. For broken $SU(3)$, according to the size of hadron-level $SU(3)$-breaking effects elsewhere, one would expect this asymmetry to be of the order of ± 0.2 [24], and not of the order of -1 as indicated in Table 6. The situation was further confounded by a number of theoretical calculations that violated Hara's theorem (even) in the $SU(3)$ limit [21]. In particular, the large asymmetry observed in the decay $\Sigma^+ \to p\gamma$ has been fueling numerous discussions over many years and remains poorly understood at the parton level [21].

As listed in Table 6, the uncertainty on the asymmetry parameter in the $\Xi^- \to \Sigma^-\gamma$ decay is still very large and can be improved, and there is no measurement of the decay parameter for the $\Lambda \to n\gamma$ decay yet. The current data were all from the fixed target experiments more than a few decades ago, and improved or cross-checked measurements should be done in the future. BESIII will collect ∼10 billion J/ψ events, and the numbers of hyperon events from the J/ψ decays are estimated in Tables 2 and 3.

In addition to the two-body radiative decays, weak hyperon dilepton decays will provide additional information on the radiative transitions [31, 32]. According to PDG2016, the only observed hyperon dilepton decay is the $\Xi^0 \to \Lambda e^+e^-$ decay, which is measured to be $\mathcal{B}(\Xi^0 \to \Lambda e^+e^-) = (7.6 \pm 0.6) \times 10^{-6}$ [33], which is consistent with an inner bremsstrahlung-like production mechanism for the e^+e^- pair. The consistency is further supported by the e^+e^- invariance mass spectrum. The decay parameter was determined to be $\alpha_{\Xi\Lambda ee} = -0.8 \pm 0.2$ [33], which is consistent with that measured for the $\Xi^0 \to \Lambda\gamma$ decay as listed in Table 6. A detailed discussion of radiative dilepton decays is presented in the next section.

5 Rare and forbidden hyperon decays

5.1 $B_i \to B_f l^+l^-$ dilepton decays

In the Type A region as listed in Table 7, the decays $B_i \to B_f l^+l^-$ (where $l = e$, μ; i.e., Dalitz decay) can be described as proceeding through both short-distance and long-distance contributions. In the SM, the leading short-distance contribution comes from an FCNC interaction, which is allowed only at loop level [35]. As discussed in Section 4, the decays of $B_i \to B_f e^+e^-$ play an important role in helping us to understand the dynamics of radiative hyperon decays, and the decay rates are suppressed by two orders of magnitudes if we assume an inner bremsstrahlung-like mechanism producing the e^+e^- pairs [34]. For the decay $B_i \to B_f \mu^+\mu^-$, the process is dominated by long-distance contributions, which are from the $B_i \to B_f \gamma^*$ and $B_i \to B_f V^*$ (where V could be ρ/ω vector mesons) processes, namely, the so-called vector dominant model mechanism [24]. For example, the branching fraction of $\Sigma^+ \to p\mu^+\mu^-$ is predicted to be $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) \in [1.6, 9.0] \times 10^{-8}$ [35] by considering the long-distance contributions, while the short-distance SM contributions are suppressed at a branching fraction of $\sim 10^{-12}$. Dalitz decays of hyperons are of particular interest, as they also allow a direct search for a new scalar or vector particle, which could lead to an $s \to d$ transition at the tree level [36]. Recently, the Large Hadron Collider beauty experiment (LHCb) searched for $\Sigma^+ \to p\mu^+\mu^-$ decay and observed an excess of events with respect to the background expectations with a signal significance of 4.0 standard deviations. No significant structure is observed in the dimuon invariant mass distribution. Owing to the difficulty of normalization in the absence of signal, only an upper limit on the branching fraction is set to be 6.3×10^{-8} at 95% C.L. [37], which agrees with the SM prediction [35], whereas the sensitivities for the decays $B_i \to B_f l^+l^-$ are estimated to be 10^{-6}–10^{-7} as listed in Table 7 (Type A) with the BESIII data.

5.2 $B_i \to B_f \nu\bar{\nu}$ decays via a Z-type penguin

Analogous to the rare $K \to \pi\nu\bar{\nu}$ decays [38], the rare $B_i \to B_f \nu\bar{\nu}$ decays are important tools for testing the SM and for searching for possible new physics. As they proceed through an FCNC process, though they are very suppressed in the SM, they show an exceptional sensitivity to short-distance physics that is similar to the $K \to \pi\nu\bar{\nu}$ decays [39, 40]. There are many discussions on the new physics models that may contribute to the $s \to d\nu\bar{\nu}$ transition at the loop or even tree level; for a recent review, see Ref. [41]. Unfortunately, no $B_i \to B_f \nu\bar{\nu}$ decays have been searched for experimentally so far. As

Table 7 Rare and forbidden hyperon decays and expected sensitivities with 10^{10} events on the J/ψ peak and 3×10^9 events on the $\psi(2S)$ peak. Type A decay modes are through a photon–penguin-like weak neutral current; Type B decay modes are through a Z–penguin-like weak neutral current; Type C decay modes are neutrinoless double β decays, which violate lepton number. The current data are from the world average in PDG2016 [3]. "–" indicates "not available".

Decay mode	Current data $\mathcal{B}$ ($\times 10^{-6}$)	Sensitivity $\mathcal{B}$ (90% C.L.) ($\times 10^{-6}$)	Type
$\Lambda \to n e^+ e^-$	–	< 0.8	Type A
$\Sigma^+ \to p e^+ e^-$	< 7	< 0.4	
$\Xi^0 \to \Lambda e^+ e^-$	7.6 ± 0.6	< 1.2	
$\Xi^0 \to \Sigma^0 e^+ e^-$	–	< 1.3	
$\Xi^- \to \Sigma^- e^+ e^-$	–	< 1.0	
$\Omega^- \to \Xi^- e^+ e^-$	–	< 26.0	
$\Sigma^+ \to p \mu^+ \mu^-$	$(0.09^{+0.09}_{-0.08})$	< 0.4	
$\Omega^- \to \Xi^- \mu^+ \mu^-$	–	< 30.0	
$\Lambda \to n \nu \bar{\nu}$	–	< 0.3	Type B
$\Sigma^+ \to p \nu \bar{\nu}$	–	< 0.4	
$\Xi^0 \to \Lambda \nu \bar{\nu}$	–	< 0.8	
$\Xi^0 \to \Sigma^0 \nu \bar{\nu}$	–	< 0.9	
$\Xi^- \to \Sigma^- \nu \bar{\nu}$	–	–*	
$\Omega^- \to \Xi^- \nu \bar{\nu}$	–	< 26.0	
$\Sigma^- \to \Sigma^+ e^- e^-$	–	< 1.0	Type C
$\Sigma^- \to p e^- e^-$	–	< 0.6	
$\Xi^- \to p e^- e^-$	–	< 0.4	
$\Xi^- \to \Sigma^+ e^- e^-$	–	< 0.7	
$\Omega^- \to \Sigma^+ e^- e^-$	–	< 15.0	
$\Sigma^- \to p \mu^- \mu^-$	–	< 1.1	
$\Xi^- \to p \mu^- \mu^-$	< 0.04	< 0.5	
$\Omega^- \to \Sigma^+ \mu^- \mu^-$	–	< 17.0	
$\Sigma^- \to p e^- \mu^-$	–	< 0.8	
$\Xi^- \to p e^- \mu^-$	–	< 0.5	
$\Xi^- \to \Sigma^+ e^- \mu^-$	–	< 0.8	
$\Omega^- \to \Sigma^+ e^- \mu^-$	–	< 17.0	

*It is hard to reconstruct the $\Xi^- \to \Sigma^- \nu \bar{\nu}$ decay since the Σ^- decays into final states including neutron. Thus both neutron and neutrinos can not be detected at BESIII, and the "tag technique" will not work.

an example, assuming that the decay $\Sigma^+ \to p \nu \bar{\nu}$ is dominated by the short-distance contribution, one can make an estimation based on the following relation [38, 42]:

$$\frac{\Gamma(K^+ \to \pi^+ \nu \bar{\nu})}{\Gamma(K^+ \to \pi^0 e^+ \nu)} \approx \frac{\Gamma(\Sigma^+ \to p \nu \bar{\nu})}{\Gamma(\Sigma^- \to n e^+ \nu)}. \tag{5}$$

Thus, in the SM, one can estimate the branching fraction to be $\mathcal{B}(\Sigma^+ \to p \nu \bar{\nu}) \sim 5 \times 10^{-13}$ by considering the lifetime difference between Σ^+ and Σ^- and isospin rotation [42]. Obviously, BESIII cannot reach a sensitivity of 10^{-13}.

Since the neutrinos in the final states are "invisible" in the detector and, at BESIII, the initial energy and momentum of electron and positron are known, one can use the "tag technique" to fully reconstruct one of the hyperons and look at the recoil side in the ψ decay into hyperon pairs. It would be interesting to make a first study of the $\Sigma^+ \to p \nu \bar{\nu}$ decay, and one should obtain a sensitivity of 10^{-8} with 10^{10} J/ψ decay events. More examples of these decays are listed in Table 7 (Type B), which will be unique accomplishments of the BESIII experiment.

5.3 Lepton-number-violating decays with $\Delta L = 2$

Nonzero neutrino mass is now well established [43–56]; therefore, it is crucially important to study the properties of these nonzero-mass neutrinos. One interesting question is whether neutrinos are Majorana or Dirac neutrinos [57, 58]. Lepton-number-violating (LNV) interactions with $\Delta L = 2$ are widely viewed as the most robust test of the Majorana nature of massive neutrinos [57, 58]. Currently, neutrinoless double β ($0\nu\beta\beta$) decays of heavy nuclei [59] have become the most sensitive way to search for the effects of very light Majorana neutrinos. However, theoretical analysis of these processes is complicated by the nuclear matrix elements, which are very difficult to calculate reliably. Here we focus on the $\Delta L = 2$ transitions between spin-1/2 hyperons, $B_i^- \to B_f^+ l^- l'^-$ (where l, $l' = e$ or μ). Examples of these decays are listed in Table 7 (Type C).

Only one experimental upper limit for the channels listed in Table 7 (Type C) has been reported so far, namely, $\mathcal{B}(\Xi^- \to p \mu^- \mu^-) < 4.0 \times 10^{-8}$. In the case of the decays listed in Table 7 (Type C), two down-type (d or s) quarks convert into two up-quarks, changing the charge of hyperons according to the $\Delta Q = \Delta L = +2$ rule. These quark transitions are assumed to occur at the same space-time location and, therefore, they are driven by local four-quark operators [60–62]. Thus the study of the relatively simpler case provided by $0\nu\beta\beta$ hyperons decays may shed some light on the approximations used to evaluate the hadronic matrix elements relevant for similar nuclear decays [60–62]. In Ref. [61], based on the model where $\Sigma^- \to p e^- e^-$ decay is induced by a loop of baryons and light Majorana neutrinos, the predicted branching fraction for $\Sigma^- \to p e^- e^-$ decay, as an example, is $<10^{-33}$, whereas, in Ref. [62], based on a model with four-quark operators, the predicted branching fraction is $<10^{-23}$, which is still too small to be observed in any future high-intensity experiment. Thus, any observable rates for these decays must indicate a new interaction beyond the SM.

It will be very interesting to search for the $B_i^- \to B_f^+ e^- e^-$ decays at BESIII with 10^{10} J/ψ decay into hyperon–antihyperon final states, which will produce 10^7–10^8 hyperons. Therefore, the sensitivities will be on the order of 10^{-7} with clean backgrounds. Note that the decays of $B_i^- \to B_f^+ \mu^- \mu^-$ can be also searched for at LHCb with higher sensitivities owing to the huge production cross section there.

5.4 Other decays violating lepton number and baryon number

The SM has been proved to be extremely successful. As we discussed in Section 5.3, the nonzero neutrino mass indicates that the lepton number (L) may be violated. There are also a number of reasons to consider baryon number violation: (i) there is a suggestion originally from Sakharov theory that CP violation combined with a baryon-number-violating (BNV) interaction can explain the baryon asymmetry of the universe [63]; (ii) many grand unified theories allow the proton to decay [64–66]; (iii) B–L is an important symmetry and, therefore, if ΔL exists, there is also a ΔB interaction. In particular, in the SM, in the electroweak phase transition, there is a possibility of a ΔB, ΔL transition that conserves B–L, an essential component of theories of leptogenesis [67]. Recently, searches for the BNV and LNV decays of Λ were performed by the CLAS experiment [68] by using a data set for photoproduction off of the proton collected with the CLAS detector at Jefferson Laboratory containing $\sim 1.8 \times 10^6$ reconstructed $\gamma p \to K^+ \Lambda$ events. The sensitivities on the branching fraction for each of the processes studied ranged from 7×10^{-7} to 2×10^{-5} [68]. All BNV and LNV decays can be further studied with data from J/ψ decay into hyperon pairs as listed in Table 8. Some of them (Σ and Ξ hyperon decays) were never searched for, and the sensitivities will be 10^{-7} or better. In addition, baryon-number violation with $\Delta B = 2$ processes can be searched for in the $\Lambda \to \bar{p}\pi^+$ decays that were also presented by the CLAS experiment [68] for the first time. At BESIII, possible baryon-number-violation can be probed in $J/\psi \to \Lambda\bar{\Lambda}$ decay with better sensitivity than that of CLAS. Furthermore, Λ–$\bar{\Lambda}$ oscillations can be investigated by using coherent productions of Λ pairs in $J/\psi \to \Lambda\bar{\Lambda}$ decay; for details, see Refs. [69, 70].

In conclusion, the search for baryon and lepton number nonconservation represents an important probe of physics beyond the SM and particularly new physics at a very high mass scale.

Table 8 Lepton- or baryon-number-violating hyperon decays and expected sensitivities with 10^{10} events on the J/ψ peak and 3×10^9 events on the $\psi(2S)$ peak. The current data are from CLAS [68] as listed in PDG2016 [3]. "–" indicates "not available," $l = e$ or μ, and $M^\pm$ refers to the charged stable mesons ($M^\pm = \pi^\pm$ or $K^\pm$). Each reaction shows evidence of $\Delta L = \pm 1$ or/and $\Delta B \neq 0$, and each reaction conserves electric charge and angular momentum.

Decay mode	Current data $\mathcal{B}$ ($\times 10^{-6}$) (90% C.L.)	Sensitivity $\mathcal{B}$ ($\times 10^{-6}$)	ΔL	ΔB
$\Lambda \to p l^-$	–	< 0.05	+1	0
$\Sigma^+ \to n l^+$	–	< 0.5	−1	0
$\Sigma^0 \to p l^-$	–	< 0.03	+1	0
$\Sigma^- \to n l^-$	–	< 1.0	+1	0
$\Xi^0 \to p l^-$	–	< 0.1	+1	0
$\Xi^0 \to \Sigma^+ l^-$	–	< 0.3	+1	0
$\Xi^0 \to \Sigma^- l^+$	–	< 1.0	−1	0
$\Xi^- \to \Lambda l^-$	–	< 0.2	+1	0
$\Xi^- \to \Sigma^0 l^-$	–	< 0.5	+1	0
$\Omega^- \to \Lambda l^-$	–	< 13	+1	0
$\Omega^- \to \Sigma^0 l^-$	–	< 14	+1	0
$\Omega^- \to \Xi^0 l^-$	–	< 16	+1	0
$\Lambda \to M^+ l^-$	< 0.4–3.0 [68]	< 0.1	+1	−1
$\Lambda \to M^- l^+$	< 0.4–3.0 [68]	< 0.1	−1	−1
$\Lambda \to K_S \nu$	< 20 [68]	< 0.6	+1	−1
$\Sigma^+ \to K_S l^+$	–	< 0.2	−1	−1
$\Sigma^- \to K_S l^-$	–	< 1.0	+1	−1
$\Xi^- \to K_S l^-$	–	< 0.2	+1	−1
$\Xi^0 \to M^+ l^-$	–	< 0.1	+1	−1
$\Xi^0 \to M^- l^+$	–	< 0.1	−1	−1
$\Xi^0 \to K_S \nu$	–	< 2.0	+1	−1

6 Summary

Ever since the discovery of hyperons and of their weak decays it has been a challenge to measure with precision the properties of their decays and to test the SM and beyond. Hyperon semileptonic and radiative decay are still a challenge on both experimental and theoretical fronts. The rare and forbidden hyperon decays will play important role in the search for new physics [3, 71–82]. In this paper, we propose studying hyperon decays at BESIII with events in the J/ψ or $\psi(2S)$ decay into hyperon pairs. We learned that the two-body decays of the J/ψ and $\psi(2S)$ will provide a pristine experimental environment; especially, rare decays and decays with invisible final states can be probed by using the "tag technique" with the e^+e^- collision experiment. With one year's integrated luminosity at BESIII, $\sim 10^6$–10^8 hyperons, Λ, Σ, Ξ, and Ω, will be produced in the J/ψ and $\psi(2S)$ decays. Based on those samples, the sensitivity for the measurements of the branching fractions of the hyperon decays is in the range of 10^{-5}–10^{-8}. Study of hyperon decays will no doubt prove be an unexpected and rewarding research field at BESIII.

In addition, the hyperon program will be one of the strong motivations for collecting data at the J/ψ and $\psi(2S)$ peaks at the planned super-τ-charm factory [83, 84]. Meanwhile, the decay modes with $\mu^\pm$ final states can be probed using the LHCb, where the production cross sections are huge [37].

Discussion: We need theoretical input for these rare decays; for example, the radiative dilepton decays $B_i \to B_f l^+ l^-$ should be revisited with the recent development of chiral perturbation theory [85]. More theoretical efforts should be focused on the $\Delta L = 2$ LNV decays $B_i^- \to B_f^+ l^- l'^-$, which may have an impact on massive neutrinos [86]. There are no theoretical estimations of the $B_i \to B_f \nu\bar{\nu}$ decays, and efforts on the analogous $K^+(K_L) \to \pi^+(\pi^0)\nu\bar{\nu}$ decay could be applied to hyperon decays, for example, to the recent lattice QCD calculations on the Z–penguin-like kaon decays [87–89].

Note that the estimations of the sensitivities at BESIII are all based on educated guesses of the detection efficiencies and thus may deviate from the true values; more studies with correct angular distributions [90, 91] should be done in the future.

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