Prospects for rare and forbidden hyperon decays at BESIII (Postprint)

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Abstract

The study of hyperon decays at the Beijing Electron Spectrometer III (BESIII) is proposed to investigate the events of J/ 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., Λ, Σ, Ξ, and Ω, will be produced in the J/ and (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.

Full Text

Preamble

We propose studying hyperon decays at the Beijing Electron Spectrometer III (BESIII) to investigate J/ψ decays into hyperon-antihyperon pairs, which provide a pristine experimental environment at the Beijing Electron–Positron Collider II. With the proposed data samples at BESIII, approximately 10^6–10^8 hyperons (Λ, Σ, Ξ, and Ω) will be produced in J/ψ and $\psi(2S)$ decays. Based on these samples, the measurement sensitivity for hyperon decay branching fractions will reach the range of 10^{-5}–10^{-8}. Furthermore, leveraging the known center-of-mass energy and "tag technique," rare decays and decays with invisible final states can be effectively probed.

Keywords: BESIII, J/ψ decay, Hyperon, Rare decay, FCNC, Lepton flavor violation
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Introduction

This paper surveys the hyperon physics program at the Beijing Electron Spectrometer III/Beijing Electron–Positron Collider II (BESIII/BEPCII) and prospects for its upgrade. Even with the designed luminosity of BEPCII, substantial J/ψ and $\psi(2S)$ event samples can be collected within a one-year running period. The inclusive hyperon production rate can reach 10^{-3}, while the hyperon-pair production rate in J/ψ decays is a few percent. With these data, the decay properties of the spin-1/2 baryon octet can be revisited, and decay parameters can be probed through the coherent production of hyperon pairs in J/ψ decays (where the spin-1/2 hyperon pairs are produced in the 1^{--} state). This survey focuses on hyperon decays that can be studied at BESIII, particularly rare decays for which searches have not yet begun.

II. Status of BESIII

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

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

[TABLE I]

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

[TABLE II]

Three-body J/ψ decays producing hyperons are listed in Table III.

[TABLE III]

III. Semileptonic Hyperon Decays

The Cabibbo–Kobayashi–Maskawa matrix elements characterize quark mixings in $d \to ue^-\bar{\nu}_e$ and $s \to ue^-\bar{\nu}_e$ processes [4,5] within the Standard Model (SM). Thus far, the most precise determinations have been obtained 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 the CKM matrix elements [9,10].

Furthermore, one can test the $V - A$ structure of charged currents in semileptonic hyperon decays [10–12]. These decays provide essential information on the structures of nucleons and low-lying hyperons, revealing experimentally the pattern of flavor $SU(3)$ symmetry breaking [13]. In exact flavor $SU(3)$ symmetry, the ratios of axial-vector to vector constants g_1/f_1 are expressed solely in terms of two constants F and D. Similarly, the ratios of vector constants f_2/f_1 are written in terms of the anomalous magnetic moments of the proton and neutron under flavor $SU(3)$ symmetry [9]. Details of semileptonic hyperon decay constants can be found in a review paper [9], with recent developments described elsewhere [14–18].

However, experimental data for semileptonic hyperon decays show that flavor $SU(3)$ symmetry may be manifestly broken [14], and further precision data are needed, particularly for Ξ^0, Ξ^-, and Ω^- decays as listed in Table IV. Current measured values for the form-factor ratio $g_1(0)/f_1(0)$ in the Cabibbo model [19] are also shown. The decays $\Sigma^- \to \Sigma^0 e^-\bar{\nu}_e$ and $\Xi^- \to \Xi^0 e^-\bar{\nu}_e$ have not yet been observed. Since the lepton pairs $(e^-\bar{\nu}_e)$ are too soft to be detected by BESIII, alternative strategies are required.

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

[TABLE IV]

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

[TABLE V]

IV. Radiative Hyperon Decays

Since their discovery, the nature of (weak) radiative hyperon decays has remained an open question [20,21]. Study of these decays provides an important tool for investigating the interplay of electromagnetic, weak, and strong interactions. Describing these processes in terms of well-understood electroweak forces is complicated by the presence of strong interactions [22,23]. Hyperons in the baryon octet provide multiple reactions of this class with varying quark content in the initial and final state baryons, as listed in Table VI.

[TABLE VI]

The transition matrix element T for a general radiative decay of a hyperon B_i with momentum p to a baryon B_f with momentum p' and a photon with momentum q is given by [24]:

$$B_i(p) \to B_f(p') + \gamma(q), \quad T = G_F \epsilon_\nu \bar{u}(p')(A + B\gamma_5)\sigma_{\mu\nu} q^\mu u(p),$$

where $\bar{u}(p')$ and $u(p)$ are the spinor wave functions of the final baryon and initial hyperon, respectively, ϵ_ν is the photon polarization vector, A and B are the parity-conserving (M1) and parity-violating (E1) amplitudes, $\sigma_{\mu\nu}$ and γ_5 are combinations of Dirac gamma matrices, G_F is the Fermi constant, and e is the electron charge. The asymmetry parameter is [25]:

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

Both nonzero A and B amplitudes are required for nonzero asymmetry.

For a polarized spin-1/2 hyperon decaying radiatively via a $\Delta Q = 0$, $\Delta S = 1$ transition—a flavor-changing-neutral-current (FCNC) process—the angular distribution of the direction $\hat{p}$ of the final spin-1/2 baryon in the hyperon rest frame is $(1+\alpha_\gamma P_i \cdot \hat{p})$, where P_i is the polarization of the decaying hyperon. If the decaying hyperon is unpolarized, the decay baryon has longitudinal polarization given by $P_f = \alpha_\gamma$ [26].

Hara's theorem [27] states that parity-violating B amplitudes for weak radiative hyperon decays should vanish in the $SU(3)$ limit. For broken $SU(3)$, one would expect this asymmetry to be of order 0.2 [24], not of order 1 as indicated in Table VI. The situation is further complicated by theoretical calculations that violate Hara's theorem even in the $SU(3)$ limit [21]. In particular, the large asymmetry observed in $\Sigma^+ \to p\gamma$ decay has fueled numerous discussions over many years and remains poorly understood at the parton level [21].

As listed in Table VI, the uncertainty on the asymmetry parameter in $\Xi^- \to \Sigma^-\gamma$ decay is still very large and can be improved, and no measurement exists for the decay parameter of $\Lambda \to n\gamma$. Current data come from fixed-target experiments conducted several decades ago, and improved or cross-checked measurements are needed. BESIII will collect 10 billion J/ψ events, with hyperon production numbers estimated in Tables II and III.

In addition to two-body radiative decays, weak hyperon dilepton decays provide complementary information. According to PDG2016, the only observed hyperon dilepton decay is $\Xi^0 \to \Lambda e^+e^-$ with branching fraction $(7.6 \pm 0.6) \times 10^{-6}$ [30], consistent with an inner bremsstrahlung-like production mechanism for the e^+e^- pair, further supported by the e^+e^- invariant mass spectrum. The decay parameter was determined to be $\alpha_{\Xi\Lambda ee} = 0.2$ [30], consistent with that measured for $\Xi^0 \to \Lambda\gamma$ decay as listed in Table VI. Detailed discussion of radiative dilepton decays appears in the next section.

V. Rare and Forbidden Hyperon Decays

A. $B_i \to B_f\ell^+\ell^-$ Dilepton Decays

Hyperon dilepton decays $B_i \to B_f\ell^+\ell^-$ (where $\ell = e, \mu$; i.e., Dalitz decays) proceed through both short-distance and long-distance contributions. In the SM, the leading short-distance contribution comes from an FCNC interaction allowed only at loop level [32]. As discussed in Section IV, these decays help us understand the dynamics of radiative hyperon decays, with rates suppressed by two orders of magnitude assuming an inner bremsstrahlung-like mechanism for e^+e^- pair production [31]. In the Type A region listed in Table VII, the process is dominated by long-distance contributions from $B_i \to B_f\gamma^*$ (where the virtual photon converts to $\ell^+\ell^-$) and $B_i \to B_fV^*$ (where V could be ρ/ω vector mesons) processes—the so-called vector dominance model mechanism [24]. For example, the branching fraction of $\Sigma^+ \to pe^+e^-$ is estimated to be 10^{-8} [32] when considering long-distance contributions, while short-distance SM contributions are suppressed to 10^{-12}. Dalitz decays are particularly interesting as they allow direct searches for new scalar or vector particles that could induce $s \to d$ transitions at tree level [33].

Recently, the LHCb experiment searched for $\Sigma^+ \to p\mu^+\mu^-$ decay, observing an excess of events over background expectations with a signal significance of 4.0 standard deviations. No significant structure appears in the dimuon invariant mass distribution. Due to normalization difficulties in the absence of a clear signal, only an upper limit on the branching fraction is set: $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) < 6.3 \times 10^{-8}$ at 95% C.L. [34], which agrees with SM predictions [32]. Sensitivities for $B_i \to B_f\ell^+\ell^-$ decays with BESIII data are estimated to be 10^{-6}–10^{-7}, as listed in Table VII (Type A).

[TABLE VII]

B. $B_i \to B_f\nu\bar{\nu}$ Decays via Z-type Penguin

Analogous to rare $K \to \pi\nu\bar{\nu}$ decays [40], rare $B_i \to B_f\nu\bar{\nu}$ decays are important tools for testing the SM and searching for new physics. Proceeding through FCNC processes, they are highly suppressed in the SM but show exceptional sensitivity to short-distance physics [36,37]. Many new physics models may contribute to $s \to d\nu\bar{\nu}$ transitions at loop or even tree level; for a recent review, see Ref. [38]. Unfortunately, no $B_i \to B_f \nu\bar{\nu}$ decays have been experimentally searched for thus far.

Assuming $\Sigma^+ \to p\nu\bar{\nu}$ is dominated by short-distance contributions, one can estimate its branching fraction based on the relation [39,40]:

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

Thus, in the SM, one can estimate the branching fraction to be approximately 10^{-13} by considering the lifetime difference between Σ^+ and Σ^- and isospin rotation [39]. Obviously, BESIII cannot reach this sensitivity. Since neutrinos in the final states are invisible at BESIII but the initial e^+e^- energy and momentum are known, the "tag technique" can be used to fully reconstruct one hyperon and examine the recoil side in ψ decays into hyperon pairs. It would be interesting to perform a first study of $\Sigma^+ \to p\nu\bar{\nu}$ decay, achieving a sensitivity of 10^{-8} with 10^{10} J/ψ decay events. Additional examples are listed in Table VII (Type B), representing unique accomplishments possible with BESIII.

C. Lepton-Number-Violating Decays with $\Delta L = 2$

Nonzero neutrino mass is now well established [41–44], making it crucially important to study the properties of these massive neutrinos. A key question is whether neutrinos are Majorana or Dirac particles [45,46]. Lepton-number-violating (LNV) interactions with $\Delta L = 2$ are widely viewed as the most robust test of the Majorana nature of massive neutrinos [45,46]. Currently, neutrinoless double β ($0\nu\beta\beta$) decays of heavy nuclei [47] provide the most sensitive probe for very light Majorana neutrinos. However, theoretical analysis is complicated by nuclear matrix elements that are difficult to calculate reliably.

Here we focus on $\Delta L = 2$ transitions between spin-1/2 hyperons, $B_i \to B_f \ell^- \ell'^-$ (where $\ell, \ell' = e$ or μ). Examples are listed in Table VII (Type C). Only one experimental upper limit has been reported thus far: $\mathcal{B}(\Xi^- \to p\mu^-\mu^-) < 4.0 \times 10^{-8}$. In these decays, two down-type (d or s) quarks convert into two up-quarks, changing the hyperon charge according to the $\Delta Q = \Delta L = +2$ rule. These transitions are assumed to occur at the same space-time location and are therefore driven by local four-quark operators [48–50]. Studying the relatively simpler case of $0\nu\beta\beta$ hyperon decays may shed light on approximations used to evaluate hadronic matrix elements relevant for nuclear decays [48–50].

In Ref. [49], based on a model where $\Sigma^- \to pe^-e^-$ decay is induced by a baryon loop with light Majorana neutrinos, the predicted branching fraction is $< 10^{-33}$. In Ref. [50], based on a model with four-quark operators, the prediction is $< 10^{-23}$, still too small for any future high-intensity experiment. Thus, any observable rate for these decays must indicate new physics beyond the SM. With 10^{10} J/ψ decays into hyperon-antihyperon final states producing 10^7–10^8 hyperons, BESIII can achieve sensitivities on the order of 10^{-7} with clean backgrounds. Note that $B_i \to B_f \mu^- \mu^-$ decays can also be searched for at LHCb with higher sensitivity due to the huge production cross sections there.

D. Other Decays Violating Lepton Number and Baryon Number

The SM has proven extremely successful. As discussed in Subsection V C, nonzero neutrino mass indicates that lepton number (L) may be violated. There are also compelling reasons to consider baryon number violation: (1) Sakharov's theory suggests that CP violation combined with baryon-number-violating (BNV) interactions can explain the baryon asymmetry of the universe [51]; (2) many grand unified theories allow proton decay [52]; (3) $B-L$ is an important symmetry, so if ΔL exists, ΔB interactions may also exist. In particular, in the electroweak phase transition, $\Delta B, \Delta L$ transitions that conserve $B-L$ are possible, an essential component of leptogenesis theories [53].

Recently, the CLAS experiment searched for BNV and LNV decays of Λ using a photoproduction data set on protons collected at Jefferson Laboratory containing $K^+\Lambda$ events [54]. Sensitivities on branching fractions for studied processes ranged from 10^{-7} to 2×10^{-5} [54]. All BNV and LNV decays can be further studied with J/ψ decay data into hyperon pairs, as listed in Table VIII. Some modes (Σ and Ξ hyperon decays) have never been searched for, and BESIII will achieve sensitivities of 10^{-7} or better. Additionally, baryon-number violation with $\Delta B = 2$ processes can be searched for in $\Lambda \to \bar{p}\pi^+$ decays, first presented by CLAS [54]. At BESIII, baryon-number violation can be probed in $\Lambda\bar{\Lambda}$ decay with better sensitivity than CLAS. Furthermore, $\Lambda - \bar{\Lambda}$ oscillations can be investigated using coherent $\Lambda\bar{\Lambda}$ production in $J/\psi \to \Lambda\bar{\Lambda}$ decay; for details, see Refs. [55,56].

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

VI. Summary

Since the discovery of hyperons and their weak decays, precision measurement of their decay properties has been a challenge for testing the SM and beyond. Hyperon semileptonic and radiative decays remain challenging on both experimental and theoretical fronts. Rare and forbidden hyperon decays will play an important role in searching for new physics [3,57–67]. This paper proposes studying hyperon decays at BESIII using J/ψ or $\psi(2S)$ decays into hyperon pairs. The two-body decays of J/ψ and $\psi(2S)$ provide a pristine experimental environment where rare decays and decays with invisible final states can be probed using the "tag technique" with e^+e^- collisions. With one year's integrated luminosity at BESIII, 10^6–10^8 hyperons (Λ, Σ, Ξ, and Ω) will be produced in J/ψ and $\psi(2S)$ decays. Based on these samples, the sensitivity for measuring hyperon decay branching fractions will be in the range of 10^{-5}–10^{-8}. Study of hyperon decays will undoubtedly prove to be a rewarding research field at BESIII.

Furthermore, the hyperon program provides strong motivation for collecting data at the J/ψ and $\psi(2S)$ peaks at the planned super-τ-charm factory [68,69]. Meanwhile, decay modes with $\mu^+\mu^-$ final states can be probed using LHCb, where production cross sections are enormous [34].

Discussion: Theoretical input is needed for these rare decays. For example, radiative dilepton decays $B_i \to B_f \ell^+\ell^-$ should be revisited with recent developments in chiral perturbation theory [70]. More theoretical effort should focus on $\Delta L = 2$ LNV decays $B_i \to B_f \ell^-\ell'^-$, which may have implications for massive neutrinos [71]. There are no theoretical estimations for $B_i \to B_f \nu\bar{\nu}$ decays, but recent lattice QCD calculations on Z-penguin-like kaon decays [72–74] could be applied to analogous hyperon decays. Note that sensitivity estimates for BESIII are based on educated guesses of detection efficiencies and may deviate from true values; future studies should incorporate correct angular distributions [75,76].

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References [1] M. Ablikim et al. [BESIII Collaboration], Nucl. Instrum. Meth. A 614, 345 (2010) [arXiv:0911.4960 [physics.ins-det]].
[2] D. M. Asner et al., Int. J. Mod. Phys. A 24, S1 (2009) [arXiv:0809.1869 [hep-ex]].
[3] C. Patrignani et al. [Particle Data Group Collaboration], Chin. Phys. C 40, no. 10, 100001 (2016).
[4] N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963).
[5] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).
[6] E. Blucher, E. De Lucia, G. Isidori, V. Lubicz, H. Abele, V. Cirigliano, R. Flores-Mendieta, J. Flynn et al., arXiv:hep-ph/0512039.
[7] J. C. Hardy and I. S. Towner, J. Phys. G 41, 114004 (2014).
[8] M. Antonelli, V. Cirigliano, G. Isidori, F. Mescia, M. Moulson, H. Neufeld, E. Passemar, M. Palutan et al., Eur. Phys. J. C 69, 399 (2010).
[9] N. Cabibbo, E. C. Swallow, and R. Winston, Ann. Rev. Nucl. Part. Sci. 53, 39 (2003).
[10] N. Cabibbo, E. C. Swallow and R. Winston, Phys. Rev. Lett. 92, 251803

(2004) [hep-ph/0307214].
[11] S. Weinberg, J. Phys. Conf. Ser. 196, 012002 (2009).
[12] H. M. Chang, M. González-Alonso and J. Martin Camalich, Phys. Rev. Lett. 114, no. 16, 161802 (2015) [arXiv:1412.8484 [hep-ph]].
[13] T. N. Pham, Phys. Rev. D 87, no. 1, 016002 (2013) [arXiv:1210.3981 [hep-ph]].
[14] G. S. Yang and H. C. Kim, Phys. Rev. C 92, 035206 (2015) [arXiv:1504.04453 [hep-ph]].
[15] A. Faessler, T. Gutsche, B. R. Holstein, M. A. Ivanov, J. G. Korner and V. E. Lyubovitskij, Phys. Rev. D 78, 094005 (2008) [arXiv:0809.4159 [hep-ph]].
[16] B. Borasoy, Phys. Rev. D 59, 054021 (1999) [hep-ph/9811411].
[17] L. S. Geng, J. Martin Camalich and M. J. Vicente Vacas, Phys. Rev. D 79, 094022 (2009).
[18] T. Ledwig, J. Martin Camalich, L. S. Geng and M. J. Vicente Vacas, Phys. Rev. D 90, no. 5, 054502 (2014).
[19] M. Bourquin and J. P. Repellin, Phys. Rept. 114, 99 (1984).
[20] J. Bernstein, G. Feinberg and T. D. Lee, Phys. Rev. 139, B1650 (1965).
[21] J. Lach and P. Zenczykowski, Int. J. Mod. Phys. A 10, 3817 (1995).
[22] I. I. Balitsky, V. M. Braun and A. V. Kolesnichenko, Nucl. Phys. B 312, 509 (1989).
[23] M. K. Gaillard, X. Li and S. Rudaz, Phys. Lett. 158B, 158 (1985).
[24] P. Zenczykowski, Phys. Rev. D 73, 076005 (2006) [hep-ph/0512122].
[25] B. Borasoy and B. R. Holstein, Phys. Rev. D 59, 054019 (1999) [hep-ph/9902431].
[26] R. E. Behrends, Phys. Rev. 111, 1691 (1958).
[27] Y. Hara, Phys. Rev. Lett. 12, 378 (1964); S. Y. Lo, Nuovo Cimento 37, 753 (1965); K. Tanaka, Phys. Rev. 140, B463 (1965); M. Gourdin, Unitary symmetry (North-Holland, Amsterdam, 1967).
[28] J. W. Bos, D. Chang, S. C. Lee, Y. C. Lin and H. H. Shih, Phys. Rev. D 54, 3321 (1996) [hep-ph/9601299].
[29] B. V. Martemyanov, Phys. Atom. Nucl. 66, 737 (2003) [Yad. Fiz. 66, 768 (2003)].
[30] J. R. Batley et al. [NA48 Collaboration], Phys. Lett. B 650, 1 (2007) [hep-ex/0703023].
[31] L. Bergstrom, R. Safadi and P. Singer, Z. Phys. C 37, 281 (1988).
[32] X. G. He, J. Tandean and G. Valencia, Phys. Rev. D 72, 074003 (2005) [hep-ph/0506067].
[33] D. S. Gorbunov and V. A. Rubakov, Phys. Rev. D 64, 054008 (2001) [hep-ph/0012033].
[34] F. Dettori [LHCb Collaboration], arXiv:1611.06717 [hep-ex].
[35] W. J. Marciano and Z. Parsa, Phys. Rev. D 53, no. 1, R1 (1996).
[36] A. J. Buras, M. Gorbahn, U. Haisch and U. Nierste, Phys. Rev. Lett. 95, 261805 (2005) [hep-ph/0508165].
[37] A. J. Buras, F. Schwab and S. Uhlig, Rev. Mod. Phys. 80, 965 (2008) [hep-ph/0405132].
[38] A. J. Buras, D. Buttazzo and R. Knegjens, JHEP 1511, 166 (2015)

[arXiv:1507.08672 [hep-ph]].
[39] Xu Feng, private discussion.
[40] W. J. Marciano and Z. Parsa, Phys. Rev. D 53, no. 1, R1 (1996).
[41] SuperKamiokande Collaboration, Y. Fukuda et al., Phys. Rev. Lett. 81, 1158 (1998); 81, 1562 (1998); 82, 2644 (1999); 85, 3999 (2000); Y. Suzuki, Nucl. Phys. B, Proc. Suppl. 77, 35 (1999); S. Fukuda et al., Phys. Rev. Lett. 86, 5651 (2001); Y. Ashie et al., Phys. Rev. Lett. 93, 101801 (2004).
[42] KamLAND Collaboration, K. Eguchi et al., Phys. Rev. Lett. 90, 021802 (2003); T. Araki et al., Phys. Rev. Lett. 94, 081801(2005).
[43] SNO Collaboration, Q. R. Ahmad et al., Phys. Rev. Lett. 89, 011301 (2002); 89, 011302 (2002); 92, 181301 (2004); B. Aharmim et al., Phys. Rev. C 72, 055502 (2005).
[44] F. P. An et al. [Daya Bay Collaboration], Phys. Rev. Lett. 108, 171803 (2012) [arXiv:1203.1669 [hep-ex]].
[45] B. Pontecorvo, Sov. Phys. JETP 7, 172 (1958) [Zh. Eksp. Teor. Fiz. 34, 247 (1957)].
[46] V. N. Gribov and B. Pontecorvo, Phys. Lett. 28B, 493 (1969).
[47] W. Rodejohann, Int. J. Mod. Phys. E 20, 1833 (2011) [arXiv:1106.1334 [hep-ph]].
[48] C. Barbero, G. Lopez Castro and A. Mariano, Phys. Lett. B 566, 98 (2003) [nucl-th/0212083].
[49] C. Barbero, L. F. Li, G. Lopez Castro and A. Mariano, Phys. Rev. D 76, 116008 (2007) [arXiv:0709.2431 [hep-ph]].
[50] C. Barbero, L. F. Li, G. López Castro and A. Mariano, Phys. Rev. D 87, no. 3, 036010 (2013) [arXiv:1301.3448 [hep-ph]].
[51] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5, 32 (1967) [JETP Lett. 5, 24 (1967)] [Sov. Phys. Usp. 34, 392 (1991)] [Usp. Fiz. Nauk 161, 61 (1991)].
[52] J. C. Pati and A. Salam, Phys. Rev. D 8, 1240 (1973); H. Georgi and S. L. Glashow, Phys. Rev. Lett. 32, 438 (1974); R. N. Mohapatra and R. E. Marshak, Phys. Lett. 91B, 222 (1980).
[53] H. An, S. L. Chen, R. N. Mohapatra and Y. Zhang, JHEP 1003, 124 (2010) [arXiv:0911.4463 [hep-ph]].
[54] M. E. McCracken et al., Phys. Rev. D 92, no. 7, 072002 (2015) [arXiv:1507.03859 [hep-ex]].
[55] X. W. Kang, H. B. Li and G. R. Lu, Phys. Rev. D 81, 051901 (2010) [arXiv:0906.0230 [hep-ph]].
[56] Z. Berezhiani and A. Vainshtein, arXiv:1506.05096 [hep-ph].
[57] K. T. Chao, Phys. Rev. D 41, 920 (1990).
[58] X. G. He and G. Valencia, Phys. Rev. D 52, 5257 (1995) [hep-ph/9508411].
[59] J. F. Donoghue, X. G. He and S. Pakvasa, Phys. Rev. D 34, 833 (1986).
[60] D. Chang, X. G. He and S. Pakvasa, Phys. Rev. Lett. 74, 3927 (1995) [hep-ph/9412254].
[61] X. G. He and S. Pakvasa, hep-ph/9409236.
[62] J. Tandean, Phys. Rev. D 69, 076008 (2004) [hep-ph/0311036].
[63] J. Tandean and G. Valencia, Phys. Rev. D 67, 056001 (2003) [hep-ph/0211165].

[64] J. Tandean, Phys. Rev. D 70, 076005 (2004) [hep-ph/0406274]; J. Tandean and G. Valencia, Phys. Lett. B 451, 382 (1999) [hep-ph/9811376].
[65] X. G. He, J. P. Ma and B. McKellar, Phys. Rev. D 47, R1744 (1993) [hep-ph/9211276].
[66] X. W. Kang, H. B. Li, G. R. Lu and A. Datta, Int. J. Mod. Phys. A 26, 2523 (2011) [arXiv:1003.5494 [hep-ph]].
[67] A. Abdesselam et al. [Belle Collaboration], arXiv:1611.06648 [hep-ex].
[68] A. E. Bondar et al. [Charm-Tau Factory Collaboration], Phys. Atom. Nucl. 76, 1072 (2013) [Yad. Fiz. 76, no. 9, 1132 (2013)].
[69] Z. Zhou, Q. Luo, L. Wang, W. Xu and B. Zhang, "Preliminary Concept and Key Technologies of HIEPA Accelerator," talk at the 7th International Particle Accelerator Conference (IPAC 2016) 08-13 May 2016, Busan, Korea.
[70] D. Kimura, T. Morozumi and H. Umeeda, arXiv:1609.09235 [hep-ph].
[71] H. R. Dong, F. Feng and H. B. Li, Chin. Phys. C 39, no. 1, 013101 (2015).
[72] N. H. Christ et al. [RBC and UKQCD Collaborations], Phys. Rev. D 93, no. 11, 114517 (2016) [arXiv:1605.04442 [hep-lat]].
[73] N. H. Christ, X. Feng, A. Jüttner, A. Lawson, A. Portelli and C. T. Sachrajda, PoS CD 15, 033 (2016).
[74] N. H. Christ et al. [RBC and UKQCD Collaborations], Phys. Rev. D 92, no. 9, 094512 (2015) [arXiv:1507.03094 [hep-lat]].
[75] T. D. Lee and C. N. Yang, Phys. Rev. 108, 1645 (1957).
[76] A. Kadeer, J. G. Körner and U. Moosbrugger, Eur. Phys. J. C 59, 27 (2009) [hep-ph/0511019].

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