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Rare Charm and Charmonium Decays at BESIII

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Rare decays of charm hadrons and charmonium provide a powerful laboratory for testing the Standard Model (SM) at the intensity frontier. These processes are forbidden at tree level or strongly suppressed by the Glashow–Iliopoulos–Maiani (GIM) mechanism, making them sensitive probes of physics beyond the SM, including heavy virtual particles, Majorana neutrinos, and interactions with a dark sector. Using the world's largest data samples collected at the τ–charm threshold and more than 10^{10} J/ψ events, the BESIII experiment has carried out a comprehensive program of searches for flavor-changing neutral currents (FCNC), lepton and baryon number violation, weak decays of the J/ψ meson, and invisible decays. While no unambiguous signal of new physics has been observed, several rare processes are studied for the first time and the most stringent limits to date are established in multiple channels.

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1. Introduction

Rare decays of charm hadrons and charmonium constitute an important part of the global flavor physics program. In the Standard Model (SM), many such processes are forbidden at tree level or strongly suppressed by the Glashow–Iliopoulos–Maiani (GIM) mechanism, resulting in extremely small branching fractions. As a consequence, rare charm decays provide a sensitive window on physics beyond the SM, complementary to searches performed in the kaon and B-meson sectors.

Flavor-changing neutral current (FCNC) transitions such as $c \to u\ell^+\ell^-$ arise only at loop level in the SM and are further suppressed by cancellations among different quark generations. The expected branching fractions are typically below 10^{-8}, well below current experimental sensitivity. Any observation of a significant enhancement would therefore signal the presence of new particles or non-standard interactions.

Lepton number violating (LNV) processes, for example $D_s^+ \to h^- e^+ e^+$, are strictly forbidden in the SM. Their observation would imply the violation of a fundamental symmetry and point to the existence of Majorana neutrinos or other exotic mechanisms for neutrino mass generation. Similarly, baryon number violating (BNV) processes are closely related to the origin of the matter–antimatter asymmetry in the Universe.

Charmonium decays provide an additional and unique testing ground. Weak decays of the J/ψ meson probe an extreme regime in which a tightly bound heavy quarkonium state undergoes a weak transition. The expected branching fractions are at the level of 10^{-11} or below, making any observable signal a clear indication of new physics. Invisible decays, such as $K_S^0 \to$ invisible, offer complementary access to dark sector scenarios in which the final-state particles do not interact with the detector.

Operating at the charm threshold, the BESIII experiment offers a clean experimental environment with well-defined initial states, low combinatorial background, and excellent detector performance. These features make BESIII particularly well suited for the study of rare charm and charmonium decays at the intensity frontier.

2. Theoretical Framework and Physics Motivation

From a theoretical perspective, charm decays occupy a unique position between kaon and B-meson systems. In contrast to B decays, where short-distance amplitudes often dominate, charm decays are strongly affected by long-distance hadronic effects. This complicates theoretical predictions but also provides complementary sensitivity to new physics scenarios involving light mediators or non-standard flavor structures.

FCNC processes probe up-type quark transitions, which are not accessible in rare kaon or B decays. LNV and baryon number violating (BNV) processes address fundamental questions related to neutrino masses and the matter–antimatter asymmetry of the Universe. Weak and invisible decays of charmonium states represent clean null tests of the SM, as their predicted branching fractions are far below current experimental sensitivities.

3. The BEPCII Collider and BESIII Detector

The BEPCII collider operates in the τ–charm energy region, covering center-of-mass energies from 1.85 to 4.95 GeV. It has achieved a peak luminosity of 1.1×10^{33} cm^{-2}s^{-1} at $\sqrt{s} = 3.773$ GeV.

The BESIII detector is a general-purpose magnetic spectrometer. Its main components include a helium-based main drift chamber, a time-of-flight system, a CsI(Tl) electromagnetic calorimeter, and a muon detector based on resistive plate chambers. Large data samples of J/ψ, $\psi(3686)$, and open-charm production form the experimental basis of the analyses summarized here.

4. Flavor-Changing Neutral Currents

4.1 $D_s^+ \to h(h')e^+e^-$

Motivation. FCNC decays of charm mesons probe the only experimentally accessible FCNC transitions involving up-type quarks. In the SM, short-distance contributions to $c \to ue^+e^-$ transitions are highly suppressed, and decay amplitudes are dominated by long-distance hadronic effects mediated by vector mesons. A systematic experimental separation of resonant and non-resonant contributions is therefore essential for disentangling SM dynamics from potential new physics effects.

Using 7.33 fb^{-1} collected at $\sqrt{s} = 4.128$–4.226 GeV, BESIII observed clear signals for $D_s^+ \to \pi^+\phi(\phi \to e^+e^-)$ and $D_s^+ \to K^+\phi(\phi \to e^+e^-)$. No significant signals were found in non-resonant four-body decays, and upper limits at the level of 10^{-5} were set [1]. These results provide the first systematic study of $D_s^+ \to h(h')e^+e^-$ decays and constrain scenarios predicting enhanced short-distance FCNC contributions.

4.2 $J/\psi \to D^0\mu^+\mu^-$

Motivation. FCNC decays of charmonium states probe a qualitatively different regime from open-charm decays. The J/ψ meson is a tightly bound $c\bar{c}$ system, and FCNC transitions require a weak interaction to occur within this bound state. SM predictions are extremely small, making any observable signal a clear indication of new physics.

With more than 10^{10} J/ψ events, BESIII searched for $J/\psi \to D^0\mu^+\mu^-$. No signal was observed, and an upper limit of $\mathcal{B}(J/\psi \to D^0\mu^+\mu^-) < 1.1 \times 10^{-7}$ was established [2], representing the most stringent constraint to date.

5. Lepton and Baryon Number Violation

5.1 $D_s^+ \to h(h^0)e^+e^+$

Motivation. Lepton number violation by two units is forbidden in the SM and is closely connected to the Majorana nature of neutrinos. Charm decays provide a complementary probe of such effects, involving second-generation quarks and flavor structures distinct from those tested in kaon and B-meson decays.

Searches for six D_s^+ LNV decay modes yielded no significant signals, and upper limits at the level of 10^{-5}–10^{-4} were set [3]. These results constrain models predicting enhanced LNV effects in charm decays.

PoS(HQL2025)079

5.2 Majorana Neutrino Searches

Motivation. If a Majorana neutrino with a mass in the GeV range exists, it could be produced on-shell in charm decays and subsequently decay into a charged lepton and a hadron. Such processes would produce resonant structures in invariant mass distributions, providing a striking experimental signature.

Assuming $D_s^+ \to \phi e^+ \nu_m$ with $\nu_m \to \pi^- e^+$, BESIII scanned $m_{\nu_m} = 0.2$–0.8 GeV/c^2 and found no signal, setting limits depending on the assumed mass [3].

5.3 Other LNV and BNV Channels

Motivation. LNV and BNV processes can also be searched for in vector meson and baryonic final states, which probe different combinations of exotic couplings. Baryon number violating decays of the J/ψ meson, in particular, provide a clean experimental environment with negligible SM background.

BESIII set upper limits on $\phi \to \pi^+\pi^- e^+ e^-$ and $J/\psi \to p e^-$, with the latter providing the most stringent constraint to date [4, 5].

6. Weak Decays of J/ψ

Motivation. Weak decays of the J/ψ meson are among the rarest processes accessible at current experiments. In the SM, they are suppressed both by the weak interaction and by the need to overcome the strong binding of the $c\bar{c}$ system. Their expected branching fractions are far below current experimental sensitivities, making them excellent null tests of the SM.

BESIII searched for $J/\psi \to \gamma D^0$ and $J/\psi \to D^- \mu^+ \nu_\mu$, setting upper limits at the 10^{-7}–10^{-8} level [6, 7].

7. Invisible Decays

Motivation. Invisible decays of neutral mesons provide a direct probe of dark sector scenarios involving weakly interacting or invisible particles. Such searches are complementary to invisible Higgs and quarkonium decays at high-energy colliders and benefit from the clean environment of threshold experiments.

Using tagged $J/\psi \to \phi K_S^0 K_S^0$ events, BESIII searched for $K_S^0 \to$ invisible decays. No signal was observed, and the first upper limit $\mathcal{B}(K_S^0 \to \text{invisible}) < 8.4 \times 10^{-4}$ was established.

8. Summary and Outlook

BESIII has carried out a comprehensive program of searches for rare charm and charmonium decays. By combining FCNC, LNV, weak, and invisible decay searches, BESIII provides complementary constraints on a wide range of new physics scenarios. With future high-luminosity charm facilities, the sensitivity to many of these processes is expected to improve significantly.

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