Thesis title: Study of baryon production and decay at BESIII

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Abstract: The Standard Model (SM) of particle physics, especially the electroweak theory, has achieved remarkable success. The calculations of quantum chromodynamics (QCD) under high momentum transfer conditions have also been verified by many experiments. However, due to the inapplicability of perturbation theory in the low energy region, the generalization of QCD has gradually lost its predictive power. The charmonium and charmed baryon produced at the Beijing Spectrometer (BESIII) are located in the transition energy region between perturbation and non-perturbation of QCD, so different non-perturbative theoretical models can be tested by studying baryon production and decay. Currently, symmetry plays a very important role in these theoretical models, and charge conjugation parity (CP) symmetry is particularly important. CP symmetry is one of the three basic conditions to explain the excess of matter over antimatter in the universe. In fact, CP violation has been observed in the decays of K, B, and D mesons, and has been theoretically described in the SM of particle physics through the Kobayashi-Maskawa mechanism. However, the violations observed in these processes are not sufficient to explain the asymmetry between matter and antimatter. The weak decay of hyperons is considered to be a promising place to search for CP violation at BESIII experiment. In addition, the threshold enhancement of proton-antiprotons is observed for the first time by BESII experiment, providing information on the dependence of mass near the threshold, which was also confirmed by the BESIII experiment. Many theoretical assumptions, including new resonance states, final state interactions (FSI) of $p\bar{p}$, bound states of $p\bar{p}$, and glueballs, can be used to explain the threshold anomalous behavior of proton-antiproton. However, the study of the threshold enhancement of neutron-antineutron has been blank. Besides, experimental studies of charmed baryon decays have provided important information on strong and weak interactions in heavy quarks. The lightest charmed baryon Λ_c^+ was first observed in e^+e^- annihilation. So far, 20% of Λ_c^+ decays remain unexplored so that it is necessary to study multi-body hadronic decays including potential intermediate processes. In order to solve important scientific issues, the baryon production and decay from J/ψ, $\psi(3686)$, and $4599.53-4698.82$ MeV experimental data is systematically studied in this thesis, including:

The branching fraction of $\psi(3686) \to \Sigma^-\bar{\Sigma}^+$ and angular distribution parameter are measured to be $(2.82 \pm 0.04_{\rm stat} \pm 0.08_{\rm syst}) \times 10^{-4}$ and $\alpha_{\Sigma^-} = 0.96 \pm 0.09_{\rm stat} \pm 0.03_{\rm syst}$ for the first time. The branching fraction result deviates from the theoretical prediction by 2.3σ, indicating that the interference effect between the strong interaction amplitude and the electromagnetic interaction amplitude has a significant impact on the charmonium decay. There are also significant differences between α_{Σ^-} and its isospin processes α_{Σ^+} and α_{Σ^0}. By comparing the branching fractions and angular parameters of $\psi(3686) \to \Sigma^+\bar{\Sigma}^-$, $\Sigma^0\bar{\Sigma}^0$, and $\Sigma^-\bar{\Sigma}^+$, we can better understand the isospin effect and related mechanisms.

A five-dimensional angular analysis of $J/\psi \to \Sigma^+\bar{\Sigma}^-$ and $\psi(3686) \to \Sigma^+\bar{\Sigma}^-$ is conducted. The accuracy of the decay parameter $\alpha_+ = 0.0481 \pm 0.0031_{\rm stat} \pm 0.0019_{\rm syst}$ for $\Sigma^+ \to n\pi^+$ is improved

by 4 times. The decay parameters $\bar{\alpha}_- = -0.0565 \pm 0.0047_{\rm stat} \pm 0.0022_{\rm syst}$ and $A_{CP}(\Sigma^+ \to n\pi^+) = -0.080 \pm 0.052_{\rm stat} \pm 0.028_{\rm syst}$ of $\bar{\Sigma}^- \to \bar{n}\pi^-$ are measured for the first time. The accuracy of the decay parameter $\alpha_0 = -0.9753 \pm 0.0106_{\rm stat} \pm 0.0018_{\rm syst}$ and $\bar{\alpha}_0 = 0.9986 \pm 0.0108_{\rm stat} \pm 0.0040_{\rm syst}$ are improved by 3 times, and average decay parameter $\langle\alpha_0\rangle = -0.9869 \pm 0.0011_{\rm stat} \pm 0.0016_{\rm syst}$ and $A_{CP}(\Sigma^+ \to p\pi^0) = -0.0118 \pm 0.0083_{\rm stat} \pm 0.0028_{\rm syst}$ are determined with the highest accuracy. In the current data, no CP violation is observed in the processes of hyperon decay to neutrons and protons, and the results are consistent with the prediction of SM.

The $J/\psi \to \gamma X(n\bar{n}) \to \gamma n\bar{n}$ branching fraction, mass, width, and mass difference with $X(p\bar{p})$ are measured to be $(5.32 \pm 0.20 \pm 0.79) \times 10^{-5}$, $M_{X(n\bar{n})} = 1882.6 \pm 4.1_{\rm stat} \pm 21.1_{\rm syst}$ MeV/c^2, $\Gamma_{X(n\bar{n})} = 58.6 \pm 3.7 \pm 18.8$ MeV, and $\Delta M = 50.6^{+6.5}_{-19.4}$ MeV/c^2. $\frac{Br(J/\psi\to\gamma X(n\bar{n})\to\gamma n\bar{n})}{Br(J/\psi\to\gamma X(p\bar{p})\to\gamma p\bar{p})}$ is determined to be less than 1 and greater than 0.5, indicating that $X(N\bar{N})$ is caused by the FSI effect and the contribution of the bound states of nucleons and antinucleons. All the widths of $\Gamma_{X(n\bar{n})}$ and $\Gamma_{X(p\bar{p})}$ are smaller than that of $X(1835)$, which may indicate that $X(n\bar{n})$, $X(p\bar{p})$ and $X(1835)$ may be mixed. These provide direct evidence for determining the threshold enhancement of nucleons-antinucleons and the properties of $X(1835)$.

The branching fraction of $\Lambda_c^+ \to nK_S^0\pi^+\pi^0$ is measured to be $(0.85 \pm 0.13 \pm 0.03)\%$, with a significance of 9.2σ. This measurement result differs from the theoretical prediction based on isospin symmetry by 4.4σ, suggesting the possible existence of intermediate resonance effects or other contributions in the four-body decay of charmed baryons, providing the input for the theoretical model of charmed baryon decay.

Summary and Outlook: This thesis focuses on the transition region between perturbative and non-perturbative QCD, utilizing the BESIII experimental platform to conduct systematic studies on baryon production and decay. We investigated the branching fractions, angular distribution parameters, SU(3) symmetry, hyperon CP symmetry, and the $n\bar{n}$ threshold structure, providing high-precision results for optimizing theoretical models.

Using $(448.1 \pm 2.9) \times 10^6$ $\psi(3686)$ events at BESIII, we performed the first measurement of the branching fraction and angular distribution parameter α_{Σ^-} for the $\psi(3686) \to \Sigma^-\bar{\Sigma}^+$ decay (with $\Sigma^- \to n\pi^-$, $\bar{\Sigma}^+ \to \bar{n}\pi^+$). The results yield a branching fraction of $(2.82 \pm 0.04_{\rm stat} \pm 0.08_{\rm syst}) \times 10^{-4}$ and $\alpha_{\Sigma^-} = 0.96 \pm 0.09_{\rm stat} \pm 0.03_{\rm syst}$. Compared to the theoretical prediction of $(2.46 \pm 0.13) \times 10^{-4}$, our measurement shows a discrepancy of about 2.3σ, which may be related to strong interactions, electromagnetic interactions, and their interference. Additionally, α_{Σ^-} exhibits significant differences from its isospin counterparts α_{Σ^+} and α_{Σ^0}. In the future, with larger datasets accumulated by BESIII, we can further improve the precision of the branching fraction of $\psi(3686) \to \Sigma^-\bar{\Sigma}^+$ and angular parameter measurements, enabling more stringent tests of theoretical predictions. A systematic study of isospin symmetry breaking effects in baryon pair production by comparing results from other isospin-related processes such as $\psi(3686) \to \Sigma^+\bar{\Sigma}^-$ and $\psi(3686) \to \Sigma^0\bar{\Sigma}^0$ will help elucidate the complex interplay between strong and electromagnetic interactions. Furthermore, cross-comparisons with other experiments (e.g., Belle II) and discussions with theorists could validate the universality of these findings. These efforts will not only deepen our understanding of baryon structure and interactions but may also provide clues for new physics beyond the SM.

Based on $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events collected by BESIII, we performed a five-dimensional angular analysis of the $J/\psi \to \Sigma^+\bar{\Sigma}^-$ decay (with $\Sigma^+ \to p\pi^0$, $\bar{\Sigma}^- \to \bar{n}\pi^-$ and its charge conjugate $\Sigma^+ \to n\pi^+$, $\bar{\Sigma}^- \to \bar{p}\pi^0$). The decay parameters $\alpha_{J/\psi}$ and $\Delta\Phi_{J/\psi}$ are measured to be $-0.5156 \pm 0.0030_{\rm stat} \pm 0.0061_{\rm syst}$ and $(-0.2772 \pm 0.0044_{\rm stat} \pm 0.0041_{\rm syst})$ rad, respectively. These results significantly surpass previous measurements in precision and confirm the transverse polarization of Σ^+. Additionally, using two different Σ^+ decay channels, we determined the decay asymmetry parameters α_+ and $\bar{\alpha}_-$. While α_+ and α_+/α_0 are consistent with PDG averages, $\bar{\alpha}_-$ and $\bar{\alpha}_-/\bar{\alpha}_0$ are measured for the first time. We also report the first CP asymmetry measurement for $A_{CP}(\Sigma^+ \to n\pi^+) = -0.080 \pm 0.052_{\rm stat} \pm 0.028_{\rm syst}$.

Moreover, a joint analysis of $J/\psi \to \Sigma^+\bar{\Sigma}^-$ and $\psi(3686) \to \Sigma^+\bar{\Sigma}^-$ (with $\Sigma^+ \to p\pi^0$, $\bar{\Sigma}^- \to \bar{p}\pi^0$) was performed to test $A_{CP}(\Sigma^+ \to p\pi^0)$ symmetry using $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ and $(2.7124 \pm 0.0143) \times 10^9$ $\psi(3686)$ events. We improved the precision of parameters such as $\alpha_{\psi(3686)}$ and $\Delta\Phi_{\psi(3686)}$ by a factor of 3–4 compared to previous results. The CP asymmetry $A_{CP}(\Sigma^+ \to p\pi^0) = -0.0118 \pm 0.0083 \pm 0.0028$ is consistent with CP conservation and SM predictions. Our measurement of the average decay parameter $\langle\alpha_0\rangle = -0.9869 \pm 0.0011 \pm 0.0016$ achieves the highest precision to date, which is crucial for future studies of Σ^+ decays and CP violation. Currently, no evidence of CP violation is observed in $\Sigma^+ \to n\pi^+$ and $\Sigma^+ \to p\pi^0$ decays, with results agreeing with SM expectations within uncertainties. Future experiments, particularly at the Super Tau-Charm Facility, will further enhance the precision of $J/\psi \to \Sigma^+\bar{\Sigma}^-$ and $\psi(3686) \to \Sigma^+\bar{\Sigma}^-$ measurements. This will not only refine $\alpha_{J/\psi}$, $\Delta\Phi_{J/\psi}$, $\alpha_{\psi(3686)}$, and $\Delta\Phi_{\psi(3686)}$ but also enable more stringent tests of CP predictions and searches for new physics beyond the SM. Extending these studies to other baryon decays (e.g., Λ, Ξ, Ω) will provide a comprehensive understanding of baryon production and decay mechanisms, potentially shedding light on the matter-antimatter asymmetry of the universe.

Using $(1.0087 \pm 0.0044) \times 10^{10}$ J/ψ events, we measured the branching fraction of $Br(J/\psi \to$

$\gamma X(n\bar{n}) \to \gamma n\bar{n}) = (5.32 \pm 0.20_{\mathrm{stat}} \pm 0.79_{\mathrm{syst}}) \times 10^{-5}$ for the first time. The mass and width of $X(n\bar{n})$ are determined to be $(1882.6 \pm 4.1_{\mathrm{stat}} \pm 21.1_{\mathrm{syst}})$ MeV$/c^2$ and $(58.6 \pm 3.7_{\mathrm{stat}} \pm 18.8_{\mathrm{syst}})$ MeV, respectively. The mass difference $\Delta(M_{X(n\bar{n})} - M_{X(p\bar{p})})$ and width ratio suggest possible final-state interaction effects, nucleon-antinucleon bound states, or mixing with $X(1835)$. Future studies, including partial-wave analyses, will explore the internal structure of these hadronic states. Extending this research to $\psi(3686) \to \gamma X(n\bar{n})$ and $\psi(3770) \to \gamma X(n\bar{n})$ could clarify the origin of the nucleon-antinucleon threshold enhancement, offering insights into exotic hadrons and strong interaction dynamics.

Based on 4.5 fb^{-1} $\Lambda_c^+\bar{\Lambda}_c^-$ data samples, we measured the branching fraction of $\Lambda_c^+ \to nK_S^0\pi^+\pi^0$ as $(0.85 \pm 0.13_{\mathrm{stat}} \pm 0.03_{\mathrm{syst}})\%$, deviating from the isospin-based theoretical prediction $(1.54 \pm 0.08)\%$ by 4.4σ. This discrepancy may indicate resonant contributions or unknown dynamical effects. Future studies, including amplitude analyses of intermediate states (e.g., K^*, Δ) and comparisons with other Λ_c^+ decays (e.g., $\Lambda_c^+ \to pK_S^0\pi^+\pi^-$), will test isospin symmetry in charmed baryon decays.

The above summary and outlook comprehensively summarize the research achievements of this thesis in the field of baryon production and decay, while clarifying potential future research directions. These research results not only contribute to the improvement of the SM, but also hold great significance for exploring new physical phenomena and understanding hadron structures. In the future, through precise measurements of the branching fractions, angular distribution parameters, CP violation, and threshold structures near nucleon-antinucleon, we will be able to further test different non-perturbative theoretical models.