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Symmetry in Σ Hyperon Decay

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Abstract: CP symmetry violation is one of the fundamental requirements for having more matter than antimatter in our universe. However, the observed CP violation is not enough to explain the matter dominance. Searching for the new CP violation in the hyperon sector is therefore attracting people's interests. In this article, we review the theoretical description of the spin one-half hyperon nonleptonic decay. In order to test the CP conservation, the asymmetry decay parameters might be compared between hyperon and antihyperon. The fixed-target experiments achieved the relevant measurements of the hyperon parameters but in the absence of the antihyperon results. The BESIII experiment with e^+e^- collision provided an entanglement environment to measure Σ^+ and $\bar{\Sigma}^-$ simultaneously. The important role of experimental inputs in CP violation evaluation is discussed in this paper, underlying the great potential of the future collider, which may allow us to reach the precision of the Standard Model predictions.

Keywords: hyperon; polarization; CP violation

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1. Introduction

The symmetry concept plays a central role in particle physics. In 1950s and 1960s, a series of new particles, such as K mesons and Λ and Σ hyperons, were discovered in cosmic ray experiments. Under a flavor SU(3) symmetry, Gell-Mann [1] and Ne'eman [2] classified them in an eightfold way and predicted the existence of Ω baryons. In 1964, Gell-Mann [3] and George Zweig [4] independently suggested the existence of the subatomic particles known as quarks. In this frame, the Σ baryons are composed of three quarks and contain one strange quark. A fundamental problem is matter–antimatter asymmetry: the Big Bang should have generated the same amount of matter and antimatter. However, there is a serious imbalance between matter and antimatter in the observable universe. In 1967, Sakharov proposed a set of three necessary conditions to explain the matter–antimatter asymmetry. They are baryon number violation, C and CP symmetry violation and the interaction out of thermal equilibrium [5].

Cronin and Fitch observed the first CP violation in the K meson decay [6]. According to Cabibbo's theory from 1963, the quark's mass eigenstates are distinct from those of the quarks involved in weak interaction [7]. Then, it was suggested that the two eigenstates of the d-quark and the s-quark were mixed, which could be described by a matrix with a Cabibbo angle. To explain why the flavor-changing neutral currents are suppressed in loop diagrams, Glashow, Iliopoulos and Maiani proposed a new mechanism, which required the existence of a fourth quark [8]. In 1973, since the observed CP violation could not be explained in the previous model, Kobayashi and Maskawa (KM) enlarged the two-quark mixing mechanism to the three generation of quarks [9]. The KM mechanism, which is currently the most successful explanation, describes the CP violation as a complex phase that can be seen in the weak interaction's quark mixing matrix. Finding the CP violation process has been the focus of experiments. According to the BaBar and Belle collaborations, the B meson decay was discovered to have an indirect CP violation in 2001 [10,11]. In the B meson rare decay, those two collaborations observed the direct CP violation [12,13]. The first CP violation in charm decays was discovered by the LHCb collaboration in 2019 [14]. The experimental findings discussed above are consistent with the KM mechanism's prediction in the Standard Model. However, it does not adequately describe why matter predominates in our universe [15]. Because of this, researchers have concentrated on finding new physics, both theoretically and experimentally, hoping that they would not only be able to explain the current experimental observations but also supply additional sources of CP violation. The search for new physics has included investigating CP violations in hyperon decay.

Through their two-body weak decay, the spin one-half hyperons can be used to analyze the symmetry. It was previously used to research parity conservation [16]. Searching CP violation in hyperon decay is the main subject of the current work. The final state's angular distribution in the spin-one-half hyperon could be used in the nonleptonic decay to measure the hyperon's polarization. In the Λ or Σ decay, there are nucleon and π meson in their final states; here, the nucleon could be a proton or a neutron. The initial state of the hyperon is a spin of one-half, while in the final state, the nucleon is one-half and π is zero. Thus, there are parity-conserving (P-wave) and parity-violating (S-wave) amplitudes. To well describe this process, the three decay parameters α, β and γ are used to demonstrate the P-wave and S-wave's contributions, which could be directly measured in the experiment.

$$\alpha = \frac{2\mathrm{Re}(S^*P)}{|S|^2+|P|^2}, \beta = \frac{2\mathrm{Im}(S^*P)}{|S|^2+|P|^2}, \gamma = \frac{|S|^2-|P|^2}{|S|^2+|P|^2}. \tag{1}$$

Only two of them are independent since $\alpha^2+\beta^2+\gamma^2 = 1$, therefore α and β are usually parameterized as

$$\beta = (1-\alpha^2)^{1/2}\sin\phi. \tag{2}$$

Then, CP conservation could be tested by calculating the difference in decay parameters between hyperon and antihyperon. The sensitivities of CP violation in different decay parameters range from 10^{-2} to 10^{-7} in the Standard Model predictions [17].

In this review, we mainly focus on the decay parameters measurements in the Σ nonleptonic decay. The structure of the review is organized as follows. The underlying formalism of Σ decay is described in Section 2. The experimental results are introduced in Section 3, including fixed-target and collider experiments. The theoretical and experimental efforts in CP violation predictions are discussed in Section 4. A summary and prospects are presented in Section 5.

2. Formalism for Σ Decay

First, in fixed-target experiments, the test of the $\Delta I = \frac{1}{2}$ selection rule is based on the α decay parameter measurements in the Σ nonleptonic decays. The process of $\Sigma^+ \to p\pi^0$ with the α_0, β_0 and γ_0 parameters is taken as an example. To determine these parameters, the polarization of the proton from the Σ^+ decay can be given in terms of α_0, β_0 and γ_0 by

$$\vec{\mathrm{P}} = (1+\alpha_0\vec{\mathrm{P}}_\Sigma\cdot\hat{p})^{-1}[(\alpha_0+\vec{\mathrm{P}}_\Sigma\cdot\hat{p})\hat{p}+\beta_0\vec{\mathrm{P}}_\Sigma\times\hat{p}+\gamma_0\hat{p}\times(\vec{\mathrm{P}}_\Sigma\times\hat{p})], \tag{3}$$

where $\vec{\mathrm{P}}_\Sigma$ is the Σ^+ polarization vector, $|\vec{\mathrm{P}}_\Sigma| = \mathbf{P}$, and the proton momentum unit vector in the Σ^+ rest frame is represented by $\hat{p}$. Considering the relation $\alpha_0^2+\beta_0^2+\gamma_0^2 = 1$, there are three parameters to be determined above, α_0, ϕ_0 and $\mathbf{P}$. The product of α_0 and $\mathbf{P}$ can be written as follows:

$$dN/d\Omega = \frac{1}{4\pi}(1+\alpha_0\vec{\mathrm{P}}_\Sigma\cdot\hat{p}) \tag{4}$$

To determine α_0 and ϕ_0, the polarization of the proton needs to be measured using the proton scattering with carbon plates. The initial and final momentum values of the proton can be measured before and after scattering by carbon, which are denoted as $\hat{k}_i$ and $\hat{k}_f$, and $\hat{n} = \hat{k}_i \times \hat{k}_f / |\hat{k}_i \times \hat{k}_f|$. The likelihood function is written as

$$\mathscr{L} = \prod_{j=1}^{N} [1 + A_j(\theta_j, E_j)\vec{\mathrm{P}} \cdot \hat{n}_j], \tag{5}$$

which can be calculated with the n signal events. Here, $A_j(\theta_j, E_j)$ is the coefficient related to the scattering angle θ and energy E. Using the maximum value of $\mathscr{L}$, the decay parameters α_0 and ϕ_0 can be determined.

Unlike the fixed-target experiment, the e^+e^- collider experiment can generate Σ^+ and its antiparticle $\bar{\Sigma}^-$ simultaneously, which provide a good opportunity to study the CP violation. As shown in Equation (4), the polarization of Σ^+ has to be measured in order to deduce the parameter α_0 . Considering the inner structure of Σ, the Σ electric and magnetic form factors are used to describe the process of $e^+e^- \to \Sigma^+\bar{\Sigma}^-$ [18–22]. Following those ideas, the Ψ-related electric and magnetic form factors, G_E^Ψ and G_M^Ψ, are proposed to be used in the $e^+e^- \to \Sigma^+\bar{\Sigma}^-$ at the Ψ resonance (Ψ here denotes either the J/ψ or the ψ') [23]. With two form factors, the angular parameter α_Ψ can be expressed as,

$$\alpha_\Psi = \frac{s\left|G_M^\Psi\right|^2 - 4M^2\left|G_E^\Psi\right|^2}{s\left|G_M^\Psi\right|^2 + 4M^2\left|G_E^\Psi\right|^2},$$

and the relative phase between G_E^Ψ and G_M^Ψ is measured by $\Delta\Phi$,

$$\frac{G_E^\Psi}{G_M^\Psi} = e^{i\Delta\Phi}\left|\frac{G_E^\Psi}{G_M^\Psi}\right|.$$

The $\Delta\Phi$ is the observable measurement related to the spin-polarization of Σ. If $\Delta\Phi$ is not equal to 0, Σ is polarized and perpendicular to its generation plane. Its polarization will depend on the angle between Σ^+ and the electron direction in the center-of-mass system, which is shown as below,

$$\left|\vec{\mathrm{P}}_{\Sigma^+}\right| = \frac{\sqrt{1-\alpha_\Psi^2}\cos\theta\sin\theta}{1+\alpha_\Psi\cos^2\theta}\sin(\Delta\Phi).$$

With the above equation, the $\Sigma^+\ \bar{\Sigma}^-$ production is described with two parameters α_Ψ and $\Delta\Phi$, which need to be measured in the experiments. Then, combined with the equations related to Σ^+ ($\bar{\Sigma}^-$) decays, the differential cross section is given as $d\sigma \propto \mathcal{W}(\boldsymbol{\xi})d\boldsymbol{\xi}$, where $\boldsymbol{\xi}$ includes the variables related to the angular distribution, such as the polar angle of the hyperon, the nucleon's polar angle and azimuthal angle. $\mathcal{W}(\boldsymbol{\xi})$ is expressed as:

$$\begin{aligned}\mathcal{W}(\boldsymbol{\xi}) =& \mathcal{T}_0(\boldsymbol{\xi}) + \alpha_\psi\mathcal{T}_5(\boldsymbol{\xi}) \\ &+\alpha_0\bar{\alpha}_0\left(\mathcal{T}_1(\boldsymbol{\xi}) + \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\mathcal{T}_2(\boldsymbol{\xi}) + \alpha_\psi\mathcal{T}_6(\boldsymbol{\xi})\right) \\ &+\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)(\alpha_0\mathcal{T}_3(\boldsymbol{\xi}) + \bar{\alpha}_0\mathcal{T}_4(\boldsymbol{\xi})).\end{aligned} \tag{6}$$

and $\mathcal{T}_i, (i = 0, 1...6)$ are angular functions dependent on $\boldsymbol{\xi}$. The angular function $\mathcal{T}_i(\boldsymbol{\xi})$ is defined as:

$$
\begin{aligned}
\mathcal{T}_0(\xi) =& 1 \\
\mathcal{T}_1(\xi) =& \sin^2\theta_\Sigma \sin\theta_p \sin\theta_{\bar{p}} \cos\phi_p \cos\phi_{\bar{p}} + \cos^2\theta_\Sigma \cos\theta_p \cos\theta_{\bar{p}} \\
\mathcal{T}_2(\xi) =& \sin\theta_\Sigma \cos\theta_\Sigma (\sin\theta_p \cos\theta_{\bar{p}} \cos\phi_p + \cos\theta_p \sin\theta_{\bar{p}} \cos\phi_{\bar{p}}) \\
\mathcal{T}_3(\xi) =& \sin\theta_\Sigma \cos\theta_\Sigma \sin\theta_p \sin\phi_p \\
\mathcal{T}_4(\xi) =& \sin\theta_\Sigma \cos\theta_\Sigma \sin\theta_{\bar{p}} \sin\phi_{\bar{p}} \\
\mathcal{T}_5(\xi) =& \cos^2\theta_\Sigma \\
\mathcal{T}_6(\xi) =& \cos\theta_p \cos\theta_{\bar{p}} - \sin^2\theta_\Sigma \sin\theta_p \sin\theta_{\bar{p}} \sin\phi_p \sin\phi_{\bar{p}}.
\end{aligned}
\tag{7}
$$

In Equation (6), the differential cross section consists of three parts: the Σ scattering angle distribution, the spin correlations between three components and the separate polarization contribution.

3. Experimental Results

3.1. Fixed-Target Experiment

The first asymmetry parameter α_0 measurement in the decay $\Sigma^+ \to p\pi^0$ was performed by Beall et al. [24]. Positive pions from the Bevatron were sent against a liquid hydrogen target to generate the reaction $\pi^+ p \to \Sigma^+ K^+$, $\Sigma^+ \to p\pi^0$. The polarization of proton could be determined by the reaction with a carbon-plate spark chamber. With the proton angular distribution, the α_0 was found to be -0.80 ± 0.18. The second measurement was performed by Bangerter et al. [25]. By using a beam of K^- mesons through the Lawrence Radiation Laboratory's 25-inch hydrogen bubble chamber, the reactions of $K^- p \to \Sigma^\pm \pi^\mp$ were analyzed. With a relative high statistic, α_0 was determined to be -0.986 ± 0.072, which was in good agreement with the $\left|\Delta\vec{\mathrm{I}}\right| = \frac{1}{2}$ rule. However, the value of α_0 was deduced from the distribution of $(1 + \alpha_0 P_\Sigma \mathrm{cos}\omega)$, while the polarization of $\Sigma(\ P_\Sigma)$ was determined from the $\mathrm{Y}_0^*(1520)$ phase-shift analysis. In 1970, using the technique of Ref. [24], more events were analyzed [26]. The value of α_0 was then $-0.98^{+0.05}_{-0.02}$, which confirmed the measurement in Ref. [25]. For the other two processes of $\Sigma^+ \to n\pi^+$ and $\Sigma^- \to n\pi^-$, both final states included neutron and charged pions. Therefore, the analysis techniques were almost the same. The sources of Σ^+ and Σ^- were produced with the same method in Ref. [25] in the reactions of $K^- p \to \Sigma^\pm \pi^\mp$. The values of α_+ and α_- were measured in similar experiments. The most accurate value for α_- was -0.067 ± 0.011 [27], and α_+ was 0.069 ± 0.017 [28]. In the bubble chamber, the polarized neutron could scatter with an unpolarized proton target, which provided the opportunity to measure the full decay asymmetry parameters α and ϕ.

3.2. Collider Experiment

The BEPCII storage ring [29], which runs with a peak luminosity of 1×10^{33} cm^{-2}s^{-1} in the center-of-mass energy range from 2.0 to 4.95 GeV, supplies symmetric e^+e^- collisions to the BESIII detector [30]. Large data samples have been accumulated by BESIII in this energy region [31]. Based on the data samples collected in 2009 and 2012, the processes of J/ψ and $\psi(3686) \to \Sigma^+\bar{\Sigma}^-$ were analyzed in detail [32]. To reconstruct the signal event, two charged tracks were selected and should be identified as proton and antiproton. The number of good photons was not less than four and could form at least $2\pi^0$. The four-momentum kinematic constraints were used to further reduce the background contamination. The peaking background was negligible, and nonpeaking grounds could be well estimated with the sideband method. The total background level was 5% for J/ψ decay and 1% for $\psi(3686)$. To achieve the angular information of Σ, the proton and the antiproton, the coordinate system needed to be defined as in Figure 1. The momentum unit vector of Σ^+ was chosen as the z-axis. The y-axis was perpendicular to the scatter plane, defined as $\mathbf{k}_{e^-} \times \mathbf{p}_{\Sigma^+}$. Here, $\mathbf{k}_{e^-}$ was the momentum of the electron in the center-of-mass system, and

$\mathbf{p}_{\Sigma^+}$ was the momentum of Σ^+. Then, in the right-handed coordinate system, the x-axis was defined as $(\mathbf{k} \times \mathbf{p}_{\Sigma^+}) \times \mathbf{p}_{\Sigma^+}$.

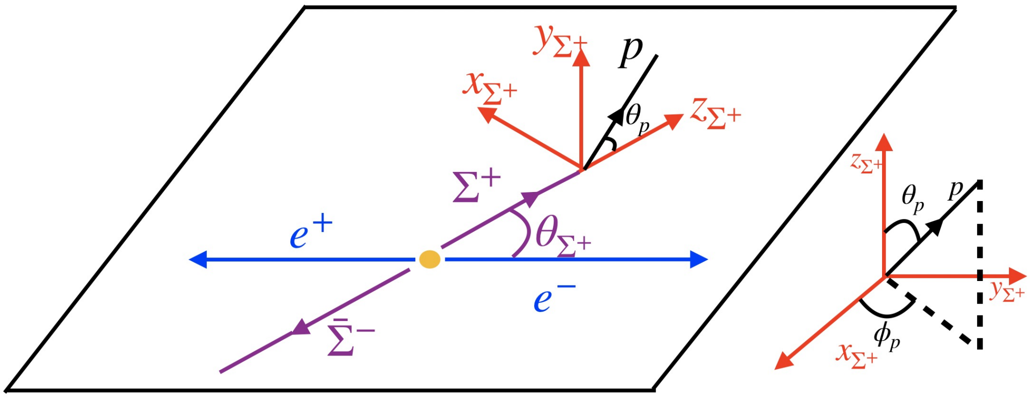

Figure 1. The coordinate system definition. The momentum unit vector of Σ^+ is chosen as the z-axis. The y-axis is perpendicular to the scatter plane and the x-axis is defined according to the right-hand coordinate system.

The parameters $\mathbf{\Omega} = \{\alpha_{J/\psi}, \alpha_{\psi'}, \Delta\Phi_{J/\psi}, \Delta\Phi_{\psi'}, \alpha_0, \bar{\alpha}_0\}$ were obtained by performing an unbinned maximum likelihood fit in the five angular dimensions. The J/ψ and ψ' shared the parameters α_0 and $\bar{\alpha}_0$ in the simultaneous fitting. The values of $\alpha_{J/\psi}$ and $\alpha_{\psi'}$ were measured to be $-0.508 \pm 0.006 \pm 0.004$ and $0.682 \pm 0.03 \pm 0.011$. The signs had the same behavior as the decay's final states $\Sigma^0\bar{\Sigma}^0$, $\Sigma(1385)^-\bar{\Sigma}(1835)^+$ and $\Sigma(1385)^+\bar{\Sigma}(1835)^-$. The relative phases $\Delta\Phi_{J/\psi}$ and $\Delta\Phi_{\psi'}$ were determined to be $-0.270 \pm 0.012 \pm 0.009$ and $0.379 \pm 0.07 \pm 0.014$, which were the first measurements in the decay of $J/\psi \to \Sigma^+\bar{\Sigma}^-$ and $\psi' \to \Sigma^+\bar{\Sigma}^-$. Due to the nonzero values of the relative phases, the decay asymmetry parameters α_0 and $\bar{\alpha}_0$ could be achieved through the differential cross section's equation. The value of α_0 was determined to be $-0.998 \pm 0.037 \pm 0.009$, which was consistent with the previous measurements and significantly improved in accuracy. $\bar{\alpha}_0$ with the value of $0.990 \pm 0.037 \pm 0.011$ was measured for the first time. By comparing α_0 and $\bar{\alpha}_0$, the CP conservation was tested and the results were in agreement with the Standard Model prediction. As seen in Figure 2, a clear polarization was observed in the real data. To demonstrate the polarization, the moment $M(\cos\theta_{\Sigma^+})$ was calculated and compared with the phase space Monte Carlo sample.

To date, there have been no decay asymmetry measurements of $\Sigma^+ \to n\pi^+$ and $\Sigma^- \to n\pi^-$ from collider experiments.

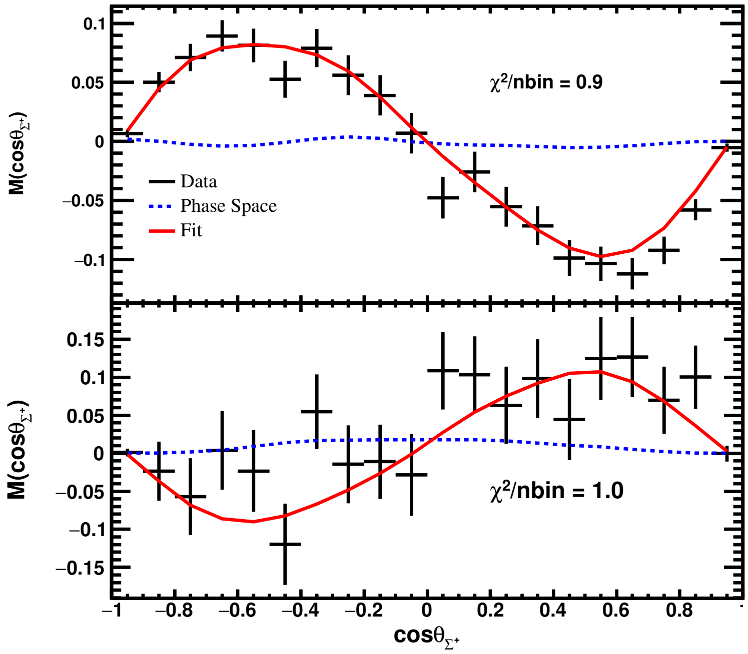

Figure 2. The moments $M(\cos\theta_{\Sigma^+})$ distributions for J/ψ and ψ' decays. The experimental data are represented by the black dots with error bars, the red solid lines are the fit results and the phase space without polarization is shown by the blue dashed line.

4. Discussion

In the widely cited Ref. [17], some observables were defined in the limit of CP conservation:

$$\Delta = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}, A = \frac{\Gamma\alpha + \bar{\Gamma}\bar{\alpha}}{\Gamma\alpha - \bar{\Gamma}\bar{\alpha}}, B = \frac{\Gamma\beta + \bar{\Gamma}\bar{\beta}}{\Gamma\beta - \bar{\Gamma}\bar{\beta}}.$$

All of them were quantities that could be measured directly. Then, based on the KM model, the CP-violation variables were calculated and are listed in Table 1.

Table 1. The CP-violation observables for the KM model.

	Δ	**A**	**B**
$\Sigma^- \to n\pi^-$	0	1.6×10^{-4}	-1.2×10^{-2}
$\Sigma^+ \to p\pi^0$	-6.2×10^{-7}	-3.2×10^{-7}	-4.2×10^{-4}
$\Sigma^+ \to n\pi^+$	6.0×10^{-7}	-1.6×10^{-4}	-8.4×10^{-7}

In Ref. [33], the authors pointed out some shortcomings and improved the method for the CP violation calculation compared with Ref. [17]. The weak-interaction phase differences between the S-wave and the P-wave are responsible for the CP violation. In the P-wave contribution calculation, the factorization results from the leading-order chiral perturbation theory arising from the baryon poles were included in Ref. [33]. In contrast, the results of Ref. [17] for the baryon poles only took into account the nonfactorizable contributions, and the kaon poles were in charge of the P-waves in these results. However, based on the chiral perturbation theory, the contribution from the kaon poles was relatively small, because it was a next-to-leading-order contribution and was suppressed by a factor of m_π^2/m_K^2. Therefore, to estimate the weak phases, the real part of the amplitudes were obtained from the experiment, and then the imaginary part was calculated from the leading-order amplitudes. The isospin amplitudes were extracted to be,

$$S_1 = -0.95 \pm 0.04, \qquad S_{13} = 1.95 \pm 0.02, \qquad S_{33} = -0.11 \pm 0.04,$$
$$P_1 = 2.64 \pm 0.04, \qquad P_{13} = 0.01 \pm 0.03, \qquad P_{33} = -0.11 \pm 0.05,$$

in the unit of $G_F m^2_{\pi^+}$, where G_F is the Fermi coupling constant.

The prediction values of the phases are listed in Table 2.

Table 2. Predicted weak phase, in units of $\eta\lambda^5 A^2$ [34].

ϕ_1^S	ϕ_{13}^S	ϕ_1^P	ϕ_{13}^P
1.0 ± 2.0	1.0 ± 2.0	0.1 ± 0.2	-40 ± 80

Combining isospin amplitudes and the phase, the CP observables of Σ were calculated to be $A(\Sigma_+^+) = 3.9 \times 10^{-4}$, $A(\Sigma_0^+) = 3.6 \times 10^{-6}$ and $A(\Sigma_-^-) = -8.3 \times 10^{-5}$ by using $\eta\lambda^5 A^2 = 1.26 \times 10^{-4}$. Those estimates were very rough because the uncertainty was larger than those for the other hyperons, which was caused by the smallness of P_{13} and the fact the measurement accuracy was not sufficient. The P_{13} was calculated thanks to the processes of $\Sigma^+ \to p\pi^0$, $\Sigma^+ \to n\pi^+$ and $\Sigma^- \to n\pi^-$ experimental inputs. However, the measurements of the decay asymmetry parameters from the collider experiment were not precise enough.

5. Summary

There were many experiments on the measurement of the Σ decay parameters half of a century ago. Their main purpose at that time was to test the $\Delta I = 1/2$ rule, so they did not provide relevant $\bar{\Sigma}$ hyperon measurement results. Moreover, the statistics were limited to perform precise symmetry tests. The BEPCII collider experiment not only provides large statistics but also entangles the hyperon–antihyperon pair production system, which is useful in the CP conservation test. Considering the isospin of Σ, the three processes of $\Sigma^+ \to p\pi^0$, $\Sigma^+ \to n\pi^+$ and $\Sigma^- \to n\pi^-$ all contribute to CP violation measurements, which require accurate experimental inputs. Until now, in experiments, we have not observed a CP violation in the hyperon sector and we can only achieve a precision at the 10^{-3} level, which is still larger than the SM predictions. In the future, $p\bar{p}$ and e^+e^- collider experiments will provide data samples orders of magnitude larger than before, which will hopefully figure out the hyperon's CP conservation problem in the SM.

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