CP Violation in Hyperon Decays

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Abstract

In this talk I review theoretical predictions for CP violation in non-leptonic hyperon decays in the Standard Model and models beyond. In the Standard Model the CP violating observable $A$ in the polarization asymmetries of $\Lambda \rightarrow p\pi^-$ and $\Xi^- \rightarrow \Lambda\pi^-$ decays are predicted to be in the ranges $(-0.61 \sim 6.8) \times 10^{-5}$ and $-(0.1 \sim 1) \times 10^{-5}$, respectively. These ranges are below the sensitivity of $1.4 \times 10^{-4}$ for $A(\Lambda^0) + A(\Xi^0)$ for E871 experiment at Fermilab. When going beyond the SM, such as, Supersymmetric and Left-Right symmetric models, $A$ can be as large as $10^{-3}$ and a few times of $10^{-4}$, respectively. Studies of hyperon decays can provide important information about CP violation.

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I. CP VIOLATING OBSERVABLES IN HYPERON DECAYS

The decay amplitude $M$ for a non-leptonic hyperon decay $B_i \rightarrow B_f \pi$ can be written as

$$M = G_F m^2 \bar{B}_f(q_f)(\tilde{A} - \tilde{B} \gamma_5)B_i(q_i).$$

In the literature one often uses $S = \tilde{A}$ and $P = \tilde{B}|\tilde{q}_f|/(E_f + m_f)$.

The polarization asymmetry interest for CP violation study is related to the polarization parameter $\alpha$ defined as follow,

$$\frac{d\Gamma}{d\Omega} = \frac{\Gamma}{4\pi}(1 + \alpha \hat{q}_f \cdot \vec{\omega}_i),$$

where $\vec{\omega}_i$ is the initial hyperon polarization direction and $\hat{q}_f$ is the final baryon momentum direction, and $\alpha = 2 \text{Re}(S^*P)/(|S|^2 + |P|^2)$.

If particle and anti-particle decays are measured, one can construct a CP violating observable [1],

$$A(B_i \rightarrow B_f \pi) = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}.$$

(1)

In the CP conserving limit, $\alpha = -\bar{\alpha}$, and therefore $A = 0$.

So far only upper bounds of $A(\Lambda^0)$ and $A(\Xi^-)$ for $\Lambda \rightarrow p\pi^-$ and $\Xi^- \rightarrow \Lambda\pi^-$ have been obtained [2]. The experiment E871 at Fermilab underway can measure $A(\Lambda \rightarrow p\pi^-) + A(\Xi^- \rightarrow \Lambda\pi^-)$ with a sensitivity of $1.4 \times 10^{-4}$ [3]. With this sensitivity, it is possible to distinguish several different models. Therefore important information for CP violation can be obtained.

To the leading order $A(\Lambda^0)$ and $A(\Xi^-)$ are given by the following [2],

$$A(\Lambda^0) \approx -\tan(\delta^p_1 - \delta^s_1) \sin(\phi^p_1 - \phi^s_1), \quad A(\Xi^-) \approx -\tan(\delta^p_2 - \delta^s_2) \sin(\phi^p_2 - \phi^s_2),$$

where $\delta^s_{1,2}$ and $\phi^s_{1,2}$ are the CP conserving final state interaction phases and CP violating weak interaction phases of the $\Delta I = 1/2$ isospin amplitudes, respectively. $\delta^p_{1,2}$ extracted from data are: $\delta^p_1 = 6.0^\circ$ and $\delta^p_2 = -1.1^\circ$ with errors of order $1^\circ$ [4]. There is no experimental information on $\delta^{s,p}_{2}$. Theoretical calculations give $\delta^p_2 = 0.5^\circ$ and $\delta^p_2 = -1.7^\circ$ [3]. We have

$$A(\Lambda^0) \approx 0.125 \sin(\phi^p_1 - \phi^s_1), \quad A(\Xi^-) \approx 0.04 \sin(\phi^p_2 - \phi^s_2).$$

(2)

To finally obtain $A$ one needs to calculate the phases $\phi^s_{1,2}$. In order to minimize uncertainties, we use experimental data for the CP conserving amplitudes and calculate the CP violating amplitudes to obtain these phases.

II. STANDARD MODEL PREDICTIONS

The CP violating decay amplitude $\text{Im}M$ is given by

$$\text{Im}M = \text{Im}(<\pi B_f|H_{\text{eff}}|B_i>) = \frac{G_F}{\sqrt{2}}V_{us}V_{ud}^*\text{Im}(\tau) \sum_i <B_f\pi|y_iO_i|B_i>.$$
Here $H_{eff}$ is the effective $\Delta S = -1$ Hamiltonian. $\tau = -V_{td}^*V_{ts}/V_{ud}^*V_{us}$, and $O_i$ are operators composed of quarks and gluons up to dimension six.

Calculations show that the dominant contribution is coming from $O_6 = \bar{d}_i\gamma_\mu(1 - \gamma_5)s_j\sum_{q'=u,d,s}s_j\gamma^\mu(1 + \gamma_5)q_i$. We will use results obtained in Ref. [1] MIT bag model as the reference values. We have

$$\phi_1^i \approx 0.42y_6Im\tau B^6_{\Lambda_s}, \quad \phi_2^i \approx 2.24y_6Im\tau B^6_{\Lambda_p};$$

$$\phi_3^i \approx 0.29y_6Im\tau B^6_{\Xi_s}, \quad \phi_4^i \approx -0.92y_6Im\tau B^6_{\Xi_p},$$

where $y_6 = -0.0995$. In the above, we have introduced the parameters $B^6_i$ to quantify the uncertainty in these matrix elements with $B^6_i = 1$ for bag model calculations. To reflect uncertainties due to our poor understanding of the hadronic matrix elements, in our numerical analysis we will, conservatively, use $0.5 < B^i_{js} < 2$ and allow $B^i_{jp}$ to vary in the range of $0.7B^i_{js} < B^i_{jp} < 1.3B^i_{js}$.

Here we also give bag model calculations for $O_{11} = \frac{g_s}{2\pi}d\sigma_{\mu\nu}G^{\mu\nu}(1 + \gamma_5)s$ which will be important for our discussions on new physics. We have [8]

$$\phi_1^i \approx 0.13y_{11}Im\tau B^{11}_{\Lambda_s}, \quad \phi_2^i \approx 0.15y_{11}B^{11}_{\Lambda_p}Im\tau;$$

$$\phi_3^i \approx 0.08y_{11}Im\tau B^{11}_{\Xi_s}, \quad \phi_4^i \approx -0.04y_{11}Im\tau B^{11}_{\Xi_p}.$$

In the SM $y_{11} = -0.34$. Combining above information, we have

$$A(\Lambda^0) = [0.28(B^{6}_{\Lambda_p} - 0.19B^6_{\Lambda_s})y_6 + 0.019(B^{11}_{\Lambda_p} - 0.87B^{11}_{\Lambda_s})y_{11}]Im(\tau),$$

$$A(\Xi^-) = -[0.037(B^{6}_{\Xi_p} + 0.32B^{6}_{\Xi_s})y_6 + 0.0016(B^{11}_{\Xi_p} + 2.0B^{11}_{\Xi_s})y_{11}]Im(\tau).$$

Using the expression $Im(\tau) = -A^2\lambda^4\eta$ with $\lambda = 0.2196$, $A = 0.835$ [4], the best fit value $\eta = 0.34$ [7] and $B^{6,11}_j = 1$, we obtain

$$A(\Lambda^0) = 1.2 \times 10^{-5}, \quad A(\Xi^-) = -0.27 \times 10^{-5}. \quad (3)$$

Other model calculations give similar values [8].

Using the 95% C.L. allowed range of $0.22 \sim 0.50$ for $\eta$ and the conservative allowed ranges for $B^{6,11}_i$, we obtain

$$A(\Lambda^0) = (-0.61 \sim 6.8) \times 10^{-5}, \quad A(\Xi^-) = -(0.1 \sim 1.0) \times 10^{-5}. \quad (4)$$

We consider the above the most conservative allowed ranges for the SM predictions. $|A(\Lambda^0)|$ is larger than $|A(\Xi^-)|$. This is a general feature in all models. From now on we will only discuss $A(\Lambda^0)$.

### III. BEYOND THE STANDARD MODEL

When going beyond the SM, $A$ can be larger. Model independent analysis shows that $A(\Lambda^0)$ as large as $10^{-3}$ is possible [8]. Here we consider two typical models, Supersymmetric and Left-Right symmetric models, to demonstrate that it is indeed possible to have a large $A$. 


A. Supersymmetric Model

In a general supersymmetric model there are more CP violating phases and new operators. Among them gluonic dipole operators with new CP violating phase due to exchange of gluino and squark with left-right mixing in the loop can produce a $A(\Lambda^0)$ considerably larger than the SM prediction. This new interaction has been shown to make large contribution to $\epsilon'/\epsilon_K$ also.

The effective Hamiltonian for the gluonic dipole operator is

$$H_{\text{eff}} = C_g \frac{g_s}{8\pi^2} m_s \bar{d} \sigma_{\mu\nu} G^{\mu\nu}(1 + \gamma_5)s + \tilde{C}_g \frac{g_s}{8\pi^2} m_s \bar{d} \sigma_{\mu\nu} G^{\mu\nu}(1 - \gamma_5)s + \text{h.c.},$$

where

$$C_g = (\delta_{12}^d)_{LR} \frac{\alpha_s \pi}{m_\tilde{g} m_s} G_0(x), \quad \tilde{C}_g = (\delta_{12}^d)_{RL} \frac{\alpha_s \pi}{m_\tilde{g} m_s} G_0(x).$$

The parameters $\delta_{12}^d$ characterize the mixing in the mass insertion approximation, and $x = m_\tilde{g}^2/m_s^2$, with $m_\tilde{g}$, $m_s$ being the gluino and averaged squark masses, respectively. The loop function can be found in Ref. [10].

Using our previous MIT bag model results, we obtain [11]

$$A(\Lambda^0)_{\text{SUSY}} = \left( \frac{\alpha_s(m_\tilde{g})}{\alpha_s(500 \text{ GeV})} \right)^2 \left( \frac{500 \text{ GeV}}{m_\tilde{g}} \right) \frac{G_0(x)}{G_0(1)} \times \left( (2.0 B_p - 1.7 B_s) \text{Im}(\delta_{12}^d)_{LR} + (2.0 B_p + 1.7 B_s) \text{Im}(\delta_{12}^d)_{RL} \right).$$

There are constraints from $\epsilon_K$ and $\epsilon'/\epsilon_K$. $\epsilon'/\epsilon_K$ constrains the linear combination of $\text{Im}(\delta_{12}^d)_{LR} - (\delta_{12}^d)_{RL}$ while $\epsilon_K$ constrains $\text{Im}(\delta_{12}^d)_{LR} + (\delta_{12}^d)_{RL}$. We consider three cases with results shown in Fig. [11]: a) $\text{Im}(\delta_{12}^d)_{RL} = 0$ (hatched horizontally), b) $\text{Im}(\delta_{12}^d)_{LR} = 0$ (hatched diagonally), and c) $\text{Im}(\delta_{12}^d)_{RL} = \text{Im}(\delta_{12}^d)_{LR}$ (below the shaded region or vertically hatched), for illustrations. The regions allowed, by the requirements that $(\epsilon'/\epsilon_K)_{\text{SUSY}}$ and $(\epsilon_K)_{\text{SUSY}}$ not to exceed their experimental values, for the three cases discussed are shown in Fig. [11]. It is clear that the SUSY contribution can be very different than that in the Standard Model. $A(\Lambda^0)$ can be as large as $1.9 \times 10^{-3}$.

B. Left-Right Symmetric Model

In Left-Right symmetric model, there are two charged gauge bosons, $W_L$ and $W_R$. In general there are mixing between these two bosons. The effective Hamiltonian for non-leptonic hyperon decays can be written as

$$H_{\text{eff}} = H_{\text{SM}} + H_R + H_{LR}.$$

In the limit of no left-right mixing, $H_{\text{SM}}$ reduces to the SM effective Hamiltonian. $H_R$ is due to the exchange of the heavy $W$ boson which can be obtained from $H_{\text{SM}}$ by replacing $m_W = m_{W_L}$ by the heavy boson mass $m_{W_R}$, the left-handed KM matrix $V_L$ by the right-handed KM matrix $V_R$, and $1 \pm \gamma_5$ by $1 \mp \gamma_5$. $H_{LR}$ is due to a non-zero parameter $\xi$ for the left-right mixing. It is given by
where $\tilde{\epsilon} = \xi I m(V^*_{Ll}V_{Rl} \pm V^*_{Rl}V_{Ll})$. Using $\xi = 4 \times 10^{-3}$, $A(\Lambda^0_0)$ can be as large as $10^{-4}$ if $I m(V^*_{Rl}V_{us})$ is larger than 0.1 which is not ruled.

The contributions from the gluonic dipole interactions can be obtained in a similar way as in the SUSY case. Including QCD corrections we obtain \cite{13}

$$\phi^\alpha_1 = -0.54 \sum_i \xi^{-}\tilde{G}(x_i) \frac{m_i}{\text{GeV}}, \quad \phi^\alpha_2 = 0.63 \sum_i \xi^{+}\tilde{G}(x_i) \frac{m_i}{\text{GeV}}.$$  \hspace{1cm} (7)

The above contributions are similar to that considered in the previous section for the SUSY contributions. However there are some differences that the parameters $\xi$ and the elements of $V_{LR}$ are constrained from other experimental data and unitarity of $V_{LR}$ which are sever than constraint from $\epsilon_K$. $A(\Lambda^0_0)$ can not be as large as that in the SUSY case. With $|V_{Ll}| = 0.003$ and $V_{Rs} \approx 0.04$, one obtains a $A(\Lambda^0_0)$ in the order of a few $\times 10^{-4}$.
IV. CONCLUSIONS

In the Standard Model the CP violating observables $A(\Lambda, \Xi)$ in the polarization asymmetries of $\Lambda \rightarrow p\pi^-$ and $\Xi^- \rightarrow \Lambda\pi^-$ decays are predicted to be in the ranges $(-0.61 \sim 6.8) \times 10^{-5}$ and $-(0.1 \sim 1.0) \times 10^{-5}$. These asymmetries are below the sensitivity of $1.4 \times 10^{-4}$ of E871 at Fermilab experiment. When going beyond the SM, such as, Supersymmetric and Left-Right symmetric models, $A$ can be as large as $10^{-3}$ and a few times of $10^{-4}$, respectively. Studies of hyperon decays can provide important information about CP violation.

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