FLAVOR MIXING IN THE B-MESON SYSTEM AS A PROBE FOR DECOHERENCE

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To Bill Fagerbakke,

whose declaration of “That’s Mr. Doctor Professor Patrick to you!” lit a fire in me that could only be extinguished by the bureaucracy of academia.

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ABSTRACT

Theses have elements. Isn't that nice?

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2.1 Introduction

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3.1 Introduction

3.2 Decoherence in B physics

In this section, we follow the work of refs [8, 44] to come up with a parametrization of the mixing induced flavor asymmetry parameter, $\mathcal{A}_{\mathrm{mix}}(\Delta t)$, that includes contributions of decoherence.

3.2.1 An open $B\bar{B}$ system

Kraus' Theorem

The notion of closed systems with a single observer is not a realistic representation of the conditions present in B factory experiments. In order to properly model the time evolution of B meson pairs, we must then treat the $B\bar{B}$ system as an *open* system and allow it to interact with its surroundings. These surroundings may include [write more here]

Kraus representations [37] are a convenient way of modeling open system dynamics. The general idea is as follows: Consider a Hilbert space $\mathcal{H}$ composed of two subsystems $\mathcal{H}_a$ and $\mathcal{H}_b$ such that $\mathcal{H} = \mathcal{H}_a \otimes \mathcal{H}_b$. If at a given time, t, we represent quantum states by density matrices $\rho(t)$, $\rho_a(t)$, and $\rho_b(t)$, respectively for $\mathcal{H}$, $\mathcal{H}_a$, and $\mathcal{H}_b$, then $\rho_a(t)$ ($\rho_b(t)$) is related to $\rho(t)$ by a partial trace over b (a), that is,

$$\begin{aligned}\rho_a(t) &= \mathrm{Tr}_b(\rho(t)) \\ \rho_b(t) &= \mathrm{Tr}_a(\rho(t)).\end{aligned} \tag{3.1}$$

Now, since $\mathcal{H}$ is unitary, $\rho(t)$ is simply a unitary transformation of $\rho(0)$:

$$\rho(t) = U(t)\rho(0)U^\dagger(t), \tag{3.2}$$

for some unitary operator $U(t)$. Plugging 3.1 into 3.2 gives us the time evolution of states in $\mathcal{H}_a$

$$\rho_a(t) = \mathrm{Tr}_b\left(U(t)\rho(0)U^\dagger(t)\right). \tag{3.3}$$

Kraus' theorem states that if $\rho_a(t)$ can be also be written as

$$\rho_a(t) = \sum_i K_i(t)\rho(0)K_i^\dagger(t), \tag{3.4}$$

with

$$\sum_i K_i(t) K_i^\dagger(t) = \mathbb{1}, \tag{3.5}$$

then $K_i(t)$ is a Kraus operator, and $\rho_a(t)$ is completely positive and has a Kraus representation.

3.2.2 Open system $B\bar{B}$ dynamics

To consider the effects of decoherence on the time evolution of neutral $B\bar{B}$ pairs, we start with an orthonormal basis of states

$$\left|B^0\right\rangle \doteq \begin{pmatrix}1\\0\\0\end{pmatrix}, \quad \left|\bar{B}^0\right\rangle \doteq \begin{pmatrix}0\\1\\0\end{pmatrix}, \quad |0\rangle \doteq \begin{pmatrix}0\\0\\1\end{pmatrix}. \tag{3.6}$$

Here, $\left|B^0\right\rangle$ ($\left|\bar{B}^0\right\rangle$) represent flavor eigenstates for neutral (anti) B-mesons, and $|0\rangle$ is the vacuum state used to describe decays. In this basis, initial meson flavor states are written as $\rho_{B^0}(0) = \left|B^0\right\rangle\left\langle B^0\right|$ and $\rho_{\bar{B}^0}(0) = \left|\bar{B}^0\right\rangle\left\langle \bar{B}^0\right|$. The time evolution of $\rho_{B^0}(0)$ and $\rho_{\bar{B}^0}(0)$ are governed by Kraus operators $\{K_i(t)\}_{i=0}^5$ that encode decoherence. In particular

$$\rho_{B^0,\bar{B}^0}(t) = \sum_{i=0}^{5} K_i(t) \rho^{(i)}_{B^0,\bar{B}^0}(0) K_i^\dagger(t), \tag{3.7}$$

with

$$K_0 = |0\rangle\langle 0| \tag{3.8}$$

$$K_1 = \mathcal{K}_{1+}\left(\left|B^0\right\rangle\left\langle B^0\right| + \left|\bar{B}^0\right\rangle\left\langle \bar{B}^0\right|\right) + \mathcal{K}_{1-}\left(\frac{p}{q}\left|B^0\right\rangle\left\langle \bar{B}^0\right| + \frac{q}{p}\left|\bar{B}^0\right\rangle\left\langle B^0\right|\right) \tag{3.9}$$

$$K_2 = \mathcal{K}_2\left(\frac{p+q}{2p}|0\rangle\left\langle \bar{B}^0\right| + \frac{p+q}{2q}|0\rangle\left\langle \bar{B}^0\right|\right) \tag{3.10}$$

$$K_3 = \mathcal{K}_{3+}\frac{p+q}{2p}|0\rangle\left\langle \bar{B}^0\right| + \mathcal{K}_{3-}\frac{p+q}{2q}|0\rangle\left\langle \bar{B}^0\right| \tag{3.11}$$

$$K_4 = \mathcal{K}_4\left(\left|B^0\right\rangle\left\langle B^0\right| + \left|\bar{B}^0\right\rangle\left\langle \bar{B}^0\right| + \frac{p}{q}\left|B^0\right\rangle\left\langle \bar{B}^0\right| + \frac{q}{p}\left|\bar{B}^0\right\rangle\left\langle B^0\right|\right) \tag{3.12}$$

$$K_5 = \mathcal{K}_5\left(\left|B^0\right\rangle\left\langle B^0\right| + \left|\bar{B}^0\right\rangle\left\langle \bar{B}^0\right| - \frac{p}{q}\left|B^0\right\rangle\left\langle \bar{B}^0\right| - \frac{q}{p}\left|\bar{B}^0\right\rangle\left\langle B^0\right|\right). \tag{3.13}$$

[Define p and q here]. Substituting equations 3.8–3.13 into 3.7, we find

$$\rho^{(0)}_{B^0}(t) = |0\rangle\langle 0|B^0\rangle\langle B^0|0\rangle\langle 0| = \mathbf{0} \tag{3.14}$$

$$\begin{aligned}
\rho^{(1)}_{B^0}(t) &= \left(\mathcal{K}_{1+}\left(|B^0\rangle\langle B^0| + |\bar{B}^0\rangle\langle\bar{B}^0|\right) + \mathcal{K}_{1-}\left(\frac{p}{q}|B^0\rangle\langle\bar{B}^0| + \frac{q}{p}|\bar{B}^0\rangle\langle B^0|\right)\right)|B^0\rangle\langle B^0| \\
&\times \mathcal{K}^*_{1+}\left(|B^0\rangle\langle B^0| + |\bar{B}^0\rangle\langle\bar{B}^0|\right) + \mathcal{K}^*_{1-}\left(\left(\frac{p}{q}\right)^*|\bar{B}^0\rangle\langle B^0| + \left(\frac{q}{p}\right)^*|B^0\rangle\langle\bar{B}^0|\right) \\
&= \left(\mathcal{K}_{1+}|B^0\rangle\langle B^0| + \mathcal{K}_{1-}\frac{q}{p}|\bar{B}^0\rangle\langle B^0|\right) \\
&\times \left(\mathcal{K}^*_{1+}\left(|B^0\rangle\langle B^0| + |\bar{B}^0\rangle\langle\bar{B}^0|\right) + \mathcal{K}^*_{1-}\left(\left(\frac{p}{q}\right)^*|\bar{B}^0\rangle\langle B^0| + \left(\frac{q}{p}\right)^*|B^0\rangle\langle\bar{B}^0|\right)\right) \\
&= |\mathcal{K}_{1+}|^2|B^0\rangle\langle B^0| + \mathcal{K}_{1+}\mathcal{K}^*_{1-}\left(\frac{q}{p}\right)^*|B^0\rangle\langle\bar{B}^0| \\
&+ \mathcal{K}_{1-}\mathcal{K}^*_{1+}\frac{q}{p}|\bar{B}^0\rangle\langle B^0| + |\mathcal{K}_{1-}|^2\left|\frac{q}{p}\right|^2|\bar{B}^0\rangle\langle\bar{B}^0|
\end{aligned} \tag{3.15}$$

$$\begin{aligned}
\rho^{(2)}_{B^0}(t) &= \mathcal{K}_2\left(\frac{p+q}{2p}|0\rangle\langle B^0| + \frac{p+q}{2q}|0\rangle\langle\bar{B}^0|\right)|B^0\rangle\langle B^0| \\
&\times \mathcal{K}^*_2\left(\left(\frac{p+q}{2p}\right)^*|B^0\rangle\langle 0| + \left(\frac{p+q}{2q}\right)^*|\bar{B}^0\rangle\langle 0|\right) \\
&= |\mathcal{K}_2|^2\left|\frac{p+q}{2p}\right|^2|0\rangle\langle 0|
\end{aligned} \tag{3.16}$$

$$\begin{aligned}
\rho^{(3)}_{B^0}(t) &= \left(\mathcal{K}_{3+}\frac{p+q}{2p}|0\rangle\langle B^0| + \mathcal{K}_{3-}\frac{p+q}{2q}|0\rangle\langle\bar{B}^0|\right)|B^0\rangle\langle B^0| \\
&\times \left(\mathcal{K}^*_{3+}\left(\frac{p+q}{2p}\right)^*|B^0\rangle\langle 0| + \mathcal{K}^*_{3-}\left(\frac{p+q}{2q}\right)^*|\bar{B}^0\rangle\langle 0|\right) \\
&= |\mathcal{K}_{3+}|^2\left|\frac{p+q}{2p}\right|^2|0\rangle\langle 0|
\end{aligned} \tag{3.17}$$

$$\begin{aligned}
\rho^{(4)}_{B^0}(t) &= \mathcal{K}_4\left(|B^0\rangle\langle B^0| + |\bar{B}^0\rangle\langle\bar{B}^0| + \frac{p}{q}|B^0\rangle\langle\bar{B}^0| + \frac{q}{p}|\bar{B}^0\rangle\langle B^0|\right)|B^0\rangle\langle B^0| \\
&\times \mathcal{K}^*_4\left(|B^0\rangle\langle B^0| + |\bar{B}^0\rangle\langle\bar{B}^0| + \left(\frac{p}{q}\right)^*|\bar{B}^0\rangle\langle B^0| + \left(\frac{q}{p}\right)^*|B^0\rangle\langle\bar{B}^0|\right) \\
&= \mathcal{K}_4\left(|B^0\rangle\langle B^0| + \frac{q}{p}|\bar{B}^0\rangle\langle B^0|\right) \\
&\times \mathcal{K}^*_4\left(|B^0\rangle\langle B^0| + |\bar{B}^0\rangle\langle\bar{B}^0| + \left(\frac{p}{q}\right)^*|\bar{B}^0\rangle\langle B^0| + \left(\frac{q}{p}\right)^*|B^0\rangle\langle\bar{B}^0|\right) \\
&= |\mathcal{K}_4|^2|B^0\rangle\langle B^0| + |\mathcal{K}_4|^2\left(\frac{q}{p}\right)^*|B^0\rangle\langle\bar{B}^0| + |\mathcal{K}_4|^2\frac{q}{p}|\bar{B}^0\rangle\langle B^0| + |\mathcal{K}_4|^2\left|\frac{q}{p}\right|^2|\bar{B}^0\rangle\langle\bar{B}^0|
\end{aligned} \tag{3.18}$$

$$
\begin{aligned}
\rho^{(5)}_{B^0}(t) &= \mathcal{K}_5 \left(\left|B^0\right\rangle \left\langle B^0\right| + \left|\bar{B}^0\right\rangle \left\langle \bar{B}^0\right| - \frac{p}{q} \left|B^0\right\rangle \left\langle \bar{B}^0\right| - \frac{q}{p} \left|\bar{B}^0\right\rangle \left\langle B^0\right| \right) \left|B^0\right\rangle \left\langle B^0\right| \\
&\times \mathcal{K}_5^* \left(\left|B^0\right\rangle \left\langle B^0\right| + \left|\bar{B}^0\right\rangle \left\langle \bar{B}^0\right| - \left(\frac{p}{q}\right)^* \left|\bar{B}^0\right\rangle \left\langle B^0\right| - \left(\frac{q}{p}\right)^* \left|B^0\right\rangle \left\langle \bar{B}^0\right| \right) \\
&= \mathcal{K}_5 \left(\left|B^0\right\rangle \left\langle B^0\right| - \frac{q}{p} \left|\bar{B}^0\right\rangle \left\langle B^0\right| \right) \\
&\times \mathcal{K}_5^* \left(\left|B^0\right\rangle \left\langle B^0\right| + \left|\bar{B}^0\right\rangle \left\langle \bar{B}^0\right| - \left(\frac{p}{q}\right)^* \left|\bar{B}^0\right\rangle \left\langle B^0\right| - \left(\frac{q}{p}\right)^* \left|B^0\right\rangle \left\langle \bar{B}^0\right| \right) \\
&= |\mathcal{K}_5|^2 \left|B^0\right\rangle \left\langle B^0\right| - |\mathcal{K}_5|^2 \left(\frac{q}{p}\right)^* \left|B^0\right\rangle \left\langle \bar{B}^0\right| - |\mathcal{K}_5|^2 \frac{q}{p} \left|\bar{B}^0\right\rangle \left\langle B^0\right| + |\mathcal{K}_5|^2 \left|\frac{q}{p}\right|^2 \left|\bar{B}^0\right\rangle \left\langle \bar{B}^0\right|
\end{aligned}
\tag{3.19}
$$

Summing everything up in equations 3.14-3.19 and writing in matrix form, we find

$$
\rho_{B^0}(t) = \begin{pmatrix} |\mathcal{K}_{1+}|^2 + |\mathcal{K}_4|^2 + |\mathcal{K}_5|^2 & \left(\frac{q}{p}\right)^* \left(\mathcal{K}_{1+}\mathcal{K}_{1-}^* + |\mathcal{K}_4|^2 - |\mathcal{K}_5|^2\right) & 0 \\ \left(\frac{q}{p}\right) \left(\mathcal{K}_{1+}^*\mathcal{K}_{1-} + |\mathcal{K}_4|^2 - |\mathcal{K}_5|^2\right) & \left|\frac{q}{p}\right|^2 \left(|\mathcal{K}_{1-}|^2 + |\mathcal{K}_4|^2 + |\mathcal{K}_5|^2\right) & 0 \\ 0 & 0 & \left|\frac{p+q}{2p}\right|^2 \left(|\mathcal{K}_2|^2 + |\mathcal{K}_3|^2\right) \end{pmatrix}.
\tag{3.20}
$$

The $\mathcal{K}$ coefficients in equations 3.8-3.20 are defined as follows [44]:

$$
\begin{aligned}
\mathcal{K}_{1\pm} &= \frac{1}{2}\left(e^{-(2im_L+\Gamma_L+\lambda)t/2} \pm e^{-(2im_H+\Gamma_H+\lambda)t/2}\right) \\
\mathcal{K}_2 &= \sqrt{\frac{\mathrm{Re}\left[\frac{p-q}{p+q}\right]}{|p|^2-|q|^2}\left(1 - e^{-\Gamma_L t} - \frac{(|p|^2-|q|^2)^2|1-e^{-(\Gamma+\lambda-i\Delta m)t}|^2}{1-e^{-\Gamma_H t}}\right)} \\
\mathcal{K}_{3\pm} &= \sqrt{\frac{\mathrm{Re}\left[\frac{p-q}{p+q}\right]}{(|p|^2-|q|^2)(1-e^{-\Gamma_H t})}} \left[1 - e^{-\Gamma_H t} \pm (1-e^{-(\Gamma+\lambda-i\Delta m)t})(|p|^2-|q|^2)\right] \\
\mathcal{K}_4 &= \frac{e^{-\Gamma_L t/2}}{2}\sqrt{1-e^{-\lambda t}} \\
\mathcal{K}_5 &= \frac{e^{-\Gamma_H t/2}}{2}\sqrt{1-e^{-\lambda t}},
\end{aligned}
\tag{3.21}
$$

where λ is a decoherence parameter that takes into account the evolution of the system under the influence of the surrounding environment, $\Gamma = \frac{1}{2}(\Gamma_L + \Gamma_H)$ is the mean decay width between mass eigenstates, $\Delta m = m_H - m_L$ is the mass difference between the B mass eigenstates $\left|B_L^0\right\rangle$ and $\left|B_H^0\right\rangle$, related to the B flavor eigenstates by

$$
\left|B_L^0\right\rangle = p\left|B^0\right\rangle + q\left|\bar{B}^0\right\rangle, \quad \left|B_H^0\right\rangle = p\left|B^0\right\rangle - q\left|\bar{B}^0\right\rangle,
\tag{3.22}
$$

with $|p|^2 + |q|^2 = 1$. Substituting the expressions for $\mathcal{K}_{1\pm}$, $\mathcal{K}_4$ and $\mathcal{K}_5$[1] into 3.20, we first find:

$$\begin{aligned}
\rho_{B^0}(t)_{00} &= |\mathcal{K}_{1+}|^2 + |\mathcal{K}_4|^2 + |\mathcal{K}_5|^2 \\
&= \frac{1}{4}\left(e^{-(2im_L+\Gamma_L+\lambda)t/2} + e^{-(2im_H+\Gamma_H+\lambda)t/2}\right)\left(e^{-(-2im_L+\Gamma_L+\lambda)t/2} + e^{-(-2im_H+\Gamma_H+\lambda)t/2}\right) \\
&+ \left(\frac{1-e^{-\lambda t}}{4}\right)(e^{-\Gamma_L t} + e^{-\Gamma_H t}) \\
&= \frac{1}{4}\left(e^{-(\Gamma_L+\lambda)t} + e^{-(\Gamma_H+\lambda)t} + e^{-(\Gamma+\lambda)t}\left(e^{i\Delta m t} + e^{-i\Delta m t}\right)\right) + \left(\frac{1-e^{-\lambda t}}{4}\right)(e^{-\Gamma_L t} + e^{-\Gamma_H t}) \\
&= \frac{1}{4}(e^{-\Gamma_L t} + e^{-\Gamma_H t}) + \frac{e^{-(\Gamma+\lambda)t}}{2}\cos(\Delta m t) \\
&= \frac{e^{\Delta\Gamma t}+1}{4e^{\Gamma_L t}} + \frac{e^{-(\Gamma+\lambda)t}}{2}\cos(\Delta m t) \\
&= \frac{e^{\frac{\Delta\Gamma t}{2}} + e^{-\frac{\Delta\Gamma t}{2}}}{4e^{\Gamma_L t}e^{-\frac{\Delta\Gamma t}{2}}} + \frac{e^{-(\Gamma+\lambda)t}}{2}\cos(\Delta m t) \\
&= \frac{\cosh\left(\frac{\Delta\Gamma t}{2}\right)}{2e^{(\Gamma_L+\Gamma_H)t/2}} + \frac{e^{-(\Gamma+\lambda)t}}{2}\cos(\Delta m t) \\
&= \frac{e^{-\Gamma t}}{2}\left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) + \cos(\Delta m t)e^{-\lambda t}\right) \\
&= \frac{e^{-\Gamma t}}{2}\left(a_{ch} + a_c e^{-\lambda t}\right),
\end{aligned} \tag{3.23}$$

[1]We leave $\mathcal{K}_{2,3\pm}$ as is because as we'll soon see, they don't have an effect on our calculations of interest.

where $a_{ch} \equiv \cosh\left(\frac{\Delta\Gamma t}{2}\right)$ and $a_c \equiv \cos(\Delta m t)$. Doing the same for $\rho_{B^0}(t)_{01}$, $\rho_{B^0}(t)_{10}$, and $\rho_{B^0}(t)_{11}$:

$$\begin{aligned}
\rho_{B^0}(t)_{01} &= \left(\frac{q}{p}\right)^* (\mathcal{K}_{1+}\mathcal{K}_{1-}^* + |\mathcal{K}_4|^2 - |\mathcal{K}_5|^2) \\
&= \frac{1}{4}\left(\frac{q}{p}\right)^* \left(e^{-(2im_L+\Gamma_L+\lambda)t/2} + e^{-(2im_H+\Gamma_H+\lambda)t/2}\right)\left(e^{-(-2im_L+\Gamma_L+\lambda)t/2} - e^{-(-2im_H+\Gamma_H+\lambda)t/2}\right) \\
&+ \left(\frac{q}{p}\right)^* \left(\frac{1-e^{-\lambda t}}{4}\right)(e^{-\Gamma_L t} - e^{-\Gamma_H t}) \\
&= \frac{1}{4}\left(\frac{q}{p}\right)^* \left(e^{-(\Gamma_L+\lambda)t} - e^{-(\Gamma_H+\lambda)t} + e^{-(\Gamma+\lambda)t}\left(e^{-i\Delta m t} - e^{i\Delta m t}\right)\right) + \left(\frac{q}{p}\right)^* \left(\frac{1-e^{-\lambda t}}{4}\right)(e^{-\Gamma_L t} - e^{-\Gamma_H t}) \\
&= \left(\frac{q}{p}\right)^* \frac{e^{-\Gamma_L t} - e^{-\Gamma_H t}}{4} - \left(\frac{q}{p}\right)^* \frac{ie^{-(\Gamma+\lambda)t}}{2}\sin(\Delta m t) \\
&= \left(\frac{q}{p}\right)^* \frac{1-e^{\Delta\Gamma t}}{4e^{\Gamma_2 t}} - \left(\frac{q}{p}\right)^* \frac{ie^{-(\Gamma+\lambda)t}}{2}\sin(\Delta m t) \\
&= \left(\frac{q}{p}\right)^* \frac{e^{-\frac{\Delta\Gamma t}{2}} - e^{\frac{\Delta\Gamma t}{2}}}{4e^{\Gamma_2 t}e^{-\frac{\Delta\Gamma t}{2}}} - \left(\frac{q}{p}\right)^* \frac{ie^{-(\Gamma+\lambda)t}}{2}\sin(\Delta m t) \\
&= \left(\frac{q}{p}\right)^* \frac{-2\sinh\left(\frac{\Delta\Gamma t}{2}\right)}{4e^{\Gamma t}} - \left(\frac{q}{p}\right)^* \frac{ie^{-(\Gamma+\lambda)t}}{2}\sin(\Delta m t) \\
&= -\left(\frac{q}{p}\right)^* \frac{e^{-\Gamma t}}{2}\left(a_{sh} + ia_s e^{-\lambda t}\right), \qquad (3.24) \\
\rho_{B^0}(t)_{10} &= \left(\frac{q}{p}\right) (\mathcal{K}_{1+}^*\mathcal{K}_{1-} + |\mathcal{K}_4|^2 - |\mathcal{K}_5|^2) \\
&= \frac{1}{4}\left(\frac{q}{p}\right) \left(e^{-(-2im_L+\Gamma_L+\lambda)t/2} + e^{-(-2im_H+\Gamma_H+\lambda)t/2}\right)\left(e^{-(2im_L+\Gamma_L+\lambda)t/2} - e^{-(2im_H+\Gamma_H+\lambda)t/2}\right) \\
&+ \left(\frac{q}{p}\right) \left(\frac{1-e^{-\lambda t}}{4}\right)(e^{-\Gamma_L t} - e^{-\Gamma_H t}) \\
&= \frac{1}{4}\left(\frac{q}{p}\right) \left(e^{-(\Gamma_L+\lambda)t} - e^{-(\Gamma_H+\lambda)t} + e^{-(\Gamma+\lambda)t}\left(e^{i\Delta m t} - e^{-i\Delta m t}\right)\right) + \left(\frac{q}{p}\right) \left(\frac{1-e^{-\lambda t}}{4}\right)(e^{-\Gamma_L t} - e^{-\Gamma_H t}) \\
&= \left(\frac{q}{p}\right) \frac{e^{-\Gamma_L t} - e^{-\Gamma_H t}}{4} + \left(\frac{q}{p}\right) \frac{ie^{-(\Gamma+\lambda)t}}{2}\sin(\Delta m t) \\
&= \left(\frac{q}{p}\right) \frac{1-e^{\Delta\Gamma t}}{4e^{\Gamma_2 t}} + \left(\frac{q}{p}\right) \frac{ie^{-(\Gamma+\lambda)t}}{2}\sin(\Delta m t) \\
&= \left(\frac{q}{p}\right) \frac{e^{-\frac{\Delta\Gamma t}{2}} - e^{\frac{\Delta\Gamma t}{2}}}{4e^{\Gamma_2 t}e^{-\frac{\Delta\Gamma t}{2}}} + \left(\frac{q}{p}\right) \frac{ie^{-(\Gamma+\lambda)t}}{2}\sin(\Delta m t) \\
&= \left(\frac{q}{p}\right) \frac{-2\sinh\left(\frac{\Delta\Gamma t}{2}\right)}{4e^{\Gamma t}} + \left(\frac{q}{p}\right) \frac{ie^{-(\Gamma+\lambda)t}}{2}\sin(\Delta m t) \\
&= \left(\frac{q}{p}\right) \frac{e^{-\Gamma t}}{2}\left(-a_{sh} + ia_s e^{-\lambda t}\right), \qquad (3.25)
\end{aligned}$$

$$
\begin{aligned}
\rho_{B^0}(t)_{11} &= \left|\frac{q}{p}\right|^2 \left(|\mathcal{K}_{1-}|^2 + |\mathcal{K}_4|^2 + |\mathcal{K}_5|^2\right) \\
&= \frac{1}{4}\left|\frac{q}{p}\right|^2 \left(e^{-(2im_L+\Gamma_L+\lambda)t/2} - e^{-(2im_H+\Gamma_H+\lambda)t/2}\right)\left(e^{-(-2im_L+\Gamma_L+\lambda)t/2} - e^{-(-2im_H+\Gamma_H+\lambda)t/2}\right) \\
&+ \left|\frac{q}{p}\right|^2 \left(\frac{1-e^{-\lambda t}}{4}\right)\left(e^{-\Gamma_L t} + e^{-\Gamma_H t}\right) \\
&= \frac{1}{4}\left|\frac{q}{p}\right|^2 \left(e^{-(\Gamma_L+\lambda)t} + e^{-(\Gamma_H+\lambda)t} - e^{-(\Gamma+\lambda)t}\left(e^{i\Delta m t} + e^{-i\Delta m t}\right)\right) + \left|\frac{q}{p}\right|^2 \left(\frac{1-e^{-\lambda t}}{4}\right)\left(e^{-\Gamma_L t} + e^{-\Gamma_H t}\right) \\
&= \frac{1}{4}\left|\frac{q}{p}\right|^2 \left(e^{-\Gamma_L t} + e^{-\Gamma_H t}\right) - \left|\frac{q}{p}\right|^2 \frac{e^{-(\Gamma+\lambda)t}}{2}\cos(\Delta m t) \\
&= \left|\frac{q}{p}\right|^2 \frac{e^{\Delta\Gamma t}+1}{4e^{\Gamma_L t}} - \left|\frac{q}{p}\right|^2 \frac{e^{-(\Gamma+\lambda)t}}{2}\cos(\Delta m t) \\
&= \left|\frac{q}{p}\right|^2 \frac{e^{\frac{\Delta\Gamma t}{2}} + e^{-\frac{\Delta\Gamma t}{2}}}{4e^{\Gamma_L t}e^{-\frac{\Delta\Gamma t}{2}}} - \left|\frac{q}{p}\right|^2 \frac{e^{-(\Gamma+\lambda)t}}{2}\cos(\Delta m t) \\
&= \left|\frac{q}{p}\right|^2 \frac{\cosh\left(\frac{\Delta\Gamma t}{2}\right)}{2e^{(\Gamma_L+\Gamma_H)t/2}} - \left|\frac{q}{p}\right|^2 \frac{e^{-(\Gamma+\lambda)t}}{2}\cos(\Delta m t) \\
&= \left|\frac{q}{p}\right|^2 \frac{e^{-\Gamma t}}{2}\left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) - \cos(\Delta m t)e^{-\lambda t}\right) \\
&= \left|\frac{q}{p}\right|^2 \frac{e^{-\Gamma t}}{2}\left(a_{ch} - a_c e^{-\lambda t}\right),
\end{aligned}
\tag{3.26}
$$

where $a_{sh} \equiv \sinh\left(\frac{\Delta\Gamma t}{2}\right)$ and $a_s \equiv \sin(\Delta m t)$. Plugging this all into 3.20 we find

$$
\rho_{B^0}(t) = \frac{e^{-\Gamma t}}{2}\begin{pmatrix} a_{ch} + e^{-\lambda t}a_c & -\left(\frac{q}{p}\right)^*\left(a_{sh} + ie^{-\lambda t}a_s\right) & 0 \\ \left(\frac{q}{p}\right)\left(-a_{sh} + ie^{-\lambda t}a_s\right) & \left|\frac{q}{p}\right|^2\left(a_{ch} - e^{-\lambda t}a_c\right) & 0 \\ 0 & 0 & \rho_{B^0}(t)_{22} \end{pmatrix}. \tag{3.27}
$$

We can perform this same procedure and time evolve $\rho_{\bar{B}^0}(0)$ using these same six Kraus operators $\{K_i(t)\}_{i=1}^6$ to get $\rho_{\bar{B}^0}(t)$. We summarize the results after doing so as follows

$$
\rho_\pm(t) = \frac{e^{-\Gamma t}}{2}\begin{pmatrix} a_{ch} \pm e^{-\lambda t}a_c & -\left(\frac{q}{p}\right)^*\left(a_{sh} \pm ie^{-\lambda t}a_s\right) & 0 \\ \left(\frac{q}{p}\right)\left(-a_{sh} \pm ie^{-\lambda t}a_s\right) & \left|\frac{q}{p}\right|^2\left(a_{ch} \mp e^{-\lambda t}a_c\right) & 0 \\ 0 & 0 & \rho_\pm(t)_{22}) \end{pmatrix}, \tag{3.28}
$$

where $\rho_+(t)$ and $\rho_-(t)$ correspond to B^0 and $\bar{B}^0$, respectively.

In the $\{\left|B^0\right\rangle, \left|\bar{B}^0\right\rangle, |0\rangle\}$ basis, we're interested in observables that encode the information about a B decaying into final state f. If we define $A_f \equiv A(B^0 \to f)$ and $\bar{A}_f \equiv A(\bar{B}^0 \to f)$ to be the amplitudes of a B^0 and $\bar{B}^0$, respectively, decaying into a final state f, we can construct an observable as follows:

$$\mathcal{O}_f(t) = \begin{pmatrix} |A_f|^2 & A_f^* \bar{A}_f & 0 \\ A_f \bar{A}_f^* & |\bar{A}_f|^2 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \tag{3.29}$$

In the formalism of density operators, the time dependent expectation value of this observable is a physical quantity that characterizes the probability of a B^0 or $\bar{B}^0$ decaying into state f at time t

$$\langle \mathcal{O}_f \rangle(t) = \mathrm{Tr}(\mathcal{O}_f \rho_\pm(t)) = P_{f\pm}(t), \tag{3.30}$$

with P_+ corresponding to $B^0 \to f$ and P_-, corresponding to $\bar{B}^0 \to f$. 3.30 is enough to compute asymmetries that are measurable at B-factory experiments, and since our construction of $\rho_\pm(t)$ explicitly includes decoherence effects of neutral B-mesons interacting with their surrounding environment, these asymmetries will depend on decoherence parameter λ.

3.2.3 Observable for $\sin(2\phi_1)$

If we let our final state f be the golden mode, $J/\psi K_S$, we can, from 3.30, immediately construct the CP violating observable used to measure $\sin(2\phi_1)$ in [6]:

$$\mathcal{A}_{f=J/\psi K_S}(t,\lambda) = \frac{P_-(t,\lambda) - P_+(t,\lambda)}{P_-(t,\lambda) + P_+(t,\lambda)}, \tag{3.31}$$

where we are now explicitly writing out the dependence of this asymmetry on decoherence parameter λ. Computing the probabilities in 3.31 using 3.29, 3.28 and 3.30, we find

$$\begin{aligned} P_{J/\psi K_S \pm}(t,\lambda) = \frac{1}{2} e^{-\Gamma t} \Bigg(& |A_f|^2 (a_{ch} \pm e^{-\lambda t} a_c) + |\bar{A}_f|^2 \left| \frac{q}{p} \right|^2 (a_{ch} \mp e^{-\lambda t} a_c) \\ & - A_f^* \bar{A}_f \frac{q}{p} (a_{sh} \mp i e^{-\lambda t} a_s) - A_f \bar{A}_f^* \left(\frac{q}{p} \right)^* (a_{sh} \pm i e^{-\lambda t} a_s) \Bigg) \end{aligned} \tag{3.32}$$

Factoring out $|A_f|^2$ from both the numerator and denominator of 3.31 and defining $z \equiv \frac{q}{p} A(\bar{B}^0 \to J/\psi K_S)/A(B^0 \to J/\psi K_S)$, we obtain

$$\begin{aligned}
\mathcal{A}_{J/\Psi K_S}(t,\lambda) &= \frac{2(|z|^2-1)a_c - 2iza_s + 2iz^* a_s}{2(|z|^2+1)a_{ch} - 2za_{sh} - 2z^* a_{sh}} e^{-\lambda t} \\
&= \frac{(|z|^2-1)a_c + 2\,\mathrm{Im}(z)a_s}{(|z|^2+1)a_{ch} - 2\,\mathrm{Re}(z)a_{sh}} e^{-\lambda t} \\
&= \frac{(|z|^2-1)\cos(\Delta m_d t) + 2\,\mathrm{Im}(z)\sin(\Delta m_d t)}{(|z|^2+1)\cosh(\Delta\Gamma_d t/2) - 2\,\mathrm{Re}(z)\sinh(\Delta\Gamma_d t/2)} e^{-\lambda t}.
\end{aligned} \tag{3.33}$$

where we used the fact that the decay amplitudes are complex numbers, so $\mathrm{Re}(z) = \frac{z+z^*}{2}$ and $\mathrm{Im}(z) = \frac{z-z^*}{2i}$. If we set $|z| = 1$, $\Delta\Gamma \approx 0$, and note that $\mathrm{Im}(z) \approx \sin(2\phi_1)$, we find

$$\mathcal{A}_{J/\Psi K_S}(t,\lambda) \approx \sin(\Delta m_d t)\sin(2\phi_1)e^{-\lambda t}, \tag{3.34}$$

which, in the limit of no decoherence ($\lambda = 0$), is the well-known mixing and decay-induced CP asymmetry expression used to measure $\sin(2\phi_1)$ in Refs. [6, 7]. Furthermore, the presence of $e^{-\lambda t}$ in 3.34 suggests that the measurement of $\sin(2\phi_1)$ is blurred by decoherence.

3.2.4 Observable in $B\bar{B}$ mixing

In the case where a B^0 decays into a state that is inaccessible from a $\bar{B}^0$ decay, it follows that $z = 0$ [15], which will lead us to an expression for the time dependent mixing asymmetry $\mathcal{A}_{\mathrm{mix}}$. Indeed, if we consider 3.32 and set the final state to B^0 (or $\bar{B}^0$), we can compute flavor mixing probabilities. For example, if we were to compute $P_{B^0\to\bar{B}^0}(t)$, we set $A_f = 0$ and $\bar{A}_f = 1$ in 3.32, we would find

$$P_{B^0\to\bar{B}^0}(t) \sim \cosh(\Delta\Gamma_d t/2) - e^{-\lambda t}\cos(\Delta m_d t), \tag{3.35}$$

where we set $\left|\frac{p}{q}\right|^2 = 1$ which is true in B sector where $\Delta\Gamma \ll \Delta m$ [15]. For the other mixing combinations, we would set $A_f = 0$ and $\bar{A}_f = 1$ for $P_{\bar{B}^0\to\bar{B}^0}(t)$, and we would set $A_f = 1$ and $\bar{A}_f = 0$ for $P_{\bar{B}^0\to B^0}(t)$ and $P_{B^0\to B^0}(t)$, giving

$$P_{\bar{B}^0\to\bar{B}^0}(t) \sim \cosh(\Delta\Gamma_d t/2) + e^{-\lambda t}\cos(\Delta m_d t) \tag{3.36}$$

$$P_{B^0\to B^0}(t) \sim \cosh(\Delta\Gamma_d t/2) + e^{-\lambda t}\cos(\Delta m_d t) \tag{3.37}$$

$$P_{\bar{B}^0\to B^0}(t) \sim \cosh(\Delta\Gamma_d t/2) - e^{-\lambda t}\cos(\Delta m_d t). \tag{3.38}$$

Now let's consider a $B\bar{B}$ produced from the hadronization of $e^+e^- \to \Upsilon(4S) \to b\bar{b}$, which is the mechanism for B production at Belle. Since the $\Upsilon(4S)$ is spin 1, it follows from conservation of angular momentum that the resulting $B\bar{B}$ pair will be in a coherent P-wave state, which means that at a certain time t_0, nominally the decay time of the first B^0 in the $B\bar{B}$ pair, the flavor the decaying B *must* be the opposite of the flavor of the other B. This means the probability of observing opposite flavor $P_{B^0\bar{B}^0\to B^0\bar{B}^0}$ or same flavor pairs $P_{B^0\bar{B}^0\to(B^0B^0 \text{ or } \bar{B}^0\bar{B}^0)}$ is determined from the proper time difference between the decays of the two B's, $\Delta t \equiv t_1 - t_0$. With this knowledge at our disposal, we see from equations 3.35–3.38 that *mixing* (creation of same flavor pair) is the result of second B changing flavor and thus has a minus sign in its oscillation probability, whereas an unmixed (opposite flavor) pair has a plus sign in its oscillation probability. This means we can write

$$P_{B^0\bar{B}^0\to B^0\bar{B}^0}(\Delta t) \sim \cosh(\Delta\Gamma_d\Delta t/2) + e^{-\lambda\Delta t}\cos(\Delta m_d\Delta t) = P_+(\Delta t) \tag{3.39}$$

$$P_{B^0\bar{B}^0\to B^0B^0 \text{ or } \bar{B}^0\bar{B}^0}(\Delta t) \sim \cosh(\Delta\Gamma_d\Delta t/2) - e^{-\lambda\Delta t}\cos(\Delta m_d\Delta t) = P_-(\Delta t). \tag{3.40}$$

Finally, we now define the time dependent mixing asymmetry, $\mathcal{A}_{\text{mix}}(\Delta t)$ as

$$\mathcal{A}_{\text{mix}}(\Delta t) \equiv \frac{P_+(\Delta t) - P_-(\Delta t)}{P_+(\Delta t) + P_-(\Delta t)} = \frac{\cos(\Delta m_d\Delta t)}{\cosh(\Delta\Gamma_d\Delta t/2)}e^{-\lambda\Delta t}. \tag{3.41}$$

Just like with 3.33, we see that we now have an expression for the time-dependent asymmetry which also manifestly depends on decoherence parameter λ.

Note: Make sure to cite [14] for the construction of the decoherence parameter in the Kaon system, [10] for the explicit treatment of B mesons as an open system, [11] and [24] and [8] for their explicit usage of Go's dataset to show how updates using Belle I data can still be helpful. And of course, cite Go [31]. Also, also, it looks like [44] explicitly constructs $\rho(t)$ and $\mathcal{O}$ that I use in this chapter. [40] and [32] when bringing up dynamical positive semigroup formalism.

CHAPTER 4
KEKB AND BELLE

4.1 Introduction

CHAPTER 5
EVENT SELECTION

5.1 Introduction

CHAPTER 6
SYSTEMATIC UNCERTAINTIES

6.1 Introduction

CHAPTER 7
RESULTS

7.1 Introduction

CHAPTER 8
DISCUSSION AND OUTLOOK

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