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.

ACKNOWLEDGMENTS

I want to “thank” my committee, without whose ridiculous demands, I would have graduated so, so, very much faster.

ABSTRACT

Theses have elements. Isn't that nice?

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MODELING DECOHERENCE

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

In this section, we follow the work of ref [8] to come up with a parametrization of mixing induced flavor asymmetry parameter that includes contributions of decoherence.

$$\mathcal{O}_f = \begin{pmatrix} |A_f|^2 & A_f^*\bar{A}_f & 0 \\ A_f\bar{A}_f^* & |\bar{A}_f|^2 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \tag{2.1}$$

where $A_f \equiv A(B^0 \to f)$ and $\bar{A}_f \equiv A(\bar{B}^0 \to f)$.

$$\rho_\pm(t) = \frac{1}{2}e^{-\Gamma_d t} \begin{pmatrix} a_{ch} \pm e^{\lambda t}a_c & -a_{sh} \mp ie^{-\lambda t}a_s & 0 \\ -a_{sh} \pm ie^{-\lambda t}a_s & a_{ch} \mp e^{-\lambda t}a_c & 0 \\ 0 & 0 & 2(e^{\Gamma_d t} - a_{ch}) \end{pmatrix}, \tag{2.2}$$

where $\rho_+(t)$ and $\rho_-(t)$ correspond to B^0 and $\bar{B}^0$, respectively. With this construction, the probability of a B^0 or $\bar{B}^0$ decaying into state f at time t is computed as

$$P_{f\pm}(t) = \mathrm{Tr}(\mathcal{O}_f\rho_\pm), \tag{2.3}$$

with P_+ corresponding to an initial B^0 and P_-, an initial $\bar{B}^0$. An observable

$$\mathcal{A}_f = \frac{P_-(t) - P_+(t)}{P_-(t) + P_+(t)} \tag{2.4}$$

can be defined, and when $f = J/\psi K_S$, this observable represents CP violating asymmetry used to determine $\sin(2\phi_1)$ in [6]. To show this, we compute the probabilities in 2.4 using 2.1, 2.2 and 2.3. Doing this, we find

$$\begin{aligned} P_{J/\psi K_S\pm}(t) = \frac{1}{2}e^{-\Gamma_d t}\Big(& |A_f|^2(a_{ch} \pm e^{-\lambda t}a_c) + |\bar{A}_f|^2(a_{ch} \mp e^{-\lambda t}a_c) \\ & - A_f^*\bar{A}_f(a_{sh} \mp ie^{-\lambda t}a_s) - A_f\bar{A}_f^*(a_{sh} \pm ie^{-\lambda t}a_s)\Big); \quad f = J/\psi K_S. \end{aligned} \tag{2.5}$$

Factoring out $|A_f|^2 = A_f A_f^*$ from both the numerator and denominator of 2.4 and defining $z \equiv A(\bar{B}^0 \to J/\psi K_S)/A(B^0 \to J/\psi K_S)$, we obtain

$$\begin{aligned}
\mathcal{A}_{J/\Psi K_S}(t,\lambda) &= \frac{2(|z|^2-1)a_c - 2iza_s + 2iz^* a_s}{2(|z|^2+1)a_{ch} - 2za_{sh} - 2z^* a_{sh}} e^{-\lambda t} \\
&= \frac{(|z|^2-1)a_c + 2\,\mathrm{Im}(z)a_s}{(|z|^2+1)a_{ch} - 2\,\mathrm{Re}(z)a_{sh}} e^{-\lambda t} \\
&= \frac{(|z|^2-1)\cos(\Delta m_d t) + 2\,\mathrm{Im}(z)\sin(\Delta m_d t)}{(|z|^2+1)\cosh(\Delta\Gamma_d t/2) - 2\,\mathrm{Re}(z)\sinh(\Delta\Gamma_d t/2)} e^{-\lambda t}.
\end{aligned} \tag{2.6}$$

where we used the fact that the decay amplitudes are, in general, complex numbers, so $\mathrm{Re}(z) = \frac{z+z^*}{2}$ and $\mathrm{Im}(z) = \frac{z-z^*}{2i}$. We see that 2.6 is indeed the well-known mixing and decay-induced CP asymmetry expression with $\mathrm{Im}(z) \approx \sin(2\phi_1)$ [6, 7], however it includes an additional *decoherence* term, $e^{-\lambda t}$, where we refer to λ as the *decoherence parameter*. We see that in the case of no decoherence ($\lambda = 0$), 2.6 is exactly the CP asymmetry expression described above.

In the case where a B^0 decays into a state that is inaccessible from a $\bar{B}^0$ decay, it follows that $z = 0$ [10], which will lead us to an expression for the time dependent mixing asymmetry $\mathcal{A}_{\mathrm{mix}}$. Indeed, if we consider 2.5 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 2.5, leading us to

$$P_{B^0\to\bar{B}^0}(t) \sim \cosh(\Delta\Gamma_d t/2) - e^{-\lambda t}\cos(\Delta m_d t). \tag{2.7}$$

Similarly, 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

$$P_{\bar{B}^0\to\bar{B}^0}(t) \sim \cosh(\Delta\Gamma_d t/2) + e^{-\lambda t}\cos(\Delta m_d t) \tag{2.8}$$

$$P_{B^0\to B^0}(t) \sim \cosh(\Delta\Gamma_d t/2) + e^{-\lambda t}\cos(\Delta m_d t) \tag{2.9}$$

$$P_{\bar{B}^0\to B^0}(t) \sim \cosh(\Delta\Gamma_d t/2) - e^{-\lambda t}\cos(\Delta m_d t). \tag{2.10}$$

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 2.7–2.10 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

$$P_{B^0\bar{B}^0 \to B^0\bar{B}^0}(\Delta t) \sim \cosh(\Delta\Gamma_d \Delta t/2) + e^{-\lambda\Delta t}\cos(\Delta m_d \Delta t) = P_+(\Delta t) \tag{2.11}$$

$$P_{B^0\bar{B}^0 \to B^0 B^0 \text{ or } \bar{B}^0\bar{B}^0}(\Delta t) \sim \cosh(\Delta\Gamma_d \Delta t/2) - e^{-\lambda\Delta t}\cos(\Delta m_d \Delta t) = P_-(\Delta t). \tag{2.12}$$

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

$$\mathcal{A}_{\text{mix}}(\Delta t) \equiv \frac{P_+(\Delta t) - P_-(\Delta t)}{P_+(\Delta t) + P_-(\Delta t)} = \frac{\cos(\Delta m_d \Delta t)}{\cosh(\Delta\Gamma_d \Delta t/2)} e^{-\lambda\Delta t}. \tag{2.13}$$

Just like with 2.6, we see that we now have an expression for the time-dependent asymmetry which also manifestly depends on decoherence parameter λ.

2.2 Bibliography Citations

Citing references to your bibliography is easy [17] [44]. First you build a BibTeX file which contains the records for all of the works you wish to cite. This file ends with a "`.bib`" extension. Then in your body you use the "`\cite`" command with the label you gave to the record in question. The final steps are: run LaTeX once, run BibTeX, and then run LaTeX twice more. You should now have a bibliography that includes those citations.

CHAPTER 3
CONCLUSION

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3.1 Widgets

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