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Effect of decoherence on clean determination of $\sin 2\beta$ and Δm_d

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The important quantities of the B_d^0 system, such as $\sin 2\beta$ and Δm_d, are determined under the assumption of perfect quantum coherence. However, any real system interacts with its environment and this interaction can lead to decoherence. It is therefore desirable to re-examine the procedures of determination of $\sin 2\beta$ and Δm_d in meson systems with decoherence. We find that the present values of these two quantities are modulated by the decoherence parameter λ. Re-analysis of B_d^0 data from B-factories and LHCb can lead to a clean determination of λ, $\sin 2\beta$ and Δm_d.

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1. Introduction

The time evolution of neutral mesons is used to measure a number of important parameters in flavor physics. Here a perfect quantum coherence is usually assumed. However, any real system interacts with its environment and this interaction can lead to a loss of quantum coherence. The environmental effects may arise at a fundamental level, such as the fluctuations in a quantum gravity space-time background [1, 2]. They may also arise due to the detector environment itself. Irrespective of the origin of the environment, its effect on the neutral meson systems can be taken into account by using the ideas of open quantum systems [3, 4, 5]. This formalism enables the inclusion of effects such as decoherence and dissipation in a systematic manner [6].

We study the effect of decoherence on important observables in the B_d^0 meson system, such as the CP violating parameter $\sin 2\beta$ and the $B_d^0 - \bar{B}_d^0$ mixing parameter Δm_d. We show that these parameters are affected by decoherence [7]. We also suggest a number of methods which will enable clean determination of the decoherence parameter along with the other observables quite easily at the LHCb or B-factories [7]. We also attempt determination of the decoherence parameter and Δm_d using Belle data on the time dependent flavor asymmetry of semi-leptonic B_d^0 decays as given in Ref. [8].

2. Open time evolution of B^0 meson

We are interested in the decays of B^0 and $\bar{B}^0$ mesons as well as $B^0 \leftrightarrow \bar{B}^0$ oscillations. To describe the time evolution of all these transitions, we need a basis of three states: $|B^0\rangle$, $|\bar{B}^0\rangle$ and $|0\rangle$, where $|0\rangle$ reprents a state with no B meson and is required for describing the decays. We use the density matrix formalism to represent the time evolution of the B^0 system. $\rho_{B^0(\bar{B}^0)}(0)$ is the initial density matrix for the state which starts out as $B^0(\bar{B}^0)$. The time evolution of these matrices is governed by the Kraus operators $K_i(t)$ as $\rho(t) = \sum_i K_i(t)\rho(0)K_i^\dagger(t)$ [9]. The Kraus operators are constructed taking into account the decoherence in the system which occurs due to the evolution under the influence of the environment [10].

The time dependent density matrices are [7]

$$\frac{\rho_{B^0}(t)}{\frac{1}{2}e^{-\Gamma t}} = \begin{pmatrix} a_{ch} + e^{-\lambda t} a_c & -a_{sh} - i e^{-\lambda t} a_s & 0 \\ -a_{sh} + i e^{-\lambda t} a_s & a_{ch} - e^{-\lambda t} a_c & 0 \\ 0 & 0 & 2(e^{\Gamma t} - a_{ch}) \end{pmatrix},$$

$$\frac{\rho_{\bar{B}^0}(t)}{\frac{1}{2}e^{-\Gamma t}} = \begin{pmatrix} a_{ch} - e^{-\lambda t} a_c & -a_{sh} + i e^{-\lambda t} a_s & 0 \\ -a_{sh} - i e^{-\lambda t} a_s & a_{ch} + e^{-\lambda t} a_c & 0 \\ 0 & 0 & 2(e^{\Gamma t} - a_{ch}) \end{pmatrix}, \qquad (2.1)$$

for B^0 and $\bar{B}^0$, respectively. In the above equation, $a_{ch} = \cosh\left(\frac{\Delta\Gamma t}{2}\right)$, $a_{sh} = \sinh\left(\frac{\Delta\Gamma t}{2}\right)$, $a_c = \cos(\Delta m t)$, $a_s = \sin(\Delta m t)$, $\Gamma = (\Gamma_L + \Gamma_H)/2$, $\Delta\Gamma = \Gamma_L - \Gamma_H$, where Γ_L and Γ_H are the respective decay widths of the decay eigenstates B_L^0 and B_H^0. Also λ is the decoherence parameter, due to the interaction between one-particle system and its environment.

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3. *CP* asymmetry in $B_d^0 \to J/\psi K_S$

We define the decay amplitudes $A_f \equiv A(B^0 \to f)$ and $\bar{A}_f \equiv A(\bar{B}^0 \to f)$. The hermitian operator describing the decays of the B^0 and $\bar{B}^0$ mesons into f is

$$\mathscr{O}_f = \begin{pmatrix} |A_f|^2 & A_f{}^* \bar{A}_f & 0 \\ A_f \bar{A}_f^* & |\bar{A}_f|^2 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \tag{3.1}$$

The probability, $P_f(B^0/\bar{B}^0;t)$, of an initial $B^0/\bar{B}^0$ decaying into the state f at time t is given by $\mathrm{Tr}\left[\mathscr{O}_f \, \rho_{B^0(\bar{B}^0)(t)}\right]$.

Let us now consider $B_d^0 \to J/\psi K_S$ decay. One can define a CP violating observable

$$\mathscr{A}_{J/\psi K_S}(t) = \frac{P_{J/\psi K_S}(\bar{B}_d^0;t) - P_{J/\psi K_S}(B_d^0;t)}{P_{J/\psi K_S}(\bar{B}_d^0;t) + P_{J/\psi K_S}(B_d^0;t)}. \tag{3.2}$$

Calculating the probabilities using Eqs. (2.1) and (3.1), we get [7]

$$\mathscr{A}_{J/\psi K_S}(t) = \frac{\left(|\lambda_f|^2 - 1\right)\cos(\Delta m_d t) + 2\mathrm{Im}(\lambda_f)\sin(\Delta m_d t)}{(1+|\lambda_f|^2)\cosh\left(\frac{\Delta\Gamma_d t}{2}\right) - 2\mathrm{Re}(\lambda_f)\sinh\left(\frac{\Delta\Gamma_d t}{2}\right)} e^{-\lambda t}, \tag{3.3}$$

where $\lambda_f = A(\bar{B}_d^0 \to J/\psi K_S))/A(B_d^0 \to J/\psi K_S)$. The usual expression for $\mathscr{A}_{J/\psi K_S}(t)$ is obtained by putting $\lambda = 0$ in the above equation. With the approximations $\Delta\Gamma_d \approx 0$, $|\lambda_f| = 1$ and $\mathrm{Im}(\lambda_f) \approx \sin 2\beta$, we get

$$\mathscr{A}_{J/\psi K_S}(t) = e^{-\lambda t} \sin 2\beta \sin(\Delta m_d t). \tag{3.4}$$

Therefore we see that the coefficient of $\sin(\Delta m_d t)$ in the CP asymmetry is $e^{-\lambda t} \sin 2\beta$ and not $\sin 2\beta$! Thus the measurement of $\sin 2\beta$ is masked by the presence of decoherence.

4. Determination of Δm_d

In order to determine $\sin 2\beta$, we need to know Δm_d and λ. A legitimate question at this stage is that whether the measurement of Δm_d also affected by the presence of decoherence? LHCb, CDF and D0 experiments determine Δm_d by measuring rates that a state that is pure B_d^0 at time $t = 0$, decays as either as B_d^0 or $\bar{B}_d^0$ as function of proper decay time. In the presence of decoherence, the survival (oscillation) probability of initial B_d^0 meson to decay as $B_d^0(\bar{B}_d^0)$ at a proper decay time t is given by [7]

$$P_\pm(t,\lambda) = \frac{e^{-\Gamma t}}{2}\left[\cosh(\Delta\Gamma_d t/2) \pm e^{-\lambda t}\cos(\Delta m_d t)\right]. \tag{4.1}$$

The positive sign applies when the B_d^0 meson decays with the same flavor as its production and the negative sign when the particle decays with opposite flavor to its production. Δm_d is determined from the following time dependent asymmetry:

$$A_{\mathrm{mix}}(t,\lambda) = \frac{P_+(t,\lambda) - P_-(t,\lambda)}{P_+(t,\lambda) + P_-(t,\lambda)} = e^{-\lambda t}\frac{\cos(\Delta m_d t)}{\cosh(\Delta\Gamma_d t/2)}. \tag{4.2}$$

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Thus we see that the in the limit of neglecting $\Delta\Gamma_d$, the otherwise pure cosine dependence of mixing asymmetry is modulated by $e^{-\lambda t}$.

Belle and BaBar experiments determine Δm_d by measuring time dependent probability $P_+(t)$ of observing unoscillated $B_d^0\bar{B}_d^0$ events and $P_-(t)$ of observing oscillated $B_d^0 B_d^0/\bar{B}_d^0\bar{B}_d^0$ events for two neutral B_d mesons produced in an entangled state in the decay of the $\Upsilon(4S)$ resonance. The expressions for $P_\pm(t)$, in the presence of decoherence, are the same as those given in Eq. (4.1), except that the proper time t is replaced by the proper decay-time difference Δt between the decays of the two neutral B_d mesons. Therefore, we see that the determination of Δm_d at LHCb, CDF, D0, Belle and BaBar experiments is also masked by the presence of λ.

It can be shown that the time independent observables r_d (measured by ARGUS and CLEO) and χ_d (measured by the LEP experiments), used to determine $\Delta\Gamma_d$, are also affected by the presence of decoherence [7].

The true value of Δm_d, along with $\Delta\Gamma_d$, can be determined by a three parameter $(\Delta m_d, \Delta\Gamma_d, \lambda)$ fit to the time dependent mixing asymmetry $A_{\rm mix}(t,\lambda)$ defined in Eq. (4.2). This in turn will enable a determination of true value of $\sin 2\beta$ using Eq. (3.3).

5. Estimation of λ: An Example

We make an attempt of a clean determination of λ, Δm_d and $\Delta\Gamma_d$ using the experimental data of the time dependent flavor asymmetry of semi-leptonic B_d^0 decays as given in Ref. [8]. We perform a χ^2 fit to $A_{\rm mix}(\Delta t,\lambda)$, using the efficiency corrected distributions given in Table I of Ref. [8]. First, the fit is done by assuming no decoherence, i.e., $\lambda = 0$. In this case, we find $\Delta m_d = (0.489 \pm 0.010)$ ps^{-1} and $\Delta\Gamma_d = (0.087 \pm 0.054)$ ps^{-1} with $\chi^2/d.o.f = 8.42/9$. We then redo the fit including decoherence. This gives $\lambda = (-0.012 \pm 0.019)$ ps^{-1} along with $\Delta m_d = (0.490 \pm 0.010)$ ps^{-1} and $\Delta\Gamma_d = (0.144 \pm 0.088)$ ps^{-1} with $\chi^2/d.o.f = 8.02/8$. Thus we see that the decoherence parameter λ is very loosely bound. The upper limit on λ is 0.03 ps^{-1} at 95% C.L. We also find in this example that Δm_d is numerically unaffected where as $\Delta\Gamma_d$ can be affected by inclusion of decoherence. Given the wealth of data coming from LHCb and expected from the KEK Super B factory, a clear picture is expected to emerge.

6. Comments on approximations made

The decoherence is expected to emerge from a scale much finer than that of the flavor physics. Hence for an accurate determination, one should include all the known effects, such as CP violation in mixing and decay width $\Delta\Gamma_d$, which are usually neglected in the extraction of $\sin 2\beta$ and $\Delta\Gamma_d$.

In the determination of $\sin 2\beta$ one should also take into account the penguin contributions. The theoretical precision for the extraction of CP violating phase $\sin 2\beta$ from the CP asymmetry of $B_d^0 \to J/\psi K_S$ decay is limited by contributions from doubly Cabibbo-suppressed penguin topologies which cannot be calculated in a reliable way within QCD [11, 12]. However, $B_s^0 \to J/\psi K_S$ is related to $B_d^0 \to J/\psi K_S$ through U-spin symmetry of strong interactions and it offers a tool to control the penguin effects [13].

7. Decoherence in B_s systems

The present analysis can easily be extended to the B_s^0 system as well. The expression for the time dependent CP asymmetry in the mode $B_s^0 \to J/\psi\phi$ will be a function of four parameters: λ, $\sin 2\beta_s$, Δm_s and $\Delta\Gamma_s$. The time dependent mixing asymmetry defined in Eq. (4.2) will determine λ, Δm_s and $\Delta\Gamma_s$. These two time-dependent asymmetries should be re-analysed using a four parameter fit for a clean determination of $\sin 2\beta_s$, Δm_s, $\Delta\Gamma_s$ and λ. Also, like $\sin 2\beta_d$, the extraction of $\sin 2\beta_s$ from time dependent CP asymmetry in the mode $B_s^0 \to J/\psi\phi$ is restricted due to penguin pollution. The penguin contribution to $B_s^0 \to J/\psi\phi$ can be estimated using decays $B_d^0 \to J/\psi\rho$ and $B_s^0 \to J/\psi\bar{K}^*$ [11, 14].

8. Conclusions

We study the effect of decoherence on two important observables $\sin 2\beta$ and Δm_d in a neutral meson system. We find that the asymmetries which determine these quantities are also functions of the decoherence parameter λ. Hence it is imperative to measure λ for a clean determination of these quantities. We suggest a re-analysis of the data on the above asymmetries for an accurate measurement of all the three quantities λ, $\sin 2\beta$ and Δm_d. The present analysis can easily be extended to the B_s^0 system as well. Thus a detailed study of B^0 observables can lead to tests of physics at scales much higher than those typical of flavor physics.

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