Re-examining $\sin 2\beta$ and Δm_d from evolution of B_d^0 mesons with decoherence

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Plan of talk

1. Motivation
2. Determination of $\sin 2\beta$
3. Determination of Δm_d
4. An example of estimation of decoherence parameter
5. Conclusions

Based on the paper by
Ashutosh Kumar Alok, Subhashish Banerjee and S. Uma Sankar,
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Motivation

- The time evolution of neutral mesons are used to measure a number of important parameters in flavor physics.
- In the time evolution of neutral meson systems, 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.
- Hence with the inclusion of decoherence effects, the measured values of some of the parameters can get masked.

We study the effect of decoherence on the 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.

Decoherence

Decoherence is an unavoidable phenomenon as any physical system is inherently open due to its inescapable interactions with a pervasive environment.

Possible environment

- Environmental effects may arise at a fundamental level, such as the fluctuations in a quantum gravity space-time background.
- They may also arise due to the detector environment itself.

- The effect of environment on the neutral meson systems can be taken into account by using the ideas of open quantum systems.
- We use an effective desription which is phenomenological in nature. It is independent of the details of the actual dynamics between the system and environment.

Our phenomenological approach provides a universal framework for the study of quantum decoherence effects.

Open time evolution of B mesons

- 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: $\left|B^0\right\rangle$, $\left|\bar{B}^0\right\rangle$ 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 $\rho(t) = \sum_i K_i(t)\rho(0)K_i^\dagger(t)$.

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.

Open time evolution of B mesons

Time dependent density matrices

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

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

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

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

- We study the effect of decoherence on the 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.
- To keep expressions simple, CP violation in mixing is neglected.

Hermitian operator describing decay $B^0 \to f$ and $\bar{B}^0 \to f$

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

- $A_f \equiv A(B^0 \to f)$ and $\bar{A}_f \equiv A(\bar{B}^0 \to f)$.
- 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 $\mathrm{Tr}\left[\mathcal{O}_f \, \rho_{B^0(\bar{B}^0)(t)}\right]$.

CP asymmetry of $B_d^0 \to J/\psi K_S$ decay

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

$$= \frac{\left(|\lambda_f|^2 - 1\right)\cos(\Delta m_d t) + 2\mathrm{Im}(\lambda_f)\sin(\Delta m_d t)}{(1 + |\lambda_f|^2)\cosh\left(\frac{\Delta\Gamma_d t}{2}\right) - 2\mathrm{Re}(\lambda_f)\sinh\left(\frac{\Delta\Gamma_d t}{2}\right)} e^{-\lambda t}$$

- $\lambda_f = A(\bar{B}_d^0 \to J/\psi K_S))/A(B_d^0 \to J/\psi K_S)$.
- The standard expression for $\mathcal{A}_{J/\psi K_S}(t)$ is obtained by putting $\lambda = 0$.

With the approximations $\Delta\Gamma_d \approx 0$, $|\lambda_f| \approx 1$ and $\mathrm{Im}(\lambda_f) \approx \sin 2\beta$, we get

$$\mathcal{A}_{J/\psi K_S}(t) \approx \sin 2\beta\, e^{-\lambda t} \sin(\Delta m_d\, t)$$

The coefficient of $\sin(\Delta m_d\, t)$ is $\sin 2\beta\, e^{-\lambda t}$ and not $\sin 2\beta$!

The measurement of $\sin 2\beta$ is masked by the presence of decoherence.

Determination of Δm_d

In order to determine $\sin 2\beta$, we need to know Δm_d.

Is 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:

B_d^0 survival (oscillation) probability

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

The positive (negative) sign implies B_d^0 meson decaying with the same (opposite) flavor as its production.

Determination of Δm_d

Δm_d is determined from the following time dependent asymmetry:

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

At **BaBar** and **Belle**, Δm_d is determined by measuring the $B_d^0\bar{B}_d^0$ decay probability $P_+(\Delta t)$ and the $B_d^0 B_d^0/\bar{B}_d^0\bar{B}_d^0$ decay probability $P_-(\Delta t)$ for entangled neutral B_d meson pair produced by the decay of the $\Upsilon(4S)$ resonance.

The expressions for $P_\pm(\Delta t)$ are the same as those of $P_\pm(t)$, except that the proper time t is replaced by proper decay-time difference Δt between the decays of the two neutral B_d mesons.

Determination of Δm_d

Determination of Δm_d at LHCb, CDF, D0, Belle and BaBar experiments is 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 Δm_d, are also affected by the presence of decoherence.

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

We make an attempt to determine λ Δm_d and $\Delta\Gamma_d$ by performing a χ^2 fit to $A_{\rm mix}(\Delta t, \lambda)$, using the efficiency corrected distributions given by Belle Collaboration:

TABLE I. Time-dependent asymmetry in Δt bins, corrected for experimental effects, with statistical and systematic uncertainties. Contributions from event selection, background subtraction, wrong tag correction, and deconvolution are also shown.

				Systematic errors				
Δt bin	Window [ps]	A and total error	Statistical error	Total	Event sel.	Bkgd sub.	Wrong tags	Deconvolution
1	0.0–0.5	1.013 ± 0.028	0.020	0.019	0.005	0.006	0.010	0.014
2	0.5–1.0	0.916 ± 0.022	0.015	0.016	0.006	0.007	0.010	0.009
3	1.0–2.0	0.699 ± 0.038	0.029	0.024	0.013	0.005	0.009	0.017
4	2.0–3.0	0.339 ± 0.056	0.047	0.031	0.008	0.005	0.007	0.029
5	3.0–4.0	-0.136 ± 0.075	0.060	0.045	0.009	0.009	0.007	0.042
6	4.0–5.0	-0.634 ± 0.084	0.062	0.057	0.021	0.014	0.013	0.049
7	5.0–6.0	-0.961 ± 0.077	0.060	0.048	0.0120	0.017	0.012	0.038
8	6.0–7.0	-0.974 ± 0.080	0.060	0.053	0.034	0.025	0.020	0.025
9	7.0–9.0	-0.675 ± 0.109	0.092	0.058	0.041	0.027	0.022	0.022
10	9.0–13.0	0.089 ± 0.193	0.161	0.107	0.067	0.063	0.038	0.039
11	13.0–20.0	0.243 ± 0.435	0.240	0.363	0.145	0.226	0.080	0.231

Estimation of λ: An example

First, the fit is done by assuming no decoherence, i.e., $\lambda = 0$.
In this case, we find $\Delta m_d = (0.489 \pm 0.010)\ \mathrm{ps}^{-1}$ and $\Delta\Gamma_d = (0.087 \pm 0.054)\ \mathrm{ps}^{-1}$ with a $\chi^2/d.o.f. = 8.42/9$.

We then redo the fit including decoherence.
This gives $\lambda = (-0.012 \pm 0.019)\ \mathrm{ps}^{-1}$, $\Delta m_d = 0.490 \pm 0.010\ \mathrm{ps}^{-1}$ and $\Delta\Gamma_d = (0.144 \pm 0.088)\ \mathrm{ps}^{-1}$ with a $\chi^2/d.o.f. = 8.02/8$.

- Decoherence parameter λ is very loosely bounded.
- The upper limit on λ is $0.018\ \mathrm{ps}^{-1}$ at 90% C.L.
- Δm_d is numerically unaffected.

Given the wealth of data coming from LHCb and expected from the KEK Super B factory, a clear picture is expected to emerge.

Comment 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, which are usually neglected in the extraction of $\sin 2\beta$.

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.
However, $B_s^0 \to J/\psi K_S$ is related to $B_d^0 \to J/\psi K_S$ through the U-spin symmetry of strong interactions and it offers a tool to control the penguin effects.

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 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.

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 $B_s^0 \to J/\psi\bar{K}^*$.

Conclusions

- In this work, we have studied 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.


Thank You