EPR entanglement and decoherence in $\Upsilon(4S)$ decays to $B^0\bar{B}^0$

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The neutral B-meson pair produced at $\Upsilon(4S)$ exhibits a non-local EPR-type entanglement. At Belle experiment in KEK, we measure this entanglement using time-dependent flavour asymmetry of semileptonic B^0 decays and compare with the prediction of quantum mechanics and two local realistic models. We also measure the decoherence of the neutral B-meson pair in $B^0-\overline{B}^0$ and $B_H - B_L$ basis.

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1. Introduction

The advent of Quantum Mechanics (QM) in the 1930s has created many conceptual difficulties in our understanding of the fundamental reality of the physical world we live in. One of the difficulties was the concept of entangled states (i. e. states which cannot be represented as product states of their parts). In their 1935 paper, Einstein, Podolski, and Rosen (EPR) arrived at the conclusion that QM could not be a "complete" theory [1]. The conceptual problem is better understood considering the 1951 variant by David Bohm using spin correlations [2]. In the EPR-Bohm experiment the two-particle singlet state can be written as:

$$|\psi\rangle = \frac{1}{\sqrt{2}}[|\uparrow\rangle_1 \otimes |\downarrow\rangle_2 - |\downarrow\rangle_1 \otimes |\uparrow\rangle_2] \tag{1.1}$$

where $|\uparrow\rangle_j$ ($|\downarrow\rangle_j$) describes the spin state of j^{th} particle (j=1,2) with spin up (down) respectively. Measurement of the spin on one particle, undetermined prior to the measurement, will "collapse" the wave function to one of the eigenstates and therefore predicts with certainty the outcome of the spin measurement on the second particle without actually doing any measurement. The difficulty comes from the fact that the spin of the second particle in a given direction is defined by the choice of the polarizer orientation on the first particle. The orientation can be chosen at the "last moment", just prior to the arrival of the particle, and cannot be communicated to the second particle system unless superluminal signals are invoked. We should conclude that in a way or another the second particle carries the information needed to behave correctly for any possible choices of the measurement in the system of the first particle. Indeed, following EPR, one can define "elements of reality" for spin in S_x and S_y direction for the second particle, determined from the spin measurements done on the first particle. But according to QM the observables S_x and S_y do not commute and therefore cannot have definite values at the same time. This implies that the description of reality given by QM is incomplete and extra information, "hidden variables" (HV) are needed to complement QM. In 1964 J. S. Bell found a general scheme to test QM against HV theories: he showed that a certain inequality which is always satisfied by all local hidden variable models, can instead be violated by QM [3].

Several experiments have been performed, mostly applying a Bell test on the measurement of the polarization entanglement of low energy photons. High energy physics allow instead to probe the entanglement of massive particles. One previous experiment, CPLEAR, has measured the EPR entanglement of K^0-$\overline{K}^0$ pair produced in $\bar{p}p$ annihilation at rest where the strangeness is identified actively using copper and carbon regenerator [4]. The result is compared to the QM prediction and to the prediction when the two kaons are immediately separated into a K_L and a K_S [5] and found to be in good agreement with QM predictions while ruling out separability (Fig. 1).

Here we present a study of EPR correlation in the flavour of neutral B-meson pairs from $\Upsilon(4S)$ decays. The system is described by a wavefunction analogous to (1.1) [6, 7]:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left[|B^0\rangle_1 \otimes |\overline{B}^0\rangle_2 - |\overline{B}^0\rangle_1 \otimes |B^0\rangle_2\right]. \tag{1.2}$$

Decays occurring at the same proper time are fully anti-correlated: the flavour-specific decay of one meson fixes the (previously undetermined) flavour (B^0 or $\overline{B}^0$) of the other meson. From (1.2)

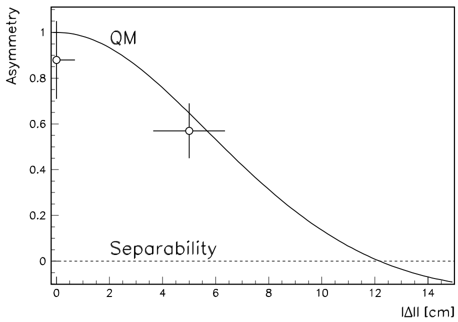

Figure 1: CPLEAR measurement of the K^0-$\overline{K}^0$ asymmetry compared to QM prediction and separability.

we deduce the time-dependent rate for decay into two flavour-specific states for opposite flavour (OF, $B^0\overline{B}^0$) and same flavour (SF, B^0B^0 or $\overline{B}^0\overline{B}^0$) decays:

$$R_{\substack{OF\\SF}} = e^{-\Delta t/\tau_{B^0}}/(4\tau_{B^0})\{1 \pm \cos(\Delta m_d \Delta t)\}, \quad (1.3)$$
$$(1.4)$$

and the corresponding time-dependent asymmetry:

$$A_{\mathrm{QM}}(\Delta t) \equiv \frac{R_{\mathrm{OF}} - R_{\mathrm{SF}}}{R_{\mathrm{OF}} + R_{\mathrm{SF}}} = \cos(\Delta m_d \Delta t) \quad (1.5)$$

$\Delta t \equiv |t_1 - t_2|$ is the proper-time difference of the decays, and Δm_d the mass difference between the two B^0-$\overline{B}^0$ mass eigenstates. The fact that the asymmetry depends only on Δt, and not on the absolute time, t_1 and/or t_2, is a manifestation of EPR-type entanglement at a distance.

Ideally, to be able to reject *all* local HV models, a Bell test should be performed. An early attempt in this direction [8] was found deficient [9, 10]. In general Bell tests are unaccessible due to the rapid decrease in time of the B-meson amplitudes, and the passive character of the flavour measurement. Therefore we limit ourselves to verify that QM reproduces the experimental asymmetry and that no other "reasonable" HV-based model can reproduce both the B^0-$\overline{B}^0$ oscillation behaviour for each meson and the experimental asymmetry. We compare our results with the predictions of QM and two other models.

In the local realistic model by Pompili and Selleri (PS) [11], each B has flavour and mass information simultaneously. There are thus four basic states: B^0_H, B^0_L, $\overline{B}^0_H$, $\overline{B}^0_L$. The model imposes flavour anti-correlations at equal times $\Delta t = 0$ but allow random simultaneous jumps in flavour within the pair. The model is also required to reproduce the QM predictions for uncorrelated B-decays. The result is an upper and a lower bound for the asymmetry,

$$\mathrm{A}^{\max}_{\mathrm{PS}}(t_1,t_2) = 1 - |\{1-\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{\min}) + \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{\min})|, \quad (1.6)$$
$$\mathrm{A}^{\min}_{\mathrm{PS}}(t_1,t_2) = 1 - \min(2+\Psi, 2-\Psi), \text{ where} \quad (1.7)$$
$$\Psi = \{1+\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{\min}) - \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{\min}). \quad (1.8)$$

Note the additional $t_{\min} = \min(t_1,t_2)$ dependence, which can be removed by integrating the OF and SF functions for fixed values of Δt. We obtain the curves $\mathrm{PS}_{\max}$ and $\mathrm{PS}_{\min}$ shown in Fig. 2.

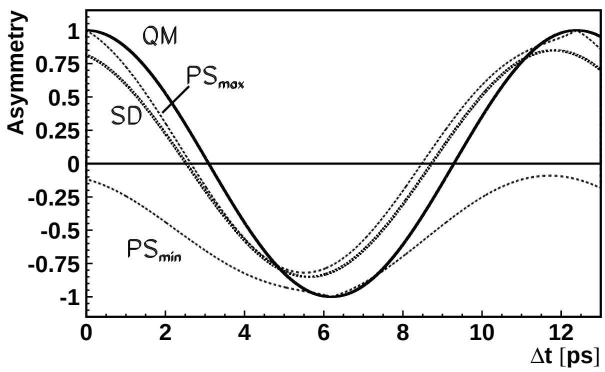

Figure 2: Time-dependent asymmetry predicted by (QM) quantum mechanics and (SD) spontaneous and immediate disentanglement of the B-pair, and (PS_{min} to PS_{max}) the range of asymmetries allowed by the Pompili and Selleri model. $\Delta m_d = 0.507\,\mathrm{ps}^{-1}$ is assumed.

In the Spontaneous and immediate Disentanglement model (SD), the B-meson pair separates into a B^0 and a $\overline{B}^0$ with well-defined flavour immediately after the $\Upsilon(4S)$ decay, which then evolve independently [5], and the asymmetry becomes

$$A_{\mathrm{SD}}(t_1,t_2) = \cos(\Delta m_d t_1)\cos(\Delta m_d t_2) = \frac{1}{2}[\cos(\Delta m_d(t_1+t_2)) + \cos(\Delta m_d \Delta t)], \tag{1.9}$$

depending on $t_1 + t_2$ in addition to Δt. After integration we obtain the curve SD of Fig. 2.

2. Data analysis

152×10^6 $B\overline{B}$ pairs collected by the Belle detector at the $\Upsilon(4S)$ resonance at the KEKB asymmetric-energy (3.5 GeV on 8.0 GeV) e^+e^- collider [12], by the Belle detector [13] were used to determine the asymmetry. The $\Upsilon(4S)$ is produced with $\beta\gamma = 0.425$ close to the z axis. As the B momentum is low in the $\Upsilon(4S)$ center-of-mass system (CMS), Δt can be determined from the z-displacement of B-decay vertices: $\Delta t \approx \Delta z/\beta\gamma c$.

The event selection for this study (see Ref. [14] for details) was optimized for theoretical model discrimination. The flavour of one neutral B was obtained by reconstructing the decay $B^0 \to D^{*-}\ell^+\nu$, with $D^{*-} \to \overline{D}^0\pi_s^-$ and $\overline{D}^0 \to K^+\pi^-(\pi^0)$ or $K^+\pi^-\pi^+\pi^-$ (charge-conjugate modes are included throughout this paper). The D^0 candidates must have a reconstructed mass compatible with the known value. A D^* is formed by constraining a D^0 and a slow pion to a common vertex. We require a mass difference $M_{\mathrm{diff}} = M_{K n\pi\pi_s} - M_{K n\pi} \in [144.4, 146.4]$ MeV$/c^2$, and CMS momentum $p^*_{D^*} < 2.6$ GeV$/c$, consistent with B-decay. We require that the CMS angle between the D^* and lepton be greater than 90°. From the relation $M_\nu^2 = (E_B^* - E_{D^*\ell}^*)^2 - |\vec{p}_B^{\,*}|^2 - |\vec{p}_{D^*\ell}^{\,*}|^2 + 2|\vec{p}_B^{\,*}||\vec{p}_{D^*\ell}^{\,*}|\cos(\theta_{B,D^*\ell})$, where $\theta_{B,D^*\ell}$ is the angle between $\vec{p}_B^{\,*}$ and $\vec{p}_{D^*\ell}^{\,*}$, we can reconstruct $\cos(\theta_{B,D^*\ell})$ by assuming a vanishing neutrino mass. We require $|\cos(\theta_{B,D^*\ell})| < 1.1$. The neutral B decay position is determined by fitting the lepton track and D^0 trajectory to a vertex, constrained to lie in the e^+e^- interaction region. The remaining tracks are used to determine the second B decay vertex and flavour [15].

Table 1: Time-dependent asymmetry in Δt bins, corrected for experimental effects, with total uncertainties.

bin	window [ps]	A and total error	bin	window [ps]	A and total error
1	0.0 – 0.5	1.013 ± 0.028	7	5.0 – 6.0	-0.961 ± 0.077
2	0.5 – 1.0	0.916 ± 0.022	8	6.0 – 7.0	-0.974 ± 0.080
3	1.0 – 2.0	0.699 ± 0.038	9	7.0 – 9.0	-0.675 ± 0.109
4	2.0 – 3.0	0.339 ± 0.056	10	9.0 – 13.0	0.089 ± 0.193
5	3.0 – 4.0	-0.136 ± 0.075	11	13.0 – 20.0	0.243 ± 0.435
6	4.0 – 5.0	-0.634 ± 0.084			

In total 8565 events are selected (6718 OF, 1847 SF). To compensate for the rapid fall in event rate with Δt, the time-dependent distributions are histogrammed in 11 variable-size bins (see Table 1). Background subtraction is then performed bin-by-bin; systematic errors are likewise determined by estimating variations in the OF and SF distributions, and calculating the effect on the asymmetry.

A GEANT-based Monte Carlo (MC) sample was analyzed with identical criteria, and used for consistency checks, background estimates and subtraction, and to build deconvolution matrices.

Four types of background events have been considered: $e^+e^- \to q\bar{q}$ continuum, fake D^*, wrong D^*–lepton combinations, and $B^+ \to \overline{D}^{**0}\ell\nu$ events. Off-resonance data (8.3 fb^{-1}) were used to estimate the continuum background, which was found to be negligible. Fake D^0 reconstruction and misassigned slow pions producing a fake D^* background were estimated from the sideband in $M_{\rm diff}$. The contamination from wrong D^*–lepton combinations was estimated from reversing the lepton momentum and the validity of which was confirmed by MC studies. A fit of the $\cos(\theta_{B,D^*\ell})$ distribution allows the extraction of the D^{**-} component. The MC is then used to compute the fraction from charged B mesons which must be subtracted (as it has no mixing).

Remaining experimental effects (e.g. resolution in Δt, selection efficiency) are corrected by a deconvolution procedure [16]. 11×11 response matrices are built separately for SF and OF events, using MC $D^*\ell\nu$ events indexed by generated and reconstructed Δt values. The procedure has been optimised, and its associated systematic errors inferred by a toy Monte Carlo where sets of several hundred simulated experiments are generated assuming the three theoretical models. We test the consistency of the method applied to our data by fitting the B^0 decay time distribution (summing OF and SF samples), leaving the B^0 lifetime as a free parameter. We obtain 1.532 ± 0.017(stat) ps, consistent with the world average [17]. We have also repeated the deconvolution procedure using a subset of events with better vertex fit quality, and hence more precise Δt values: consistent results are obtained. The final results are shown in Table 1 and Fig. 3.

3. Comparison with the theoretical models

The model testing is done by a least-square fit to $A(\Delta t)$, leaving Δm_d free, but taking the world-average Δm_d into account. To avoid bias, we discard BaBar and Belle measurements, which assume QM correlations: this yields [18] $\langle \Delta m_d \rangle = (0.496 \pm 0.014)\,\mathrm{ps}^{-1}$. Our data is in agreement with the prediction of QM: we obtain $\Delta m_d = 0.501 \pm 0.009$ ps^{-1} with $\chi^2 = 5.2$ for 11 dof (see Fig. 3). SD

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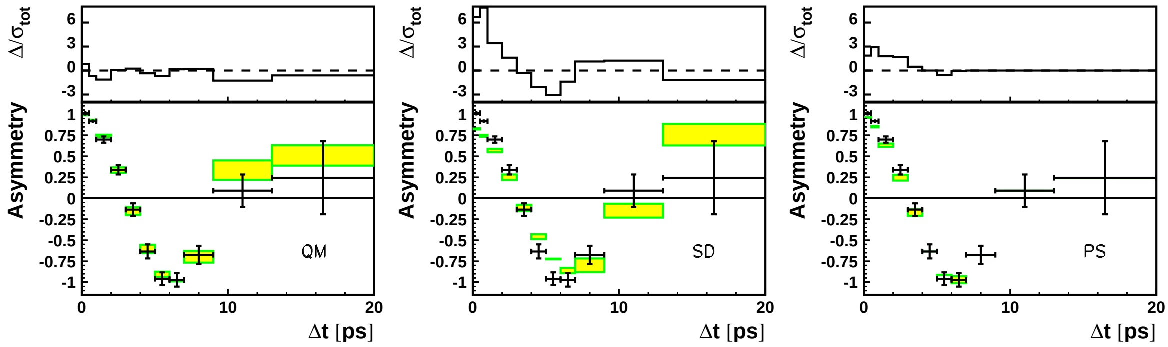

Figure 3: Bottom: time-dependent flavour asymmetry (crosses) and the results of weighted least-squares fits to the (left to right) QM, SD, and PS models (rectangles, showing $\pm 1\sigma$ errors on Δm_d). Top: differences $\Delta \equiv A_{\rm data} - A_{\rm model}$ in each bin, divided by the total experimental error $\sigma_{\rm tot}$. Bins where $\rm A_{PS}^{min} < A_{\rm data} < A_{PS}^{max}$ have been assigned a null deviation: see the text.

is rejected by $\chi^2 = 174$ ($\Delta m_d = 0.419 \pm 0.008$). To fit PS we have used the closest boundary to our data $\rm A_{PS}^{max}$, Eq. (1.6), or $\rm A_{PS}^{min}$, Eq. (1.7), but assumed a null deviation for data falling inside the boundaries. We obtain $\chi^2 = 31.3$ ($\Delta m_d = 0.447 \pm 0.010$ ps^{-1}): the data favour QM over PS at the 5.1σ level.

4. Decoherence

Assuming QM as the correct model, we consider hypothetical effects which can disturb the propagation of the entangled wave function and can affect the time-dependent asymmetry [19]. Bertlmann et.al. have fitted CPLEAR data to obtain decoherence into $K^0\ \overline{K}^0$: $\zeta_{\rm K^0\overline{K}^0}$=0.4 $\pm$ 0.7 and into K_LK_S: $\zeta_{\rm K_LK_S}$=0.13$^{+0.16}_{-0.15}$ [20, 21]. KLOE experiment has improved these measurements by comparing time-dependent K_SK_S and K_LK_S rates from ϕ decay with the result $\zeta_{\rm K_LK_S}$=0.018 $\pm$ 0.040$_{stat}$ $\pm$ 0.007$_{syst}$ and $\zeta_{\rm K^0\overline{K}^0}$=0.10 $\pm$ 0.21$_{stat}$ $\pm$ 0.04$_{syst}$ [22].

For the B^0 system, a time-integrated decoherence has been calculated from CLEO and ARGUS data to be $\zeta_{\rm B^0\overline{B}^0} = -0.41 \pm 0.31$ [23]. Another suitable parameterisations of the asymmetry for disentanglement in the flavour and mass bases are

$$A = (1-\zeta_{\rm B^0\overline{B}^0})A_{\rm QM} + \zeta_{\rm B^0\overline{B}^0}A_{\rm SD}, \text{ and} \tag{4.1}$$

$$A = (1-\zeta_{\rm B_HB_L})A_{\rm QM} \tag{4.2}$$

respectively. In a simplified approach which assumes immediate partial disentanglement into flavour or mass eigenstates, the ζ parameters correspond to the fraction of decoherent B-pairs. (Eq. (4.2) corresponds to formula 3.5 in Ref. [20], for $\Delta\Gamma = 0$). We examine this possibility of a partial loss of coherence just after the decay of the $\Upsilon(4S)$ resonance. The fraction of events with disentangled B^0 and a $\overline{B}^0$ can be estimated by fitting our asymmetry with the mixture of Eq. (4.1), leaving $\zeta_{\rm B^0\overline{B}^0}$ free. The fit finds $\zeta_{\rm B^0\overline{B}^0} = 0.029 \pm 0.057$, consistent with no decoherence. The second possibility considered is a decoherence into mass eigenstate, for which we expect a reduction in the amplitude of $A(\Delta t)$, as given by Eq. (4.2). The result of a fit gives a value of $\zeta_{\mathrm{B_H B_L}} = 0.004 \pm 0.017$ [24], also compatible with zero.

5. Conclusion

We have analysed neutral B pairs produced by $\Upsilon(4S)$ decay, determined the time-dependent asymmetry due to flavour mixing, and corrected for experimental effects by deconvolution: the results can be directly compared to theoretical models. We have compared our data to the QM hypothesis and to two other models. The local realistic model of Pompili and Selleri is strongly disfavoured compared to the entanglement predicted by QM. Immediate disentanglement, in which definite-flavour B^0 and $\overline{B}^0$ evolve independently, is ruled out. We have also found that our data is consistent with a null fraction of events with a loss of entanglement.

References

[1] A. Einstein, B. Podolski and N. Rosen, Phys. Rev. **47**, 777 (1935).

[2] D. Bohm, *Quantum Theory* (Prentice Hall, Englewood Cliffs, NJ, 1951), pp. 614-622.

[3] J. S. Bell, Physics **1**, 195 (1964).

[4] A. Apostolakis *et al.* (CPLEAR Collaboration), Phys. Lett. B **422**, 339 (1998).

[5] W. H. Furry, Phys. Rev. **49**, 393 (1936).

[6] A. Datta, and D. Home, Phys. Lett. A **119**, 3 (1986).

[7] N. Gisin and A. Go, Am. J. Phys. **69** (3), 264 (2001).

[8] A. Go, in *Proceedings of Garda Conference, 2003*, [Journal of Modern Optics **51**, 991 (2004)].

[9] R. A. Bertlmann, A. Bramon, G. Garbarino, and B. C. Hiesmayr, Phys. Lett. A **332**, 355 (2004).

[10] A. Bramon, R. Escribano, and G. Garbarino, J. Mod. Opt. **52**, 1681 (2005)

[11] A. Pompili and F. Selleri, Eur. Phys. J. C **14**, 469 (2000);

[12] S. Kurokawa and E. Kikutani, Nucl. Instr. Meth. A **499** 1 (2003), and other papers in this volume.

[13] A. Abashian *et al.* (Belle Collaboration), Nucl. Instr. Meth. A **479**, 117 (2002).

[14] A. Go, A. Bay, *et al.* (Belle Collaboration), Phys. Rev. Lett. **99**, 131802 (2007), and references within.

[15] K. Abe *et al.* (Belle Collaboration), Phys. Rev. Lett. **87**, 091802 (2001); Phys. Rev. D **66**, 32007 (2002); H. Kakuno *et al.*, Nucl. Instr. Meth. A **533**, 516 (2004).

[16] A. Höcker and V. Kartvelishvili, Nucl. Instr. Meth. A **372**, 469 (1996).

[17] W. -M. Yao *et al.*, Particle Data Group, J. Phys. G **33**, 1 (2006).

[18] E. Barberio *et al.* (Heavy Flavour Averaging Group), hep-ex/0603003 (2006).

[19] R. Omnès, Rev. Mod. Phys **64**, 339 (1992).

[20] R.A. Bertlmann, W. Grimus, and B. C. Hiesmayr, Phys. Rev. D **60**, 114032 (1999).

[21] R. A. Bertlmann, W. Grimus, Phys. Rev. D **64**, 056004 (2004), and references within.

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[22] F. Ambrosino *et al.* (KLOE Collaboration), Phys. Lett. B **642**, 315 (2006).

[23] G.V. Dass, K.V.L. Sarma, Europhy. J. **C5**, 283 (1998).

[24] A. Bay, "Measurement of EPR-Type flavour entanglement in $\Upsilon(4S) \rightarrow B^0\,\overline{B}^0$ decays", Rencontre de Moriond Electro-Weak proceeding (2007).