Measurement of EPR-type flavour entanglement in $\Upsilon(4S) \to B^0\overline{B}^0$ decays

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The neutral B-meson pair produced at the $\Upsilon(4S)$ should exhibit a non-local correlation of the type discussed by Einstein, Podolski, and Rosen. The time-dependent flavour asymmetry of the B mesons decaying into flavour eigenstates will be used to test such a correlation. The asymmetry obtained from semileptonic B^0 decays is in agreement with the prediction from quantum mechanics and far away from the predictions of local realism models. We also test for possible partial decoherence effects. Our results are consistent with no decoherence.

1 Introduction

The concept of entangled states (i. e. states which cannot be represented as product states of their parts) was born in the '30 in the midst of several conceptual difficulties with Quantum Mechanics (QM). In 1935 Einstein, Podolski, and Rosen (EPR) arrived at the conclusion that QM could not be a "complete" theory [1]. EPR considered a pair of particles produced by the same interaction, subsequently freely propagating in space but still linked by momentum conservation. EPR found a contradiction when realism and locality are applied to the predictions of QM on a couple of non-commuting observables (position and momentum, in their paper). 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:

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

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 important point is 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. EPR-Bohm then concludes that the description of reality given by QM is incomplete. This points to the need of extra information, "hidden variables" (HV) for instance, 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 trying to apply a Bell test on the measurement of the polarization of low energy photons. In the domain of high energy physics, CPLear and KLOE have studied correlations in K^0-$\overline{K}^0$ pairs, and obtained results in agreement with QM predictions [4,5]. In this paper 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) [6,7]:

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

Decays occurring at the same proper time are fully correlated: the flavour-specific decay of one meson fixes the (previously undetermined) flavour (B^0 or $\overline{B}^0$) of the other meson. From (2) 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, and the corresponding time-dependent asymmetry:

$$R_{\substack{OF\\SF}} = e^{-\Delta t/\tau_{B^0}}/(4\tau_{B^0})\{1 \pm \cos(\Delta m_d \Delta t)\}, \tag{3}$$

$$A_{\rm QM}(\Delta t) \equiv \frac{R_{\rm OF} - R_{\rm SF}}{R_{\rm OF} + R_{\rm SF}} = \cos(\Delta m_d \Delta t) \tag{4}$$

$\Delta t \equiv |t_1 - t_2|$ is the proper-time difference of the decays, and Δm_d the mass difference between the two B^0-$\overline{B}^0$ mass eigenstates. We have assumed a lifetime difference $\Delta\Gamma_d = 0$ and neglected the $O(10^{-4})$ effects of CP violation in mixing. 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. It must be noticed that experimentally it is very difficult to measure the absolute times t_1 and t_2, hence only Δt is available.

To be able to reject HV models, ideally a Bell test should be performed. An early attempt in this direction [8] was found incorrect [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. *Ultima ratio*, to probe the non-local behaviour of the B^0 pair we can pragmatically limit ourselves to verify that, first, QM reproduces the experimental asymmetry, and, second, this is not the case for any other "reasonable" HV-based model. Within the definition of "reasonable" we include the capability to reproduce the B^0-$\overline{B}^0$ oscillation behaviour for each boson taken individually, after the $\Upsilon(4S)$ decay. In conclusion, we have chosen to compare our results with the predictions of QM and two other models. We stress the fact that to keep open the possibility of testing more models we also provide a fully corrected experimental time-dependent asymmetry, i. e. the background is subtracted and the detector effects corrected by deconvolution.

In the local realistic model by Pompili and Selleri (PS) [11], each B transports flavour information (B^0 or $\overline{B}^0$), and mass (corresponding to the heavy and light B_H, B_L eigenstates). There are

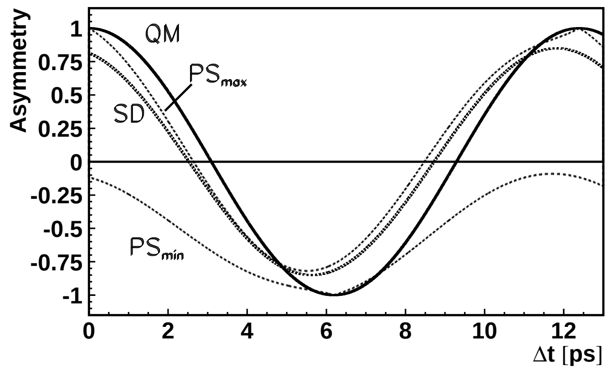

Figure 1: Time-dependent asymmetry predicted by (QM) quantum mechanics and (SD) spontaneous and immediate disentanglement of the B-pair, and (PS_{min} to PS_{max}) the range of asymmetries allowed by the Pompili and Selleri model. $\Delta m_d = 0.507\,\mathrm{ps}^{-1}$ is assumed.

thus four basic states: B^0_H, B^0_L, $\overline{B}^0_H$, $\overline{B}^0_L$. The model imposes mass and flavour anti-correlations at equal times $\Delta t = 0$; mass values are stable, but the system is programmed to allow random simultaneous jumps in flavour within the pair. The model is also required to reproduce the QM predictions for uncorrelated B-decays. No other assumptions are made: the result is an upper and a lower bound for the asymmetry,

$$\mathrm{A}^{\mathrm{max}}_{\mathrm{PS}}(t_1,t_2) = 1 - |\{1-\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{\mathrm{min}}) + \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{\mathrm{min}})|, \quad (5)$$

$$\mathrm{A}^{\mathrm{min}}_{\mathrm{PS}}(t_1,t_2) = 1 - \min(2+\Psi,\, 2-\Psi), \quad \text{where} \quad (6)$$

$$\Psi = \{1+\cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{\mathrm{min}}) - \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{\mathrm{min}}). \quad (7)$$

Note the additional $t_{\mathrm{min}} = \min(t_1, t_2)$ dependence, which can be removed by integrating the OF and SF functions for fixed values of Δt. We obtain the curves $\mathrm{PS}_{\mathrm{max}}$ and $\mathrm{PS}_{\mathrm{min}}$ shown in Fig. 1.

In the Spontaneous and immediate Disentanglement model (SD), the B-meson pair separates into a B^0 and $\overline{B}^0$ with well-defined flavour immediately after the $\Upsilon(4S)$ decay, which then evolve independently [12], and the asymmetry becomes

$$A_{\mathrm{SD}}(t_1,t_2) = \cos(\Delta m_d t_1)\cos(\Delta m_d t_2) = \frac{1}{2}[\cos(\Delta m_d (t_1+t_2)) + \cos(\Delta m_d \Delta t)], \quad (8)$$

depending on $t_1 + t_2$ in addition to Δt. After integration we obtain the curve SD of Fig. 1.

Finally, assuming QM as the correct model, we can consider hypothetical effects which can disturb the propagation of the entangled wave function [13,14], and affect the time-dependent asymmetry. Suitable parameterisations of the asymmetry for disentanglement in the flavour and mass bases are

$$A = (1-\zeta_{\mathrm{B^0\overline{B}^0}})A_{\mathrm{QM}} + \zeta_{\mathrm{B^0\overline{B}^0}}A_{\mathrm{SD}}, \quad \text{and} \quad (9)$$

$$A = (1-\zeta_{\mathrm{B_H B_L}})A_{\mathrm{QM}} \quad (10)$$

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. (10) corresponds to formula 3.5 in Ref. [5], for $\Delta\Gamma = 0$).

2 Data analysis

To determine the asymmetry we use 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 [15], by

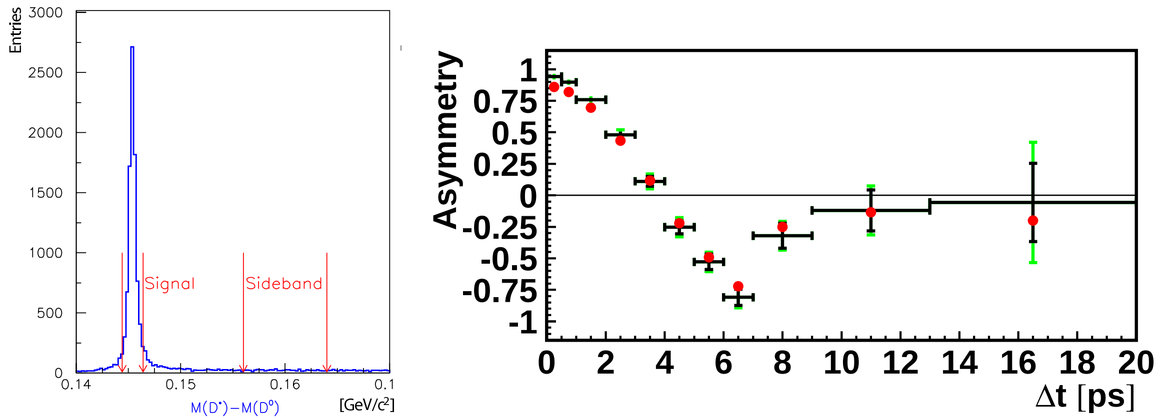

Figure 2: Left: M_{diff} distribution. Right: asymmetries before (red dots) and after (crosses) the corrections for the background and wrong flavour events. Statistical (black) and total errors (green) are superimposed.

the Belle detector [16]. 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 Belle vertex detector provides Δz with a precision of about 100 μm.

The event selection for this study (see Ref. [17] 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 $M_{\rm diff} = M_{Kn\pi\pi_s} - M_{Kn\pi} \in [144.4, 146.4]$ MeV/c^2 (Fig. 2, left), 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 [18].

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). The raw asymmetry is shown in Fig. 2, right. 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 analysed 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 $M_{\rm diff}$ (Fig. 2, left). The contamination from wrong D^*–lepton combinations was obtained by a reverse lepton momentum method, 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).

After correction for wrong flavour assignments (an event fraction of 0.015 ± 0.005) using OF and SF distributions from wrongly-tagged MC events, we obtain the time-dependent asymmetry

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			

shown in Fig. 2, right.

Remaining experimental effects (e.g. resolution in Δt, selection efficiency) are corrected by a deconvolution procedure [19]. 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 [20]. 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.

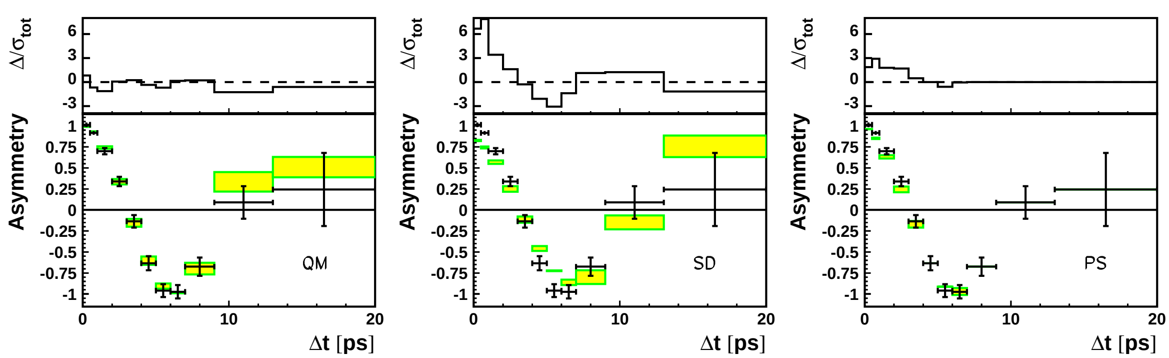

Figure 3: Bottom: time-dependent flavour asymmetry (crosses) and the results of weighted least-squares fits to the (left to right) QM, SD, and PS models (rectangles, showing $\pm 1\sigma$ errors on Δm_d). Top: differences $\Delta \equiv A_{\rm data} - A_{\rm model}$ in each bin, divided by the total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

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 [21] $\langle \Delta m_d \rangle = (0.496 \pm 0.014)\,\mathrm{ps}^{-1}$. 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 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 $\mathrm{A}_{\rm PS}^{\rm max}$, Eq. (5), or $\mathrm{A}_{\rm PS}^{\rm min}$, Eq. (6), 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.

We have examined the 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. (9), leaving $\zeta_{\mathrm{B^0\overline{B}^0}}$ free. The fit finds $\zeta_{\mathrm{B^0\overline{B}^0}} = 0.029 \pm 0.057$, 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. (10). The result of a fit gives a value of $\zeta_{\mathrm{B_H B_L}} = 0.004 \pm 0.017$ (preliminary), also compatible with zero.

4 Conclusion

We have analysed neutral B pairs produced by $\Upsilon(4S)$ decay, determined the time-dependent asymmetry due to flavour oscillations, and corrected for experimental effects by deconvolution: the results can be directly compared to theoretical models. Given the fact that there is little hope to perform a Bell test in the neutral B system, 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.

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