Measurement of Einstein-Podolsky-Rosen-Type Flavor Entanglement in $\Upsilon(4S) \to B^0 \bar{B}^0$ Decays

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The neutral B meson pair produced at the $\Upsilon(4S)$ should exhibit a nonlocal correlation of the type discussed by Einstein, Podolsky, and Rosen. We measure this correlation using the time-dependent flavor asymmetry of semileptonic B^0 decays, which we compare with predictions from quantum mechanics and two local realistic models. The data are consistent with quantum mechanics, and inconsistent with the other models. Assuming that some B pairs disentangle to produce B^0 and $\bar{B}^0$ with definite flavor, we find a decoherent fraction of 0.029 ± 0.057, consistent with no decoherence.

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The concept of entangled states, which cannot be described as product states of their parts, was born with quantum mechanics (QM). In 1935 Einstein, Podolsky, and Rosen (EPR) considered such a pair of particles and concluded that QM cannot be a "complete" theory [1]; this suggests that additional ("hidden") variables are required. In 1964 J. S. Bell showed that QM can violate a certain inequality, which is (by contrast) satisfied by all local hidden-variable models [2]. Many experiments have since been performed and found excellent agreement with the prediction of QM (although no "loophole"-free Bell test has yet been performed) [3]. Most of these studies have used pairs of optical photons; it is also interesting to test EPR correlations in massive systems [4] at much higher energies [5]. In this Letter, we present a study of EPR correlation in the flavor of B-meson pairs produced at the $\Upsilon(4S)$. Contrary to the analysis presented in [6], and as discussed in the literature [7], a Bell inequality test cannot be performed in this system due to the rapid decrease in time of the B-meson amplitudes, and the passive character of the flavor measurement, via reconstruction of B-meson decay products. Instead, we compare the data with predictions from QM and other models. Related studies have been performed in the K-meson system [8,9] to test decoherence [10] effects; $\Upsilon(4S) \to B^0\bar{B}^0$ data have also been analyzed, but using time-integrated information only [11]. Here, we use information on reconstructed B-meson decay times to test both decoherence and the Pompili-Selleri model [12], which represents a range of possible local hidden-variable theories [13].

The wave function of a $B^0\bar{B}^0$ pair from $\Upsilon(4S)$ decay is analogous to that of photons in a spin-singlet state [14,15]:

$$|\psi\rangle = \frac{1}{\sqrt{2}}[|B^0\rangle_1 \otimes |\bar{B}^0\rangle_2 - |\bar{B}^0\rangle_1 \otimes |B^0\rangle_2]. \quad (1)$$

Decays occurring at the same proper time are fully correlated: the flavor-specific decay of one meson fixes the (previously undetermined) flavor $B^0/\bar{B}^0$ of the other meson. Given (1), the time-dependent rate for decay into two flavor-specific states $R_i = e^{-\Delta t/\tau_{B^0}}/(4\tau_{B^0}) \times \{1 \pm \cos(\Delta m_d \Delta t)\}$ for opposite flavor ($B^0\bar{B}^0$; $+$, $i =$ OF) and same flavor (B^0B^0 or $\bar{B}^0\bar{B}^0$; $-$, $i =$ SF) decays. $\Delta t \equiv |t_1 - t_2|$ is the proper-time difference of the decays, and Δm_d the mass difference between the two $B^0 - \bar{B}^0$ mass eigenstates. We have assumed a lifetime difference $\Delta\Gamma_d = 0$ and neglected the effects of CP violation in mixing, which are $O(10^{-4})$ or less.

Thus in QM the time-dependent asymmetry $A(\Delta t) \equiv (R_{OF} - R_{SF})/(R_{OF} + R_{SF}) = \cos(\Delta m_d \Delta t)$, is a function of Δt but not the individual times $t_{1,2}$. This is a manifestation of entanglement. By contrast, we can consider spontaneous disentanglement (SD), an extreme case of decoherence, in which the B-meson pair immediately separates into a B^0 and $\bar{B}^0$ with well-defined flavor, which then evolve independently [16]. The asymmetry becomes

$$\begin{aligned} A_{SD}(t_1, t_2) &= \cos(\Delta m_d t_1)\cos(\Delta m_d t_2) \\ &= \tfrac{1}{2}[\cos(\Delta m_d(t_1 + t_2)) + \cos(\Delta m_d \Delta t)], \end{aligned} \quad (2)$$

depending on $t_1 + t_2$ in addition to Δt. Because of the large

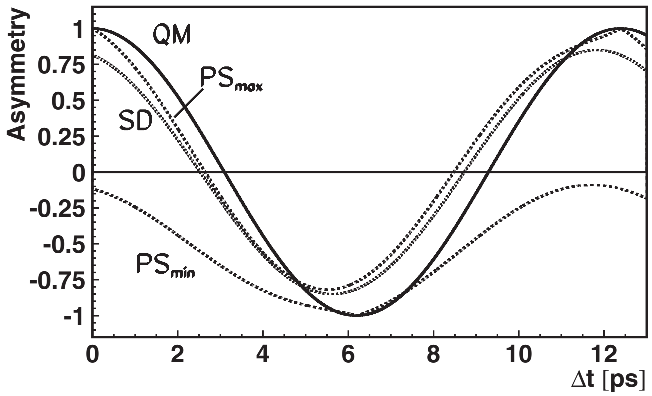

FIG. 1. Time-dependent asymmetry predicted by (QM) quantum mechanics and (SD) spontaneous and immediate disentanglement of the B pair [10,16] and (PS_{min} to PS_{max}) the range of asymmetries allowed by the Pompili-Selleri model [12]. $\Delta m_d = 0.507\ \mathrm{ps}^{-1}$ is assumed [24].

uncertainty on the $\Upsilon(4S)$ decay point, it is difficult to measure individual decay times $t_{1,2}$: only Δt is measured in this analysis. If we first integrate the OF and SF distributions keeping Δt constant we obtain the asymmetry curve shown in Fig. 1, which differs significantly from the simple cosine term due to QM (also shown).

In the model of Pompili and Selleri (PS) [12], each B has well-defined flavor, B^0 or $\bar{B}^0$, and mass, corresponding to the heavy and light $B^0 - \bar{B}^0$ eigenstates. There are thus four basic states: B_H^0, B_L^0, $\bar{B}_H^0$, $\bar{B}_L^0$. At equal times $\Delta t = 0$, the B mesons in a pair have opposite values of both mass and flavor; mass values are stable, but the flavor can change, simultaneously for the two mesons. There are no other assumptions, except a requirement that QM predictions for uncorrelated B decays are reproduced. This rather general scheme includes a range of possible local realistic models, and allows time-dependent asymmetries to lie within the bounds

$$A_{\rm PS}^{\rm max}(t_1, t_2) = 1 - |\{1 - \cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{\rm min}) + \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{\rm min})|, \quad (3)$$

and

$$A_{\rm PS}^{\rm min}(t_1, t_2) = 1 - \min(2 + \Psi, 2 - \Psi), \quad (4)$$

where

$$\Psi = \{1 + \cos(\Delta m_d \Delta t)\}\cos(\Delta m_d t_{\rm min}) - \sin(\Delta m_d \Delta t)\sin(\Delta m_d t_{\rm min}). \quad (5)$$

Note the additional $t_{\rm min} = \min(t_1, t_2)$ dependence. After integration for fixed values of Δt we obtain the asymmetry curves PS_{max} and PS_{min} shown in Fig. 1.

To determine the asymmetry, we use $152 \times 10^6 B\bar{B}$ 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 [17]. The Belle detector [18] is a large-solid-angle spectrometer consisting of a silicon vertex detector (SVD), central drift chamber (CDC), aerogel Cherenkov counters (ACC), time-of-flight counters (TOF), and a CsI(Tl) electromagnetic calorimeter (ECL) inside a 1.5 T superconducting solenoid. The flux return is instrumented to detect K_L^0 and identify muons (KLM). The $\Upsilon(4S)$ is produced with $\beta\gamma = 0.425$ close to the z axis (defined as antiparallel to the positron beam line). 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: $\Delta t \approx \Delta z/\beta\gamma c$.

We use an event selection similar to that of a previous Belle analysis [19,20], but optimized for theoretical model discrimination; in particular, we use more stringent criteria on the flavor tag purity than the previous analysis. To enable direct comparison of the result with different models, we subtract both background and mistagged-flavor events from the data, and then correct for detector effects by deconvolution.

We determine the flavor of one neutral B by reconstructing the decay $B^0 \to D^{*-} l^+ \nu$, with $D^{*-} \to \bar{D}^0 \pi_s^-$ and $\bar{D}^0 \to K^+\pi^-(\pi^0)$ or $K^+\pi^-\pi^+\pi^-$ (charge-conjugate modes are included throughout this Letter). Charged particles (except the "slow pion" π_s) are chosen from tracks with associated SVD hits and radial impact parameter $dr < 0.2$ cm, and required to satisfy kaon or pion identification criteria using combined TOF, ACC, and CDC (dE/dx) information [21]. $\pi^0 \to \gamma\gamma$ candidates are selected with $|M_{\gamma\gamma} - m_{\pi^0}| < 11\ \mathrm{MeV}/c^2$ and momenta $p_{\pi^0} > 0.2\ \mathrm{GeV}/c$; the photons must have energies $E_\gamma > 80$ MeV. We select D^0 candidates with $(M_{Kn\pi} - m_{D^0}) \in [-13, 13]\ \mathrm{MeV}/c^2$ for $K\pi(\pi\pi)$ and $[-37, 23]\ \mathrm{MeV}/c^2$ for $K\pi\pi^0$. A D^* candidate is formed by constraining a D^0 and slow pion (having opposite charge to the lepton) to a common vertex. We require a mass difference $M_{\rm diff} = M_{Kn\pi\pi_s} - M_{Kn\pi} \in [144.4, 146.4]\ \mathrm{MeV}/c^2$, and CMS momentum $p_{D^*}^* < 2.6\ \mathrm{GeV}/c$, consistent with B decay. Electron identification uses momentum and dE/dx information, ACC response, and energy deposition in the ECL. Muon identification is based on penetration depth and matching of hits in the KLM to the extrapolated track. The efficiency is about 92% (84%) for electrons (muons) in the relevant momentum region, from 1.4 to 2.4 GeV/c in the CMS; hadrons pass this selection with an efficiency of 0.2% (1.1%). 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 (smeared in the r-ϕ plane to account for the B flight length); we require $\chi^2/n_{\rm dof} < 75$.

The remaining tracks are used to determine the second B decay vertex and its flavor, using the method of Refs. [21,22]. Events are classified into six subsets according to the purity of the tag. In this analysis we use only leptonic tags from the highest purity subset.

In total, 8565 events are selected (6718 OF, 1847 SF). A GEANT-based Monte Carlo (MC) sample assuming QM correlation, with 5 times the number of events, was analyzed with identical criteria; its Δz and D^* mass distributions were tuned to those of the data. This sample was used for consistency checks, background estimates and subtraction, and to build deconvolution matrices.

To compensate for the rapid fall in event rate with Δt, the time-dependent distributions are histogrammed in 11 variable-size bins (Table I). 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. Terms due to event selection are estimated by comparing data and MC distributions for each quantity, and converting discrepancies into yield variations: effects due to each selection are added in quadrature. Estimation of the remaining terms is described below.

Four types of background events have been considered: $e^+e^- \to q\bar{q}$ continuum, non-D^* events, wrong D^*-lepton combinations, and $B^+ \to \bar{D}^{**0}\ell\nu$ is events. Off-resonance data (8.3 fb^{-1}) were used to estimate the continuum background, which was found to be negligible.

The background to the D^0 sample, and misassigned slow pions, produce a background under the D^* peak in M_{diff}. As a correction, we subtract $126 \pm 6(54 \pm 4)$ such OF (SF) events based on scaled yields from the sideband $M_{\text{diff}} \in [156.0, 164.0]$ MeV$/c^2$. The corresponding systematic uncertainty is estimated by considering statistical fluctuations, and moving cuts by ± 0.02 MeV$/c^2$ (the estimated miscalibration in M_{diff}). Alternate sidebands $[152.0, 156.0]$ and $[164.0, 168.0]$ MeV$/c^2$ are also used: the difference from default results (consistent with statistical fluctuations) is conservatively included in the systematic error.

The wrong D^*-lepton combination background is mainly due to the combination of a D^* from one B with a true lepton from the other B, with a smaller fraction due to misidentified leptons, and from charm decay. To estimate this background, for each selected lepton which forms a CMS angle to the D^* less than 90°, we reverse its CMS momentum labeling the modified lepton ℓ', and require $|\cos(\theta_{B,D^*\ell'})| < 1.1$. This procedure, intended to reject correlated $D^*\ell$ pairs while selecting events with no angular correlation, has been validated on MC events where true $B^0 \to D^{*-}\ell^+X\nu$ combinations have been excluded. (The correlated background from charm decays is negligible.) We obtain 78 ± 9 OF and 237 ± 15 SF events, which are then subtracted. Contributions to the systematic error are obtained by considering the statistical fluctuations and by moving cuts by ± 0.1 to account for possible data-MC discrepancies.

After these subtractions, three main types of events remain: $B^0 \to D^{*-}\ell^+\nu$, the signal; $B^0 \to D^{**-}\ell^+\nu$, which we retain because it undergoes mixing; and $B^+ \to \bar{D}^{**0}\ell^+\nu$ background. MC shapes for the signal and the sum of the D^{**} channels are used in a two-parameter fit to the $\cos(\theta_{B,D^*\ell})$ distribution to find the total D^{**} contribution ($\chi^2/n_{\text{dof}} = 56/46$), and its B^+ component is then estimated using MC fractions. We find 255.5 ± 16.0 events (254.0 OF and 1.5 SF), which we subtract from the data. The systematic uncertainty is estimated by adding in quadrature the fit error (6%) and variations obtained by moving the fit region (3%) and changing to a single parameter fit with forced normalization (2%). We also assign a 20% uncertainty on the ratio of branching fractions of $B^0 \to D^{**-}\ell^+\nu$ to $B^+ \to \bar{D}^{**0}\ell^+\nu$.

We correct for wrong flavor assignments using OF and SF distributions from wrongly tagged MC events. The mistag fraction 0.015 ± 0.001 (stat) is consistent with that in data [20]; we assign a systematic error of ± 0.005.

Remaining reconstruction effects (e.g., resolution in Δt, selection efficiency) are corrected by deconvolution, treating the SF and OF distributions separately. The method is

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

based on deconvolution with singular value decomposition (DSVD) [23]; 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 optimized by a toy Monte Carlo (TMC) technique where sets of several hundred simulated experiments are generated with data and MC samples identical in size to those of the real experiment, but assuming different true asymmetries $A_{\rm QM}$, $A_{\rm SD}$, and $A_{\rm PS}^{\rm max}$. In particular the following points have been studied:

(i) The effective matrix rank was reduced from 11 to 5 (6) for the OF (SF) sample, to minimize the total error. (The statistical precision of some singular values is poor.)

(ii) The MC events used to fill the response matrix, and provide an *a priori* to the regularization algorithm, introduce a potential bias: e.g., the first Δt bin contains few SF events for QM, but is well populated for SD. We therefore replace SF and OF samples with mixtures SF + $o \times$ OF and OF + $s \times$ SF, choosing $s = o = 0.2$ to minimize systematic effects; the exact values are not critical.

(iii) After DSVD, measured differences from input values are averaged (over QM, SD, and PS) and subtracted bin-by-bin from the asymmetry, to reduce the potential bias against any one model. The maximal absolute deviation of the corrected distribution from the three models is assigned as the systematic error in each Δt bin.

(iv) A 46 μm Gaussian smearing term, inferred from the difference between MC and data vertex-fit errors, is used to tune the MC Δz distribution to the data. (The average Δz resolution is ≈ 100 μm.) This term was varied by its ± 35 μm uncertainty, and the resulting bin-by-bin difference in the asymmetry taken as the systematic error.

Terms from (iii) and (iv) are added in quadrature to give the total systematic error due to deconvolution. We test the consistency of the method 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 [24]. We also repeat the deconvolution procedure using events with better vertex-fit quality, and hence more precise Δt values: consistent results are obtained.

The final results, which may be directly compared with theoretical models, are shown in Table I; addition in quadrature is used to combine the various error terms.

We perform weighted least-squares fits to $A(\Delta t)$, including a term taking the world-average Δm_d into account. To avoid bias we discard *BABAR* and Belle measurements, which assume QM correlations: this yields $\langle \Delta m_d \rangle = (0.496 \pm 0.014)$ ps^{-1} [25].

In fits to the QM, SD, and PS predictions, we obtain $\Delta m_d = 0.501 \pm 0.009$, 0.419 ± 0.008, and 0.447 ± 0.010 ps^{-1} with χ^2 of 5.2, 174, and 31.3, respectively, for 11 degrees of freedom; see Fig. 2. The data favor QM over the SD model at 13σ, and QM over the PS model at 5.1σ [26]. As noted above, *CP* violation in mixing can be neglected. Introducing a lifetime difference $\frac{\Delta\Gamma_d}{\Gamma_d} = 0.009 \pm 0.037$ [25] has a negligible effect on the fit. As a consistency check, the time-dependent asymmetry before deconvolution is compared to MC predictions for QM and (via reweighting) the SD and PS models: QM is strongly favored.

Following other phenomenological studies of decoherence (e.g., Ref. [9]) we also fit the data with the function $(1 - \zeta_{B^0\bar{B}^0})A_{\rm QM} + \zeta_{B^0\bar{B}^0}A_{\rm SD}$: this is equivalent to modifying the interference term in the $B^0 - \bar{B}^0$ basis, or to assuming that only a fraction of the neutral B pairs from $\Upsilon(4S)$ decays disentangle immediately into a B^0 and a $\bar{B}^0$. We find $\zeta_{B^0\bar{B}^0} = 0.029 \pm 0.057$, consistent with no decoherence.

In summary, we have analyzed neutral B pairs produced by $\Upsilon(4S)$ decay, determined the time-dependent asymmetry due to flavor oscillations, and corrected for experimental effects by deconvolution: the results can be directly compared to theoretical models. Any local realistic model including the assumptions of Pompili and Selleri is

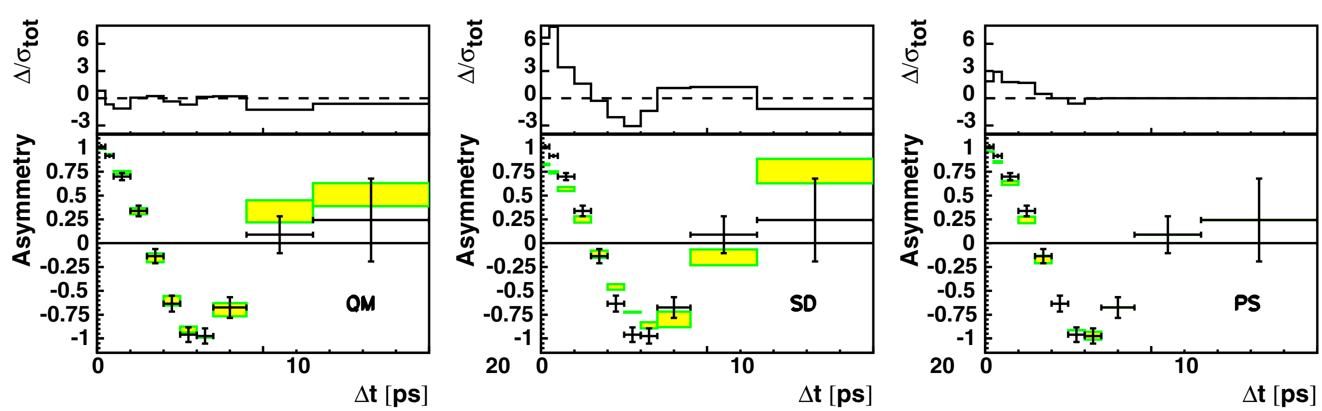

FIG. 2 (color online). Bottom: time-dependent flavor asymmetry (crosses) and the results of weighted least-squares fits to the (left to right) QM, SD, and PS models (rectangles, showing $\pm 1\sigma$ errors on Δm_d). Top: differences $\Delta \equiv A_{\rm data} - A_{\rm model}$ in each bin, divided by the total experimental error $\sigma_{\rm tot}$. Bins where $A_{\rm PS}^{\rm min} < A_{\rm data} < A_{\rm PS}^{\rm max}$ have been assigned a null deviation: see the text.

strongly disfavored compared to quantum mechanics. Immediate disentanglement, in which definite-flavor B^0 and $\bar{B}^0$ evolve independently, is ruled out; if a fraction of B pairs is assumed to decay incoherently, we find a decoherent fraction consistent with zero.

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