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CP violation in B-meson decays

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Abstract. 37 years after the discovery of *CP* violation in $\pi^+\pi^-$ decays of neutral K-mesons, the experiments BABAR and BELLE have found a second system which violates *CP* symmetry. $\mathrm{J}/\psi\mathrm{K}^0_\mathrm{S}$ decays of neutral B-mesons show very large symmetry breaking. The effect has now, with the most recent data, a significance of ten standard deviations. The presentation describes the B-meson factories, the experiments, and their analyses. The results are in agreement with the Standard Model explanation of *CP* violation, *i.e.* with different couplings of the Higgs boson to quarks and antiquarks.

PACS. 14.40.Nd Bottom mesons – 12.15.Hh Determination of Kobayashi-Maskawa matrix elements – 11.30.Er Charge conjugation, parity, time reversal, and other discretesymmetries

1 Discovery of CP Violation

In today's language, *CP* symmetry of the charged weak interaction means equal couplings of left-handed fermions ν_L, e^-_L, u^-_L, d^-_L ... , and right-handed antifermions, $CP\,\nu_\mathrm{L} = \overline{\nu}_\mathrm{R}$, $CP\,e^-_\mathrm{L} = e^+_\mathrm{R}$ ... , to $\mathrm{W}^\pm$-bosons. This symmetry was assumed to be perfect between 1957, when *P* violation was discovered, and 1964. In that year, Christenson *et al.* [1] discovered *CP* symmetry breaking in $\pi^+\pi^-$ decays of neutral K-mesons. These very strange particles have a non-exponential decay law because of transitions $\mathrm{K}^0 \leftrightarrow \overline{\mathrm{K}}^0$. There are two and only two linear superpositions which decay exponentially [2],

$$\mathrm{K}^0_\mathrm{S} = p\mathrm{K}^0 + q\overline{\mathrm{K}}^0\,, \qquad \mathrm{K}^0_\mathrm{L} = p\mathrm{K}^0 - q\overline{\mathrm{K}}^0\ . \tag{1}$$

CP symmetry requires $|p| = |q|$, but the 1964 discovery showed $|p| > |q|$. The simplest manifestation of this *CP* violation today has been observed by CPLEAR [3]. Figure 1 shows their rate asymmetry as a function of t, the time between K production and K decay,

$$A(t) = \frac{N(\overline{\mathrm{K}}^0 \to \pi^+\pi^-) - N(\mathrm{K}^0 \to \pi^+\pi^-)}{N(\overline{\mathrm{K}}^0 \to \pi^+\pi^-) + N(\mathrm{K}^0 \to \pi^+\pi^-)}\ . \tag{2}$$

It can be expressed by standard K-meson parameters [2],

$$A(t) = \frac{-2|\eta_{+-}|\mathrm{e}^{-t/2\tau}\cos(\Delta m_\mathrm{K}\cdot t - \phi_{+-})}{\mathrm{e}^{-t/\tau_\mathrm{S}} + |\eta_{+-}|^2\mathrm{e}^{-t/\tau_\mathrm{L}}}\ , \tag{3}$$

where τ_S and τ_L are the mean lives of the two states in eq. (1) and $1/\tau = 1/\tau_\mathrm{S} + 1/\tau_\mathrm{L}$, Δm_K is the mass difference of the two states, $\Delta m_\mathrm{K} = m(\mathrm{K}^0_\mathrm{L}) - m(\mathrm{K}^0_\mathrm{S})$, and

$$\eta_{+-} = \frac{\langle\pi^+\pi^-|T|\mathrm{K}^0_\mathrm{L}\rangle}{\langle\pi^+\pi^-|T|\mathrm{K}^0_\mathrm{S}\rangle} = |\eta_{+-}|\cdot\mathrm{e}^{\mathrm{i}\phi_{+-}}\ . \tag{4}$$

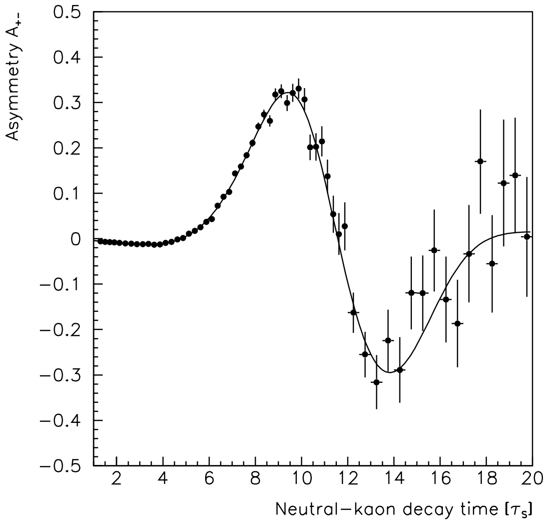

Fig. 1. The CPLEAR result [3] on the decay asymmetry of K^0 and $\overline{\mathrm{K}}^0$ in the $\pi^+\pi^-$ mode. The abscissa is t/τ_S.

The results in fig. 1 and in earlier experiments lead to a world average [4] of

$$\eta_{+-} = (2.27 \pm 0.02)\cdot 10^{-3}\cdot\mathrm{e}^{\mathrm{i}(43.3\pm0.5)^\circ}\ . \tag{5}$$

CP asymmetries have also been observed in decays of neutral kaons into the final state $\pi^0\pi^0$ and in the difference

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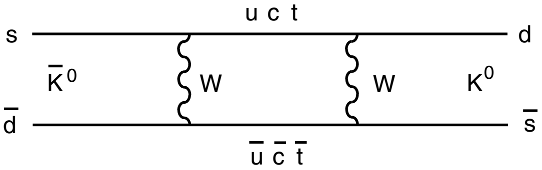

Fig. 2. Feynman diagram for transitions $K^0 \leftrightarrow \overline{K}^0$. *CP* symmetry is violated since the transition rates from left to right are larger than those from right to left.

between $\pi^+\pi^-$ and $\pi^0\pi^0$ decays. The parameters for these asymmetries are

$$\eta_{00} = \frac{\langle 2\pi^0|T|K^0_L\rangle}{\langle 2\pi^0|T|K^0_S\rangle},\ \epsilon_K = \frac{2\eta_{+-} + \eta_{00}}{3},\ \epsilon' = \frac{\eta_{+-} - \eta_{00}}{3} \tag{6}$$

and experimentally we have

$$\epsilon_K \approx \eta_{00} \approx \eta_{+-}\,, \qquad \epsilon' \approx 2 \cdot 10^{-3} \cdot \epsilon_K\,. \tag{7}$$

2 Expectations in the Standard Model

The Standard Model describes transitions $K^0 \leftrightarrow \overline{K}^0$ with the help of second-order weak interactions as shown in fig. 2. There are four weak vertices in this graph, each one contributes with the coupling constant $g_w \cdot V_{ik}$ to the transition amplitude, where g_w is the universal weak coupling and V_{ik} is the CKM matrix element [5,6] with $i = u, c, t$ and $k = d, s$. With three families of quarks, V is allowed to be a complex matrix, and the presence of six different complex V_{ik} values in the transition amplitude leads to an interference with the result

$$\Gamma(K^0 \to \overline{K}^0) < \Gamma(\overline{K}^0 \to K^0)\ . \tag{8}$$

More about the Standard Model interpretation of *CP* violation in sect. 7.

For 37 years, the K^0 was the only system in particle physics with observed *CP* symmetry breaking. In summer 2001, decays of B^0-mesons showed the second evidence. The search for this effect could be very well planned because of a clear Standard Model expectation,

$$\begin{aligned} A &= \frac{N(\overline{B}^0 \to J/\psi K^0_S) - N(B^0 \to J/\psi K^0_S)}{N(\overline{B}^0 \to J/\psi K^0_S) + N(B^0 \to J/\psi K^0_S)} \\ &= A(t) = \sin 2\beta \cdot \sin(\Delta m_B \cdot t)\ , \end{aligned} \tag{9}$$

where $\beta = \arg(V_{td}V^*_{tb}V_{cb}V^*_{cd})$ is a Standard Model parameter and $\Delta m_B = m(B^0_H) - m(B^0_L)$. The states B^0_H and B^0_L are the exponentially decaying superpositions of B^0 and $\overline{B}^0$ as in eq. (1). Early experiments with B-mesons which had discovered $B^0 \leftrightarrow \overline{B}^0$ transitions [7,8] determined Δm_B to be 0.5/ps. The result for $|\eta_{+-}|$ in eq. (5) together with later measurements of $|V_{ub}|$ [9,10] and $\Delta m(B_s)$ [11] lead to the prediction $\sin 2\beta = 0.5$ to 0.8 if *CP* violation in the K system has only Standard Model origin. A conclusive measurement of the asymmetry in eq. (9), however, needs about $3 \cdot 10^7$ B-mesons, which required the construction of special "B-meson factories". The most promising method was electron-positron annihilation at $E_{CM} = 10.58$ GeV with formation of $\Upsilon(4S)$-mesons which decay predominantly into B^+B^- and $B^0\overline{B}^0$ pairs without any extra particles.

Two such high-luminosity e^+e^- storage rings have been built in the mid-90s. With present technologies for storage ring beam sizes and present space resolutions of silicon vertex detectors, measurements in the $\Upsilon(4S)$ rest frame would give unmeasurably small *CP* asymmetries, even for large values of $\sin 2\beta$ in eq. (9). Experiments must be done with moving $\Upsilon(4S)$-mesons, but modest boosts of $\beta\gamma(\Upsilon 4S) \approx 0.5$ are sufficient for seeing the effect. Both B-meson factories have, therefore, been built with unequal beam energies for electrons and positrons.

3 The B-meson factories PEP-II and KEK-B

The double storage ring PEP-II [12] at SLAC (Stanford, California) was designed around 1988, was approved in 1993, and started operation in 1998. The ring with a circumference of 2.2 km is located in the old tunnel of PEP. Electrons and positrons are injected with their nominal energy of 9.1 and 3.0 GeV, respectively, from the 3 km long SLAC linear accelerator. The E asymmetry leads to an $\Upsilon(4S)$ motion with $\beta\gamma = 0.55$. The luminosity in the only intersection region has now reached $\dot{\mathcal{L}} = 4.5 \cdot 10^{33}/\text{cm}^2/\text{s}$, corresponding to 5.0 produced $\Upsilon(4S)$-mesons per second. To obtain this luminosity, the circulating electron current is 0.98 A, for the positrons it is 1.68 A. Both beams are colliding head-on, *i.e.* with zero crossing angle. Two good days in BABAR give the same amount of data as ARGUS [8,9] at DESY collected in its whole lifetime from 1982 to 1992.

KEK-B [13] at KEK (Tsukuba, Japan) was designed, approved, and built on the same time scale as PEP-II. The beam energies are 8.0 and 3.5 GeV for e^- and e^+, respectively, corresponding to $\beta\gamma = 0.43$. The luminosity has now reached a value of $\dot{\mathcal{L}} = 7.2 \cdot 10^{33}/\text{cm}^2/\text{s}$, *i.e.* 8.0 produced $\Upsilon(4S)$-mesons per second. One reason for the higher luminosity compared to PEP-II is the beam crossing angle of 22 mrad in the interaction region. In spite of KEK-B's luminosity record, PEP-II has still the higher integrated luminosity $\mathcal{L} = \int \dot{\mathcal{L}} dt$. Until 13 June 2002, the day before this presentation, it produced $\mathcal{L} = 91$ events/femptobarn recorded in the PEP-II detector BABAR, whereas the KEK-B detector BELLE recorded 85 events/fb until the same day.

4 The detectors BABAR and BELLE

The BABAR detector is described in detail in ref. [14]. It consits of a five-layer silicon vertex tracker, a 40-layer drift chamber, a detector of internally reflected Čerenkov light for charged-particle identification, and an electromagnetic calorimeter with 6580 CsI(Tl) crystals, all embedded in a solenoidal magnetic field of 1.5 T, and surrounded by

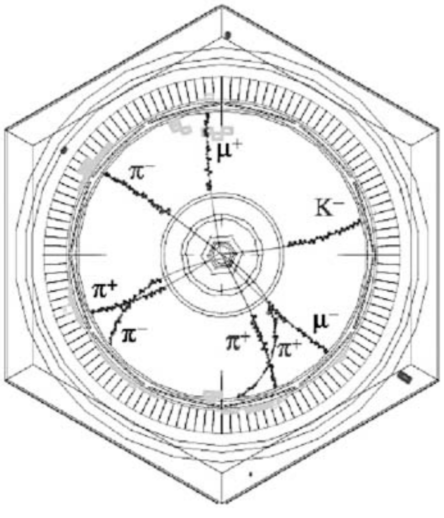

Fig. 3. A fully reconstructed event $\mathrm{e^+e^-} \to \Upsilon(4\mathrm{S}) \to \mathrm{B}^0\overline{\mathrm{B}}^0 \to [\psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S}][\mathrm{D}^{*+}\pi^-]$ in BABAR.

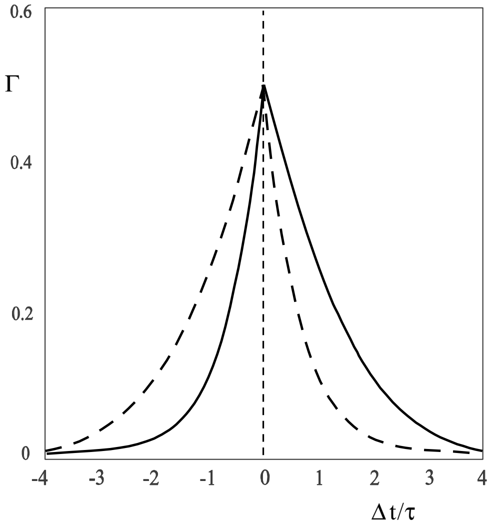

Fig. 4. The expected time dependence of B decays into $\mathrm{J}/\psi\mathrm{K}^0_\mathrm{S}$ from the $\Upsilon(4\mathrm{S})$-resonance. The solid curve shows the decays tagged by a B^0, the dashed curve those with $\overline{\mathrm{B}}^0$ tags.

an instrumented flux return for muon identification and K^0_L detection. The BABAR Collaboration has now 516 physicists from 73 institutions in USA, Italy, France, UK, Germany, Canada, Russia, Norway, and China.

The BELLE detector [15] is quite similar to BABAR. The main difference is in the charged-particle identification. Instead of a ring-image Čerenkov detector, it has a system of aerogel threshold Čerenkov detectors and scintillators for time-of-flight measurement. The BELLE Collaboration consists of about 300 physicists from 49 institutes in Australia, Austria, China, Germany, India, Korea, Japan, Philippines, Poland, Russia, Slovenia, Switzerland, Taiwan, and USA.

5 Principles of the measurement

A fully reconstructed event $\mathrm{e^+e^-} \to \Upsilon(4\mathrm{S}) \to \mathrm{B}^0\overline{\mathrm{B}}^0$ is shown in fig. 3, where one of the neutral B-mesons decays into a flavour eigenstate, $\overline{\mathrm{B}}^0 \to \mathrm{D}^{*+}\pi^-$, and the other one into the *CP* eigenstate $\psi(2\mathrm{S})\mathrm{K}^0_\mathrm{S}$ with the eigenvalue $CP = -1$. The *CP* eigenstate can be reached from either a B^0 or a $\overline{\mathrm{B}}^0$. In fact it is reached from a linear superpostition of both, with coefficients which depend on the time difference between the two B-meson decays. This time-dependent coherent superposition is an important property for *CP* asymmetry measurements on the $\Upsilon(4\mathrm{S})$-resonance.

The $\Upsilon(4\mathrm{S})$ has the quantum numbers $C = P = -1$. It decays by strong interaction, so P and C are conserved. The final state with two neutral B-mesons at polar angles θ and $\pi - \theta$ has to be

$$\psi = [\mathrm{B}^0(\theta)\overline{\mathrm{B}}^0(\pi-\theta) - \overline{\mathrm{B}}^0(\theta)\mathrm{B}^0(\pi-\theta)]/\sqrt{2}\,. \tag{10}$$

This state remains unchanged until the first of the two Beons decays. If it decays at time t_1 into a flavour-specific mode indicating that it was a B^0, the other Beon is a $\overline{\mathrm{B}}^0$ at the same time. This $\overline{\mathrm{B}}^0$ develops as single-particle state with $\mathrm{B}^0\overline{\mathrm{B}}^0$ oscillations until it decays at time t_2. The probabilities to decay as a B^0 or as a $\overline{\mathrm{B}}^0$ are well-defined functions [2] of $\Delta t = t_2 - t_1$. These are used to derive the *CP* asymmetry in eq. (9), where for $\Upsilon(4\mathrm{S})$ measurements $t = t_2 - t_1 = \Delta t$, and $\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^0_\mathrm{S}$ means a decay at t_2 with a flavour-specific decay, a so-called "tag", of a $\overline{\mathrm{B}}^0$ at time t_1. The expression in eq. (9) is the same for $\Delta t < 0$. The expected Δt distributions for decays into $\mathrm{J}/\psi\mathrm{K}^0_\mathrm{S}$ are shown in fig. 4 for $\Delta m_\mathrm{B} = 0.47/\mathrm{ps}$ and $\sin 2\beta = 0.7$.

The observed asymmetry will not be $A(\Delta t)$ because of resolution effects $r(\tilde{\Delta t} - \Delta t)$ and because of non-perfect flavour tagging resulting in a "dilution" D. The observed asymmetry $\tilde{A}$ as a function of the measured time difference $\tilde{\Delta t}$ will be

$$\tilde{A}(\tilde{\Delta t}) = D \cdot \sin 2\beta \cdot \int \sin(\Delta m_\mathrm{B} \Delta t) \cdot r(\tilde{\Delta t} - \Delta t)\mathrm{d}t\ , \tag{11}$$

where D and r have to be determined experimentally with the help of control samples. The parameter $\sin 2\beta$ can then be obtained from a fit to the observed asymmetry $\tilde{A}(\tilde{\Delta t})$. In practice, it is obtained from a simultanuous fit to the two distributions $N(\overline{\mathrm{B}}^0 \to \mathrm{J}/\psi\mathrm{K}^0_\mathrm{S})$ and $N(\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^0_\mathrm{S})$ as functions of $\tilde{\Delta t}$ and to the control samples. Before this fit, each candidate event needs to be reconstructed in several steps: reconstructing the K^0_S, the J/ψ, the B, the flavour of the tag, and the value of $\tilde{\Delta t}$.

6 Results

Examples from the BABAR analysis with 62 million $\Upsilon(4\mathrm{S})$ events [16], as obtained in March 2002, are shown in fig. 5. Selection of fully reconstructed B-mesons is performed with the help of the two quantities

$$\begin{aligned} \Delta E &= E(\mathrm{J}/\psi) + E(\mathrm{K}^0) - m(\Upsilon 4\mathrm{S})/2\,, \\ m^2_\mathrm{ES} &= [m(\Upsilon 4\mathrm{S})/2]^2 - [\boldsymbol{p}(\mathrm{J}/\psi) + \boldsymbol{p}(\mathrm{K}^0)]^2\,, \end{aligned} \tag{12}$$

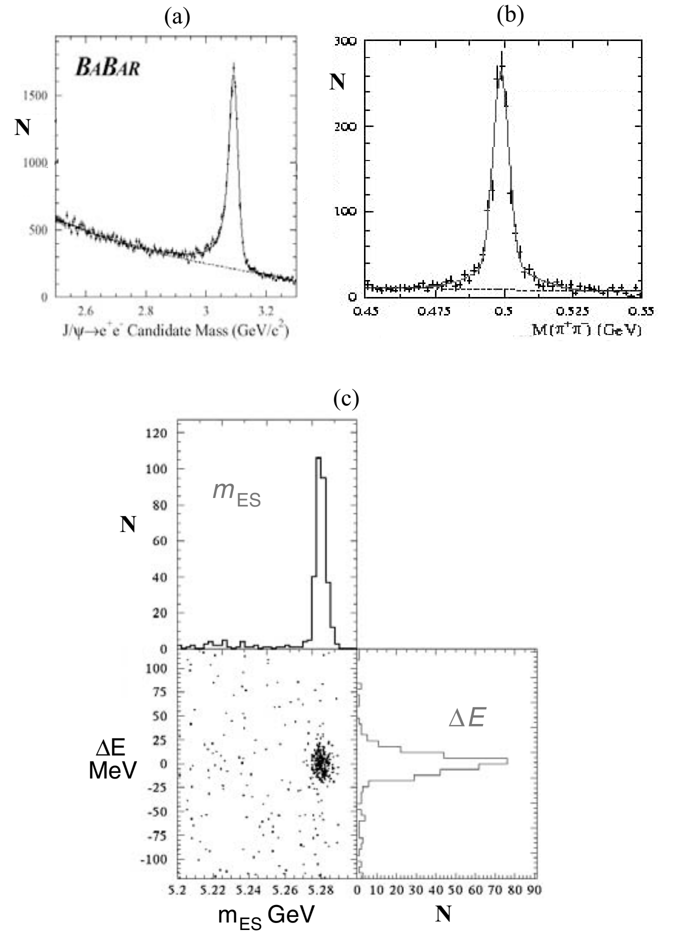

Fig. 5. Event reconstruction in BABAR. (a) $J/\psi \rightarrow e^+e^-$, (b) $K^0_S \rightarrow \pi^+\pi^-$, (c) $B \rightarrow J/\psi K^0_S$.

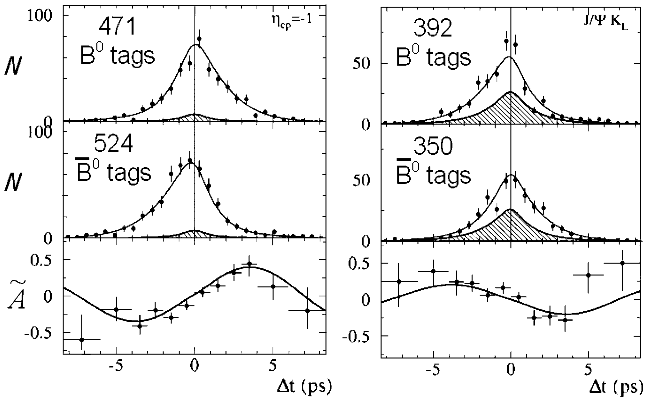

Fig. 6. BABAR results from 62M $B\overline{B}$ events. The left-hand side shows the time-dependent decay rates into $J/\psi K^0_S$ and other $c\overline{c}K$ modes with $CP = -1$, the right-hand side into $J/\psi K^0_L$ with $CP = +1$. The two top graphs show decays with B^0 tags, the middle ones with $\overline{B}^0$ tags, and the lower ones the raw asymmetries $\tilde{A}$ as defined in eqs. (9) and (11).

Table 1. All published results for the CP asymmetry $\sin 2\beta$ in B-meson decays. The first errors are statistical, the second ones systematic.

Experiment	Reference	Result
OPAL	[20]	$3.2^{+1.8}_{-2.0} \pm 0.5$
ALEPH	[21]	$0.84^{+0.82}_{-1.04} \pm 0.16$
CDF	[22]	$0.79^{+0.41}_{-0.44}$
BABAR	[16]	$0.75 \pm 0.09 \pm 0.04$
BELLE	[19]	$0.82 \pm 0.12 \pm 0.05$
Average		0.78 ± 0.08

where E and $\boldsymbol{p}$ are energies and momenta of the B decay daughters in the Υ(4S) frame. The "energy-substituted" mass m_{ES} is used because it has a smaller experimental error than the invariant mass with $E(J/\psi) + E(K^0)$ instead of $m(\Upsilon 4S)/2$. After requiring flavour tags in addition to B reconstruction, there remain 995 B candidates decaying into CP eigenstates with eigenvalue $CP = -1$ ($J/\psi K^0_S$, $\chi_{c1}K^0_S$, and $\psi(2S)K^0_S$) and 742 with $CP = +1$ ($J/\psi K^0_L$). 113 candidates are found in the mode J/ψ K^{*0} which contains events with $CP = -1$ and with $CP = +1$. Their relative contribution is determined experimentally from a Dalitz-plot analysis [17] resulting in $CP_{\mathrm{eff}} = +0.65 \pm 0.07$.

Tagging is obtained by decays of the other B-meson into electrons, muons, charged kaons, or from a combination of all event information in a neural net. $(67.5 \pm 0.5)\%$ of all reconstructed CP eigenstates are tagged. The value of this tagging efficiency is not important; essential is only the "quality factor"

$$Q = \sum_{\mathrm{i}} \epsilon_{\mathrm{i}}(1 - 2w_{\mathrm{i}})^2 ,$$

where the sum runs over the four tagging categories, ϵ_{i} is the tagging efficiency and w_{i} the mistag fraction of each category. The value of Q determines the obtainable precision on $\sin 2\beta$,

$$\sin 2\beta \approx \frac{1.9}{\sqrt{N_{\mathrm{sig}} \cdot Q}} \cdot \sqrt{1 + \frac{N_{\mathrm{bg}}}{N_{\mathrm{sig}}}} , \qquad (13)$$

where N_{sig} and N_{bg} are the numbers of signal and background events before tagging. In the presented analysis, BABAR has reached $Q = (25.1 \pm 0.8)\%$. The mistag fractions w_{i} for each tagging category are determined experimentally by tagging events of the "flavour sample", *i.e.* fully reconstructed events with known flavour like $B \rightarrow D^*\pi$, and by counting how often the tag is wrong.

The value of $\Delta\tilde{t}$ for each tagged event is determined from the distance $\Delta\tilde{z}$ between the reconstructed vertex of the CP eigenstate decay and that of the tagging decay, and

$$\Delta\tilde{t} = \Delta\tilde{z}/\beta\gamma c .$$

The Δt resolution function is determined from the $\Delta\tilde{t}$ distribution of events in which one neutral B decays into a fully reconstructed flavour state and the other one into one of the tagging categories. Because of $B^0\overline{B}^0$ oscillations, the $B^0\overline{B}^0$ events follow the distribution $e^{-|\Delta t|/\tau}(1 + \cos \Delta m_{\mathrm{B}}\Delta t)$ and those with B^0B^0 and

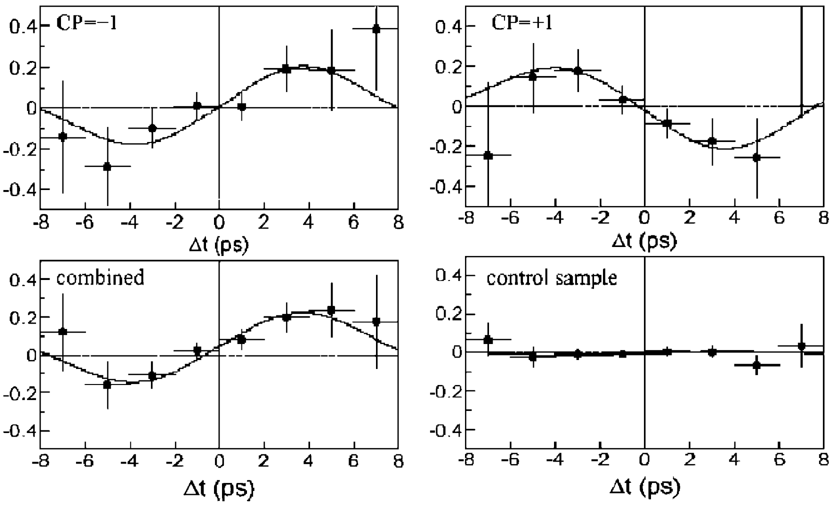

Fig. 7. BELLE results from 46M $\mathrm{B\overline{B}}$ events. Shown are the raw asymmetries $\tilde{A}$ as defined in eqs. (9) and (11) for decays into $\mathrm{c\overline{c}K}$ modes with $CP=-1$, with $CP=+1$, for both of them, and —as a control— for decays into flavour eigenstates where $\tilde{A}=0$ is expected.

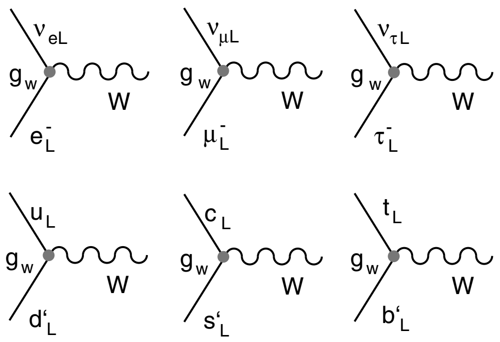

Fig. 8. Feynman diagrams for couplings of the charged weak interaction in the Standard Model.

$\mathrm{\overline{B}^0\overline{B}^0}$ follow $\mathrm{e}^{-|\Delta t|/|\tau}\,(1-\cos\Delta m_{\mathrm{B}}\Delta t)$. The two observed distributions of these events as a function of $\Delta\tilde{t}$ determine very well the time resolution function. They can also be used for a determination of the mass difference Δm_{B}, the BABAR result from this data sample is [18]

$$\Delta m_{\mathrm{B}} = (0.516 \pm 0.016 \pm 0.010)\,\mathrm{ps}^{-1}\ . \tag{14}$$

The last step in the determination of $\sin 2\beta$ is the final fit to the two $\Delta\tilde{t}$ distributions of *CP* eigenstate events, those with B^0 and those with $\mathrm{\overline{B}}^0$ tags. The distributions are shown in fig. 6 for $CP=-1$ and $CP=+1$ events. *CP* violation is clearly seen, the time dependence of events with B^0 tags is very different from that of events tagged by $\mathrm{\overline{B}}^0$. The lower part of the figure shows the raw asymmetries $\tilde{A}$ as introduced in eq. (11). The $CP=-1$ events give $\sin 2\beta = 0.76\pm0.10$, and those with $CP=+1$ give $\sin 2\beta = 0.73 \pm 0.19$. Together with the $\mathrm{J}/\psi\ \mathrm{K}^{*0}$ sample of mixed *CP* eigenvalue composition, the final BABAR result from 62M $\mathrm{B\overline{B}}$ events is

$$\sin 2\beta = 0.75 \pm 0.09 \pm 0.04\ . \tag{15}$$

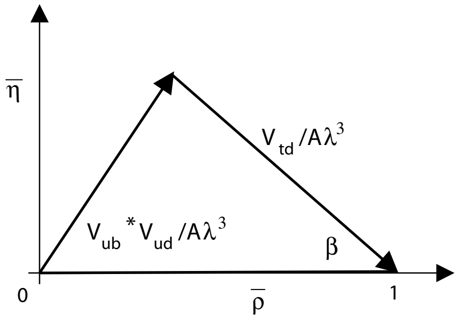

Fig. 9. The unitarity triangle of the CKM matrix, as defined by eq. (25). The angle β in this triangle determines the *CP* asymmetry $\sin 2\beta$ in $\mathrm{B}\to\mathrm{c\overline{c}K}$ decays.

Also in March 2002, the BELLE experiment has presented a $\sin 2\beta$ result obtained with 46M $\mathrm{B\overline{B}}$ meson pairs [19]. The analysis is very similar to that of BABAR. Their raw asymmetries $\tilde{A}(\Delta\tilde{t})$, again as defined in eq. (11), are shown in fig. 7. Their combined result from fits to the $CP=-1$, $CP=+1$, and $\mathrm{J}/\psi\ \mathrm{K}^{*0}$ events, is

$$\sin 2\phi_1 = 0.82 \pm 0.12 \pm 0.05\ , \tag{16}$$

where ϕ_1 is the Japanese name for β. Table 1 summarizes all $\sin 2\beta$ results obtained so far. Their mean value is

$$\sin 2\beta = 0.78 \pm 0.08\ , \tag{17}$$

i.e. *CP* asymmetry in B-meson decays is now established with a significance of about ten standard deviations.

7 Standard model explanation of CP violation in K and B decays

The measured values of $\sin 2\beta$ and ϵ_{K} are compatible with each other and with the assumption that they are completely determined by the charged weak interaction of the

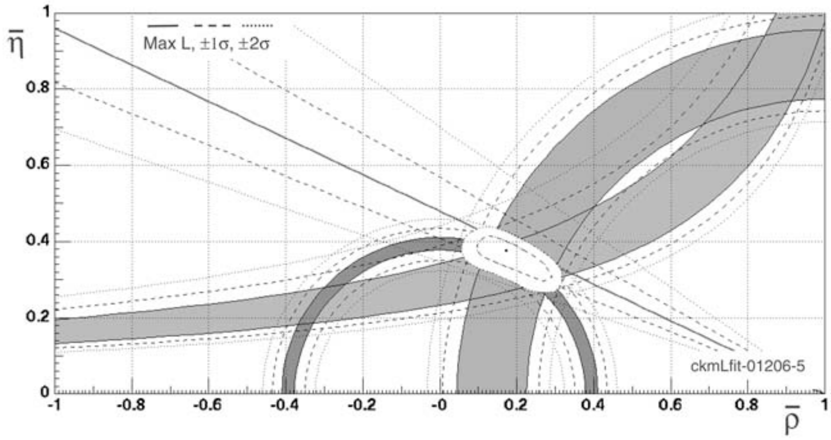

Fig. 10. Information on the CKM matrix parameters ρ and η. The circular band around $(0,0)$ is the result of exclusive and inclusive $\mathrm{b} \to \mathrm{u}\ell\nu$ decays; the circular band around $(1,0)$ results from measurements of $\mathrm{B}^0\overline{\mathrm{B}}^0$ and $\mathrm{B_s}\overline{\mathrm{B}}_\mathrm{s}$ oscillations; the hyperbolic band results from the measurement of ϵ_K; and the linear band is given by $\sin 2\beta$. Solid lines correspond to maximum likelihood, dashed lines to $\pm 1\sigma$, and dotted lines to $\pm 2\sigma$. The region around $(0.20, 0.35)$ is the maximum-likelihood fit to all information [26].

Standard Model. In perturbation theory, processes of this interaction are calculated with the Feynman diagrams in fig. 8, where all six diagrams have the same universal weak coupling strength g_w.

The index L indicates that only the left-handed fractions $\mathrm{f_L} = (1-\gamma_5)\mathrm{f}/2$ of all fermions f participate in these couplings to the W field. The quarks u, c, t are mass eigenstates; their Glashow partners (*i.e.* members in the same doublet of weak isospin) are not. These partners d′, s′, b′ are linear superpositions of mass eigenstates d, s, b:

$$\begin{aligned} \mathrm{d}' &= V_\mathrm{ud}\cdot\mathrm{d} + V_\mathrm{us}\cdot\mathrm{s} + V_\mathrm{ub}\cdot\mathrm{b}\ , \\ \mathrm{s}' &= V_\mathrm{cd}\cdot\mathrm{d} + V_\mathrm{cs}\cdot\mathrm{s} + V_\mathrm{cb}\cdot\mathrm{b}\ , \\ \mathrm{b}' &= V_\mathrm{td}\cdot\mathrm{d} + V_\mathrm{ts}\cdot\mathrm{s} + V_\mathrm{tb}\cdot\mathrm{b}\ , \end{aligned} \tag{18}$$

with the unitarity CKM matrix V as already introduced in sect. 2. In the Standard Model, the matrix elements are given by the coupling of the Higgs field to quarks. CPT symmetry requires how the Higgs couples to antiquarks, leading to the following relations between the Glashow partners of $\overline{\mathrm{u}}$, $\overline{\mathrm{c}}$, $\overline{\mathrm{t}}$ and the mass eigentates $\overline{\mathrm{d}}$, $\overline{\mathrm{s}}$, $\overline{\mathrm{b}}$:

$$\begin{aligned} \overline{\mathrm{d}}' &= V_\mathrm{ud}{}^*\cdot\overline{\mathrm{d}} + V_\mathrm{us}{}^*\cdot\overline{\mathrm{s}} + V_\mathrm{ub}{}^*\cdot\overline{\mathrm{b}}\ , \\ \overline{\mathrm{s}}' &= V_\mathrm{cd}{}^*\cdot\overline{\mathrm{d}} + V_\mathrm{cs}{}^*\cdot\overline{\mathrm{s}} + V_\mathrm{cb}{}^*\cdot\overline{\mathrm{b}}\ , \\ \overline{\mathrm{b}}' &= V_\mathrm{td}{}^*\cdot\overline{\mathrm{d}} + V_\mathrm{ts}{}^*\cdot\overline{\mathrm{s}} + V_\mathrm{tb}{}^*\cdot\overline{\mathrm{b}}\ . \end{aligned} \tag{19}$$

If the CKM matrix is not real, the Higgs couplings mix antiquarks in a different way than quarks; this is the origin of *CP* violation in the Standard Model. However, not every complexity leads to observable *CP* asymmetries. The necessary and sufficient condition for *CP* violation is given by quartets of CKM matrix elements [23],

$$J = \mathrm{Im}(V_\mathrm{ik}V_\mathrm{il}^* V_\mathrm{jl} V_\mathrm{jk}^*) \neq 0\ , \tag{20}$$

with $\mathrm{i} \neq \mathrm{j}$ and $\mathrm{k} \neq \mathrm{l}$. The CKM matrix has four observable parameters and has to be unitary, $VV^+ = 1$. The most widely used parametrisation of V was introduced by Wolfenstein [24]; a sufficient approximation is

$$V \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - \mathrm{i}\,\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\overline{\rho}-\mathrm{i}\,\overline{\eta}) & -A\lambda^2 & 1 \end{pmatrix}\ ,$$

$$\overline{\rho} = (1-\lambda^2/2)\rho\ ,\ \overline{\eta} = (1-\lambda^2/2)\eta\ ,\ J \approx A^2\lambda^6\overline{\eta}\ . \tag{21}$$

The parameters A, λ, ρ and η are four of the 18 free parameters of the Standard Model. They have to be determined experimentally. From the observed rates of K-meson β-decays we know

$$\lambda = 0.223 \pm 1\%\ , \tag{22}$$

and from B-meson β-decays

$$A = 0.82 \pm 4\%\ . \tag{23}$$

Six unitarity conditions of V can be drawn as triangles in the complex $\overline{\rho}$-$\overline{\eta}$ plane. One example,

$$V_\mathrm{ud}V_\mathrm{ub}{}^* + V_\mathrm{cd}V_\mathrm{cb}{}^* + V_\mathrm{td}V_\mathrm{tb}{}^* = 0\ , \tag{24}$$

$$\frac{V_\mathrm{ub}{}^*(1-\lambda^2/2)}{A\lambda^3} - 1 + \frac{V_\mathrm{td}}{A\lambda^3} = 0\ , \tag{25}$$

is shown in fig. 9. The area of this triangle is $\overline{\eta}/2$, that of the unscaled triangle in eq. (24) is $J/2$. The Standard Model *CP* asymmetry in $\mathrm{B} \to \mathrm{c\overline{c}K}$ decays is given by the angle β of the triangle; expressed by the Wolfenstein paremeters we have

$$\sin 2\beta = \frac{2\,(1-\overline{\rho})\,\overline{\eta}}{(1-\overline{\rho})^2 + \overline{\eta}^2}\ . \tag{26}$$

Figure 10 shows the experimental informations which constrain ρ and η. With the exception of $\sin 2\beta$, all these constraints depend not only on measured values but also on QCD parameters which have to be calculated. Details can be found in recent reviews on the CKM matrix [25]. Here I only want to show the result of a maximum-likelihood fit [26] to the informations in fig. 10:

$$\rho = 0.20 \pm 0.10\,, \qquad \eta = 0.36 \pm 0.06\ , \tag{27}$$

where the errors are given as $\pm 1\sigma$. Including the errors on λ and A, we obtain

$$J = (2.9 \pm 0.6) \cdot 10^{-5}\ . \tag{28}$$

The fit has the remarkable property that all input informations are very well compatible with each other. The now 30-year-old Standard Model contains CP violation, created by the same mechanism which gives masses to quarks and leptons, and the present value of its CP-violating parameter η accounts quantitatively for all observed CP asymmetries in K- and B-meson decays.

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