CP violation in B meson decays

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Abstract

The Universe exhibits a remarkable asymmetry without which we could not exist: it contains large quantities of matter but almost no antimatter. Yet in the interactions of elementary particles at high energy as much antimatter as matter is produced. While it is clear that this asymmetry occurred in the very early evolution of the Universe the mechanism is not understood. However one key element is the phenomenon of CP violation, which results in a small difference in the way in which particles and their antiparticles decay. CP violation was discovered in 1963 in the decays of K mesons and has been investigated in detail since then in these decays. During the 1990s new projects were developed to extend these measurements to the decay of B mesons. Two major projects, Belle at KEK in Japan and *BABAR* at SLAC in the USA, began operation in 1999 and reported first results in 2000.

This paper reviews the phenomenon of CP violation in the decays of elementary particles and demonstrates the basis for the measurements of CP violation parameters in B meson decays. A description is given of the *BABAR* detector together with an outline of the procedure for analysing the data. First results are consistent with predictions of the Standard Model of elementary particles but during the coming years additional data will provide more stringent tests that could reveal new phenomena.

1 Introduction

1.1 The Standard Model of particle physics

The Standard Model describes the elementary particles of nature and the interactions between them [1, 2]. Its principal features were described in the 1960s and 1970s with major experimental input throughout the rest of the twentieth century. Interactions between the particles are via the strong nuclear, electromagnetic, weak nuclear and gravitational forces, the second and third being described by the unified electroweak interaction. Gravity is not yet part of the Standard Model. These interactions can be described in terms of the exchange of bosons between the particles (table 1).

Interaction	Gauge bosons
Gravity	graviton
Electroweak	photon (γ), $W^{\pm}$ and Z^0 bosons
Strong	gluon (g)

Table 1: The gauge bosons which propagate the fundamental interactions.

The elementary particles are spin-$\frac{1}{2}$ fermions, less than 10^{-18} m in size. They can be grouped into the quarks, which feel the strong interaction, and the leptons which do not. Moreover the quarks and leptons can be separately grouped into pairs or doublets, one doublet of each forming a 'generation' or 'family' (table 2). The matter of the everyday world consists of first family members only since the quarks and charged leptons of the second and third families are heavier, so that although they can be produced in high energy collisions they rapidly decay with lifetimes less than 10^{-6} s. Until the last few years the neutrinos were generally assumed to be massless, although this is ultimately an experimental question and there is some recent evidence that neutrinos have a small but non-zero mass.

	Quarks		Leptons	
First generation	u	up	ν_e	electron neutrino
	d	down	e	electron
Second generation	c	charm	ν_μ	muon neutrino
	s	strange	μ	muon
Third generation	t	top	ν_τ	tau neutrino
	b	bottom	τ	tau

Table 2: The fundamental particles of nature (the term *flavour* is used to refer to the different quarks).

While the leptons can be observed as free particles this is not true for the quarks which appear only in combinations of three quarks (baryons) or as quark-antiquark pairs (mesons). Much of the discussion of this paper is concerned with the decays of mesons.

Each of the fundamental particles has an antiparticle partner. The earliest to be discovered was the positron, the antiparticle of the electron, in cosmic radiation in 1932. Positrons are also produced in the beta decay of some radioactive nuclei and through the pair production process, $\gamma \to e^+e^-$, in which the energy of the gamma ray becomes matter and antimatter in equal amounts. Indeed any of the gauge bosons can produce matter and antimatter in this way; other examples include $W^- \to \mu^-\overline{\nu}_\mu$, $Z \to c\overline{c}$, $g \to u\overline{u}$. The inverse process, in which a particle and antiparticle annihilate to produce gamma rays also occurs. A typical example is $e^+e^- \to \gamma\gamma$, a process now routinely exploited for diagnostic purposes in hospitals in positron emission tomography (PET) scanning.

These simple observations lead to an important question about a key feature of the Universe, namely why does it contain matter and no antimatter [3]? The generally accepted explanation for the origin of the Universe, that it started in a Big Bang, with a very large amount of energy in a very small volume, naturally leads to a different universe. Specifically much of the energy of the Big Bang converts to particles and antiparticles, which in turn annihilate to produce more gamma rays. The Universe is expanding, cooling as it does, until eventually the energy of the gamma rays reaches about 1 MeV. At this point the process $\gamma \to e^+e^-$ stops and only annihilation continues. It is clear that only gamma rays remain in such a universe, in clear conflict with observation.

Such a fundamental conflict with our knowledge of the Universe requires an explanation, something which has not been forthcoming in spite of decades of effort. One feature of such an explanation is likely to be the subtle difference in behaviour observed between particles and antiparticles that is the principal subject of this paper. This difference in behaviour is small and likely to lead to only a small effect on the evolution of the Universe. However an interesting aspect of the Universe is the Cosmic Microwave Background (CMB), the ubiquitous radiation that is a remnant of the Big Bang. Measurements show that there are roughly 10^9 CMB photons for every matter particle in the Universe, indeed pointing to only a small difference in the effective matter-antimatter content of the Universe. This enticing observation leads many to believe that this matter-antimatter asymmetry is the basis for an explanation of the composition of the Universe. However our current understanding gets nowhere near explaining the ratio of 10^9.

1.2 CP violation

Symmetry (invariance) principles are an important tool in physics since they are intimately related to conservation laws. Well-known examples include the connection between rotational invariance and angular momentum conservation. Rotational invariance implies that the behaviour of a system does not change if it is rotated in space or, alternatively, described in a coordinate system rotated with respect to the original system.

An important and surprising discovery of the 1950s was that weak interactions are not invariant under the parity transformation (P) in which all coordinates of a system are reflected about the origin ($\boldsymbol{r} \longrightarrow -\boldsymbol{r}$, which we write symbolically as $\mathrm{P}\boldsymbol{r} \longrightarrow -\boldsymbol{r}$). This phenomenon, known as parity violation (P violation), was first observed in the decay of polarized cobalt-60 nuclei by Wu *et al.* [4], as a difference in the number of electrons emitted in the same hemisphere as the cobalt spin compared to the opposite hemisphere.

It is also observed in the decay of muons: $\mu^- \to e^- + \overline{\nu}_e + \nu_\mu$ and $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$. In this case the angular distribution of the electron with respect to the direction of polarization of the μ^- is a reflection of the same distribution for the μ^+. The μ^+ is the antiparticle of the μ^- and the second of these decays is referred to as the charge conjugate

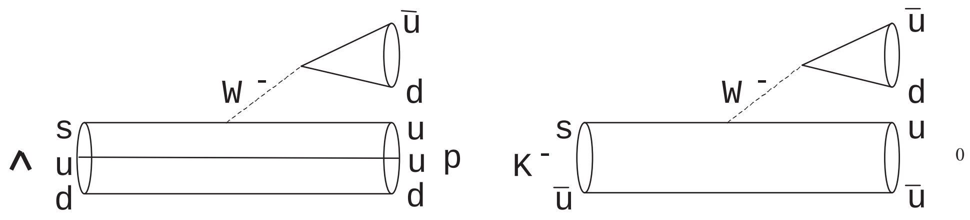

Figure 1: The decay of the Λ baryon via $\Lambda \rightarrow \pi^- p$ and of the $K^- \rightarrow \pi^-\pi^0$.

of the first. Charge conjugation is a transformation similar to the parity transformation, P, and is given the symbol C. It changes all particles to their antiparticle and in the case of the muon we write $C\,\mu^- \rightarrow \mu^+$.

Since the angular distribution is not the same for the μ^- and the μ^+ we can immediately conclude that C, like P, is not conserved in the weak interaction. However the observation that they are reflections of one another leads to the conclusion that if P and C transformations are both applied to a system then it is invariant, i.e. CP is conserved. Currently there is no experimental evidence that contradicts the observation that, while P and C are separately violated, CP is conserved in weak interaction decays involving only leptons. However this is not true in the weak interactions of quarks to which we now turn.

As noted in section 1.1 free quarks are not observed; they are only found in baryons or mesons. Such baryons and mesons are produced in strong interactions, for example when cosmic protons strike the upper atmosphere of the earth to produce cosmic rays or in experiments at particle accelerators. In such interactions an equal number of quarks and antiquarks are produced, appearing as mesons or as equal numbers of baryons and antibaryons (this observation is called baryon number conservation). In principle, given sufficient energy any quark-antiquark pair can be found. However since heavier quarks can only be produced at higher energy accelerators, experimental evidence for the existence of each of the quarks slowly emerged over many decades from the 1940s to the 1990s.

In general baryons and mesons decay after they are produced. Such decays may be via the strong interaction in which more quark-antiquark pairs are produced in a time $\mathcal{O}(10^{-23}\,\mathrm{s})$ or, if there is insufficient energy for strong interaction decays, via the weak interaction decay, in which a quark changes its species. These decays have lifetimes, τ, typically $\mathcal{O}(10^{-12}\,\mathrm{s})$. Two examples of weak decays are shown schematically in figure 1. In both a strange quark, s, emits a virtual W^- boson that in turn decays to a $\overline{u}d$ quark pair (a π^- meson). In the process the strange quark changes its flavour to a u quark, thereby changing the Λ to a proton or the K^- to a π^0.

Two important particles in our story are the K^0 and the $\overline{K}^0$ mesons with quark content $\overline{s}d$ and $s\overline{d}$ respectively. These two particles, in spite of being a particle-antiparticle pair, can change from one to the other (in quantum mechanics terminology they can *mix*). This mixing is a weak interaction process, involving the exchange of virtual W bosons, and is shown diagrammatically in figure 2.

Mixing has a dramatic effect on the behaviour of the K^0 and $\overline{K}^0$, which can no longer be regarded as two independent particles. In a strong interaction process either a K^0 or a $\overline{K}^0$ is produced, referred to as the flavour eigenstates of the system. However at

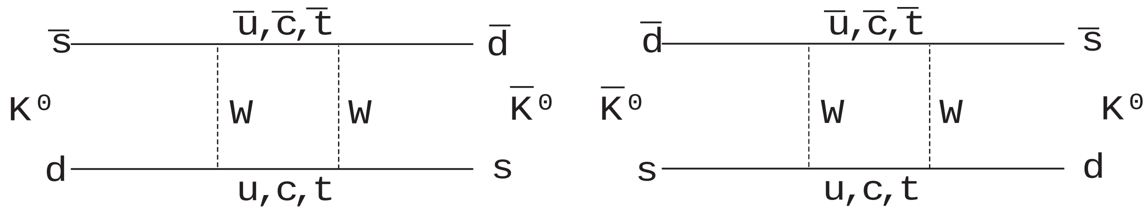

Figure 2: The $K^0 - \overline{K}^0$ mixing process. The three quarks u, c and t, and their antiparticles, take part in the process as virtual particles.

later times mixing leads to a state that is a time-dependent mixture of the two. This state eventually decays to either two or three π mesons. The two-pion final state has a much shorter lifetime (0.89×10^{-10} s compared to 5.2×10^{-8} s) and this allows the two decay modes to be studied separately. These states are eigenstates of CP, i.e. successive application of C and P produces the same state. The eigenvalues of the CP operator are +1 and −1 for the two- and three-pion state respectively. CP conservation in the decay process implies that the K meson is an eigenstate of CP with the appropriate eigenvalue. The CP eigenstates of the K meson are

$$K_1^0 = \frac{1}{\sqrt{2}}(K^0 + \overline{K}^0) \quad \text{and} \quad K_2^0 = \frac{1}{\sqrt{2}}(K^0 - \overline{K}^0)$$

with eigenvalues +1 and −1 and they should therefore decay into two and three π mesons respectively.

Then in 1964 came one of those far-reaching discoveries in physics: Christenson *et al.* [5] found that the long-lived component of the K meson could also decay into two pions with a probability of about 10^{-3}. Such an observation implies that CP is violated in K meson decays, albeit by only a small amount.

Since this discovery many experiments have been carried out to investigate and measure the effect with ever greater precision. However for a long time CP violation was a curiosity of physics, not understood, difficult to measure, yet providing a superb example of the effect of quantum mechanics in a simple two-state system. Because of the difference of a factor of about 600 in the lifetimes of the two K mesons it is relatively easy to study the two states separately.

CP violation effects are also expected in B meson decays, as discussed in section 2. However for B mesons the two mass eigenstates have similar lifetimes that are much shorter than those of the K^0. As a consequence it is only in the last few years that experimental studies of CP violation in the B meson system have been possible.

1.3 CP violation and the Universe

Shortly after the discovery of CP violation Sakharov wrote an important paper [6] setting out three conditions necessary for a universe in which an initial Big Bang, producing equal numbers of particle and antiparticles, nevertheless evolved to contain matter and no antimatter.

1. Baryon number is not conserved in all processes.

2. CP is not conserved in all processes.

3. There must be a period of non-thermal equilibrium at some point in the evolution of the Universe.

Extensive searches for evidence of non-conservation of baryon number in the form of proton decay have been carried since the 1980s. Such experiments require detectors of many thousands of tons that are left running continuously for many years. They are sensitive to the decay of individual protons, a typical decay mode sought being $\mathrm{p} \rightarrow \mathrm{e}^+\pi^0$. No evidence has been found for such a decay and the current experimental lower limit on the mean life of the proton is about 10^{33} years.

Baryon number violation by itself is not enough to explain the asymmetry of the Universe since antiprotons will show the same effect as protons, restoring the symmetry. There is therefore the requirement of a difference in decay rate between particles and antiparticles so that the Universe can have more quarks than antiquarks. This can be one of the effects of CP violation.

However, even this is not enough since the equipartition principle ensures that in a system in thermal equilibrium the number density of two particle types with the same mass must be equal. Thus we have Sakharov's third condition that there must have been a period of non-thermal equilibrium during the early evolution of the Universe.

Many difficulties arise in attributing the matter-antimatter asymmetry of the Universe to CP violation in the weak decay of quarks, the principal one being that it cannot generate a large enough effect [7]. New phenomena such as supersymmetry could enhance the effect and would manifest themselves in measurements of CP violation. The search for such effects is an important motivation for such measurements.

2 CP violation in B meson decay

B meson is the generic term for a meson containing a b or $\overline{\mathrm{b}}$ quark. The B^0_d and $\overline{\mathrm{B}}^0_\mathrm{d}$ have quark content $\overline{\mathrm{b}}\mathrm{d}$ and $\mathrm{b}\overline{\mathrm{d}}$ respectively while the B^0_s and $\overline{\mathrm{B}}^0_\mathrm{s}$ have quark content $\overline{\mathrm{b}}\mathrm{s}$ and $\mathrm{b}\overline{\mathrm{s}}$. Since the latter are not discussed further in this paper for convenience from now on we use the symbols B^0 and $\overline{\mathrm{B}}^0$to refer to $\overline{\mathrm{b}}\mathrm{d}$ and $\mathrm{b}\overline{\mathrm{d}}$. The b quark is relatively heavy and therefore so are all B mesons; for example the B^0_d has a mass of about $5.28\,\mathrm{GeV}/c^2$ compared with the K^0 mass of about $0.50\,\mathrm{GeV}/c^2$. As a consequence they have a large number of different decay modes.

In this section we turn to the Standard Model for an explanation of CP violation with particular reference to decays of B mesons.

2.1 CP violation in the Standard Model

Weak decays of leptons and quarks arise through a virtual W boson (figure 3). Although the same mechanism is present in both processes there is a difference in the coupling strength. The vertex $\mathrm{W}^- \rightarrow \overline{\nu}_\mathrm{e}\mathrm{e}^-$ is characterised by the weak interaction coupling constant, G_F, whereas for the vertex $\mathrm{W}^- \rightarrow \overline{\mathrm{u}}\mathrm{d}$ it is somewhat smaller. The s quark can decay via a similar process to $\mathrm{u}\mathrm{e}^-\overline{\nu}_\mathrm{e}$ with an even weaker coupling. This observation is

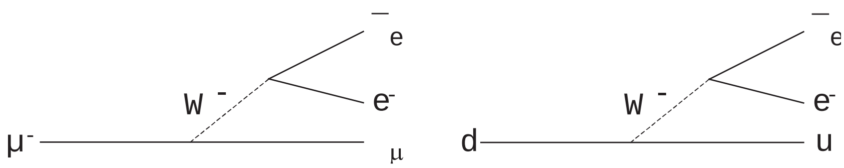

Figure 3: The decay of the muon and of the d quark through the W boson.

quantified by introducing the quark eigenstates

$$\begin{pmatrix} \mathrm{u} \\ \mathrm{d}' \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} \mathrm{c} \\ \mathrm{s}' \end{pmatrix}$$

where

$$\begin{aligned} \mathrm{d}' &= \mathrm{d}\cos\theta_\mathrm{C} + \mathrm{s}\sin\theta_\mathrm{C} \\ \mathrm{s}' &= -\mathrm{d}\sin\theta_\mathrm{C} + \mathrm{s}\sin\theta_\mathrm{C}. \end{aligned}$$

As a result of this redefinition the couplings for $\mathrm{W}^- \to \overline{\mathrm{u}}\mathrm{d}'$ and $\mathrm{W}^- \to \overline{\mathrm{c}}\mathrm{s}'$ are the same as for $\mathrm{W}^- \to \overline{\nu}_\mathrm{e}\mathrm{e}^-$ (we say that there is quark-lepton symmetry in the W coupling), and the couplings for $\mathrm{W}^- \to \overline{\mathrm{u}}\mathrm{d}$ and $\mathrm{W}^- \to \overline{\mathrm{u}}\mathrm{s}$ are reduced by the factors $\cos\theta_\mathrm{C}$ and $\sin\theta_\mathrm{C}$ respectively. This idea was introduced by Cabibbo and the parameter θ_C is called the Cabibbo angle. Its value has to be determined experimentally and is such that $\sin\theta_\mathrm{C}$ is about 0.22.

We therefore write

$$\begin{pmatrix} \mathrm{d}' \\ \mathrm{s}' \end{pmatrix} = \begin{pmatrix} \cos\theta_\mathrm{C} & \sin\theta_\mathrm{C} \\ -\sin\theta_\mathrm{C} & \cos\theta_\mathrm{C} \end{pmatrix} \begin{pmatrix} \mathrm{d} \\ \mathrm{s} \end{pmatrix}.$$

Kobayashi and Maskawa extended the idea to include the third quark generation in 1973 by introducing what is now known as the *CKM matrix*

$$\begin{pmatrix} \mathrm{d}' \\ \mathrm{s}' \\ \mathrm{b}' \end{pmatrix} = \begin{pmatrix} V_\mathrm{ud} & V_\mathrm{us} & V_\mathrm{ub} \\ V_\mathrm{cd} & V_\mathrm{cs} & V_\mathrm{cb} \\ V_\mathrm{td} & V_\mathrm{ts} & V_\mathrm{tb} \end{pmatrix} \begin{pmatrix} \mathrm{d} \\ \mathrm{s} \\ \mathrm{b} \end{pmatrix}.$$

The matrix V is unitary ($VV^\dagger$ =1) and depends on four parameters; three are real and the other is a phase angle. It is this phase angle that is the source of CP violation in weak decays of quarks. Thus in the Standard Model CP violation can only occur if there are at least three quark families.

Several of the absolute values of the elements of this matrix can be measured directly, for example from radioactive beta decay we find that $|V_\mathrm{ud}| = 0.9736 \pm 0.0010$. When the unitarity condition is imposed on these measured quantities the 90% confidence level range for each element is [8]

$$|V| = \begin{pmatrix} 0.9742-0.9757 & 0.219-0.226 & 0.002-0.005 \\ 0.219-0.225 & 0.9734-0.9749 & 0.037-0.043 \\ 0.004-0.014 & 0.035-0.043 & 0.9990-0.9993 \end{pmatrix}. \qquad (1)$$

There are a number of parameterisations that can be used to express V. One of the most useful is called the Wolfenstein parameterisation and is expressed as

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4). \tag{2}$$

Note that η represents the complex phase in V and hence η must be non-zero if CP violation is observed.

2.2 The CP triangle

Various relations amongst the elements of the CKM matrix follow from the unitarity condition $VV^\dagger$ =1. The most important for present purposes describes B^0 and $\overline{\mathrm{B}}^0$ decays

$$V_{\mathrm{ud}}V_{\mathrm{ub}}^* + V_{\mathrm{cd}}V_{\mathrm{cb}}^* + V_{\mathrm{td}}V_{\mathrm{tb}}^* = 0. \tag{3}$$

When the sum of three complex numbers is zero then the lines representing them in the complex plane form a triangle (figure 4(a)). Further, when equation (3) is transformed into the parameterisation of equation (2) the triangle can be represented in the coordinates ρ and η as shown in figure 4(b). The angles of the triangle are labelled α, β and γ and it can be seen that a non-zero value of β or γ implies that η is non-zero and hence that CP violation occurs.

Existing experimental constraints on the values of elements of V in equation (1) lead to constraints on the allowed region of the vertex A of the CP triangle. Such constraints arise from measured values of V_{ub}, the CP violation parameter in K^0 decay and the mass difference of the mass eigenstates for $\mathrm{B}^0_{\mathrm{d}}$ and $\mathrm{B}^0_{\mathrm{s}}$. The results of one such analysis [9] are shown as the shaded region in figure 4(b) from which it can be deduced that the angles of the triangle are constrained by these indirect measurements.

Measurements on the decays of B mesons allow the direct determination of several parameters in the CP triangle. The easiest to measure and the one described in detail in section 4.2 is $\sin 2\beta$. A precise measurement of $\sin 2\beta$ inconsistent with the indirect determination would reject the Standard Model explanation for CP violation.

2.3 Time-dependent decay rates in B decay

The phenomenon of mixing, discussed in section 1.2 for the K^0 system, also occurs in the B meson system via the same diagrams as figure 2 with the s quark replaced by a b quark[1]. Then, as for the K^0 system, it is possible to produce a B^0 and observe its time evolution.

The mass eigenstates of the B^0 system can be expressed as mixtures of B^0 and $\overline{\mathrm{B}}^0$ in the form $\mathrm{B}^0_{\mathrm{L}} = p\mathrm{B}^0 + q\overline{\mathrm{B}}^0$ and $\mathrm{B}^0_{\mathrm{H}} = p\mathrm{B}^0 - q\overline{\mathrm{B}}^0$, where p and q are complex numbers and $|p|^2 + |q|^2 = 1$.

For a given decay mode of B^0 and $\overline{\mathrm{B}}^0$ to a given final state f that is a CP eigenstate the amount of CP violation can be measured by the parameter λ_f given by

$$\lambda_f = \frac{q}{p}\frac{\overline{A}}{A}$$

[1] Recall that we are concentrating on $\mathrm{B}^0_{\mathrm{d}}$ mesons (quark content $\overline{\mathrm{b}}\mathrm{d}$) and ignoring $\mathrm{B}^0_{\mathrm{s}}$ mesons (quark content $\overline{\mathrm{b}}\mathrm{s}$).

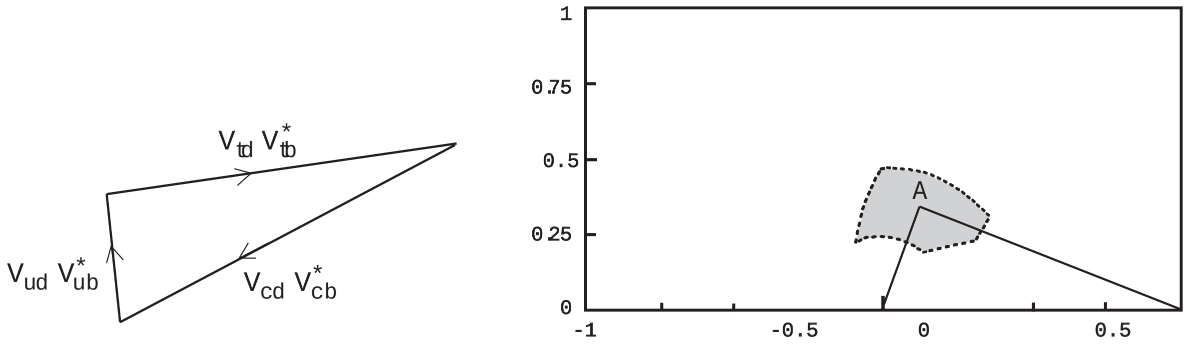

Figure 4: The CP triangle for B^0 and $\overline{B}^0$ decays arising from equation 3 and the transformed triangle in the Wolfenstein parameterisation showing the allowed region (shaded) deduced from indirect measurements.

where A and $\overline{A}$ are the amplitudes for the decay of B^0 and $\overline{B}^0$ to f respectively. $\lambda_f = \pm 1$ implies no CP violation and in this case the probability for the decay of a B meson a time t after production is simply $e^{-t/\tau}$, where τ is the B mean lifetime. When CP violation is present this expression is modified by the factor f_+ (f_-) when the particle is a B^0 ($\overline{B}^0$), with

$$f_\pm(t) = 1 + |\lambda_f|^2 \mp (1 - |\lambda_f|^2)\cos\Delta mt \pm 2\mathcal{I}m\lambda_f \sin\Delta mt$$

where Δm is the mass difference between the two B^0 mass eigenstates[2].

We now define a time-dependent asymmetry given by the difference in the number of decays of B^0 and $\overline{B}^0$ to the same state f at time t by

$$A_f(t) = \frac{n_+(t) - n_-(t)}{n_+(t) + n_-(t)}, \tag{4}$$

a quantity that can be measured as described below.

A particularly important class of decays of the B meson is where the b quark decays to $c\bar{c}s$ quarks. For this case $\lambda = \pm e^{-2i\beta}$ and equation (4) reduces to

$$A_f(t) = -\mathcal{I}m\lambda_f \sin\Delta mt = \pm\sin 2\beta \sin\Delta mt \tag{5}$$

i.e. the asymmetry has a sinusoidal time dependence and amplitude $\sin 2\beta$.

It is clearly essential to know if any individual particle started as a B^0 or a $\overline{B}^0$. Prior to 1999 the only measurements that had been attempted were at the LEP experiments at CERN and at Fermilab in the US. In these experiments the identity of particles was inferred by studying the properties of the rest of the event, which must contain an antiparticle to the decaying B. The time measurement was therefore made from the collision point, which is the B production point, to its decay point.

In 1999 two new experiments began, specifically designed to make precision measurements of CP violation parameters in B meson decays —*BABAR* at SLAC and Belle at KEK. In both experiments a B^0– $\overline{B}^0$ system is produced in the decay of the Υ(4S)

[2] In the units commonly used in particle physics in which $\hbar = c = 1$ mass has the dimension of T^{-1} (inverse time).

Experiment	Ref.	Events	$\sin 2\beta$
OPAL	[10]	24	$3.2^{+1.8}_{-2.0} \pm 0.5$
CDF	[11]	395	$0.79^{+0.41}_{-0.44}$
ALEPH	[12]	23	$0.84^{+0.84}_{-1.05}$

Table 3: Measurements of $\sin 2\beta$ at Fermilab and CERN.

resonance (a $\mathrm{b\overline{b}}$ state). They evolve coherently, each being described as a mixture of the two flavour states. At the instant of decay of the first particle the other is in the conjugate state and now evolves alone according to a well-defined time-dependence (section 4.1). By measuring the decay products of the first we can determine its state at decay (this decay is then known as the *tagging* decay). The relevant time for determining the evolution of the second particle is in this case the time between the two decays[3].

The B meson has a large number of different decay modes and the branching fraction to any individual mode is small. Important channels that are relatively clean experimentally and theoretically are[4] $\mathrm{B}^0 \to \mathrm{J}/\psi\mathrm{K}^0$ for the measurement of $\sin 2\beta$ and $\mathrm{B}^0 \to \pi\pi$ for the measurement of $\sin 2\alpha$. The former has a branching fraction $\mathcal{O}(10^{-3})$ and is the only decay mode for which a CP violation parameter had been measured prior to the *BABAR* and Belle experiments. Results from CERN and Fermilab are shown in table 3. (In the OPAL result the first error is statistical and the second is due to systematic uncertainties, a convention also used elsewhere in this paper.) The ALEPH collaboration combined these results and quoted a value $\sin 2\beta = 0.88^{+0.36}_{-0.39}$, consistent with the Standard Model prediction.

Measurement of the parameter α is even more difficult, requiring an analysis of decay modes such as $\mathrm{B}^0 \to \pi^+\pi^-$ and $\pi^0\pi^0$ with branching fractions $\mathcal{O}(10^{-5})$. It will require several years of data taking at *BABAR* and Belle before a reasonable measurement is made.

In the remainder of this paper we describe some of the first measurements from *BABAR*.

3 PEP-II and the *BABAR* detector

3.1 The PEP-II collider

The PEP-II collider at the Stanford Linear Accelerator Center consists of two circular storage rings, each of circumference 2.2 km, one storing a beam of electrons and the other a beam of positrons. The two beams are brought into collision at an interaction point, in the centre of the *BABAR* detector, where the electron beam direction is defined to be the z axis.

The beam energies are such that the resulting centre-of-mass energy is just sufficient to create an $\Upsilon(4\mathrm{S})$ particle (10.58 GeV). As the $\Upsilon(4\mathrm{S})$ decays exclusively to pairs of

[3]It doesn't matter if the first or the second decay is chosen as the tag. If we choose the second then we can determine the evolution of the first backwards in time from the point of tagging to its decay.

[4]The J/ψ particle is a $\mathrm{c\overline{c}}$ state. Its confusing name arose as a result of its simultaneous discovery by two independent groups in 1974, who separately named it the J and the ψ particle.

B mesons (either B^+B^- or $B^0\overline{B}^0$), the accelerator is a copious source of such particles, making it an ideal place to study CP violation.

The electron beam energy is greater than the positron beam energy (9.0 GeV compared to 3.1 GeV). This design feature has two significant implications in the measurement of CP violation.

- The distance in z between the points where the two B mesons decay is sufficiently large to be measurable with current detector technology. Since the $\Upsilon(4S)$ particle is not produced at rest but is moving in the laboratory frame at about half the speed of light in the direction of the incident electron beam, the B mesons to which it decays are also moving at relativistic speeds. The lifetime of the B^0 meson at rest is 1.55×10^{-12} s (1.55 ps) and time dilation significantly increases the observed lifetime of the B mesons in the laboratory frame such that the average separation of the decay points of the two B mesons in z is 250 μm. This should be compared to an average separation of 20 μm if the electron and positron beams had equal energy.

- It makes possible the direct measurement of the distance in z between the two B meson decay points since both B mesons travel in the same z direction (the incident electron beam direction) before they decay. If the $\Upsilon(4S)$ particle had been produced at rest in the laboratory frame, the two B mesons would have travelled in opposite directions, and the distance between their decay points could only be measured with knowledge of the production point of the $\Upsilon(4S)$, which cannot be accurately measured.

The electron and positron beams consist of bunches of particles about 1 cm long. When operating at the design configuration there are 1658 bunches separated in time by 4.2 ns. An electron bunch contains about 2.1×10^{10} particles and a position bunch contains about 5.9×10^{10} particles. The accelerator performance is measured in terms of the *luminosity* it achieves. Luminosity (L) is defined by

$$L = fn\frac{N_1 N_2}{A}$$

where N_1 and N_2 are the numbers of particles in each bunch, n is the number of bunches in either beam, A is the cross-sectional area of the beams and f is the revolution frequency of the beams. The higher the luminosity, the more $\Upsilon(4S)$ particles are produced every second. The design luminosity of the PEP-II accelerator is $3 \times 10^{33}\,\mathrm{cm^{-2}\,s^{-1}}$. This was achieved during the 2000 data taking run, just 16 months after the first collisions were observed.

3.2 The *BABAR* detector

The *BABAR* detector was constructed by a collaboration of physicists from nine countries [9]. Construction was approved in November 1995 and the first data were recorded just three and a half years later, in May 1999.

Like many particle detectors, *BABAR* consists of a series of components or *sub-detectors*, designed to fulfil the following requirements. The detector must be able to measure accurately the momentum of charged particles such as pions, electrons, muons

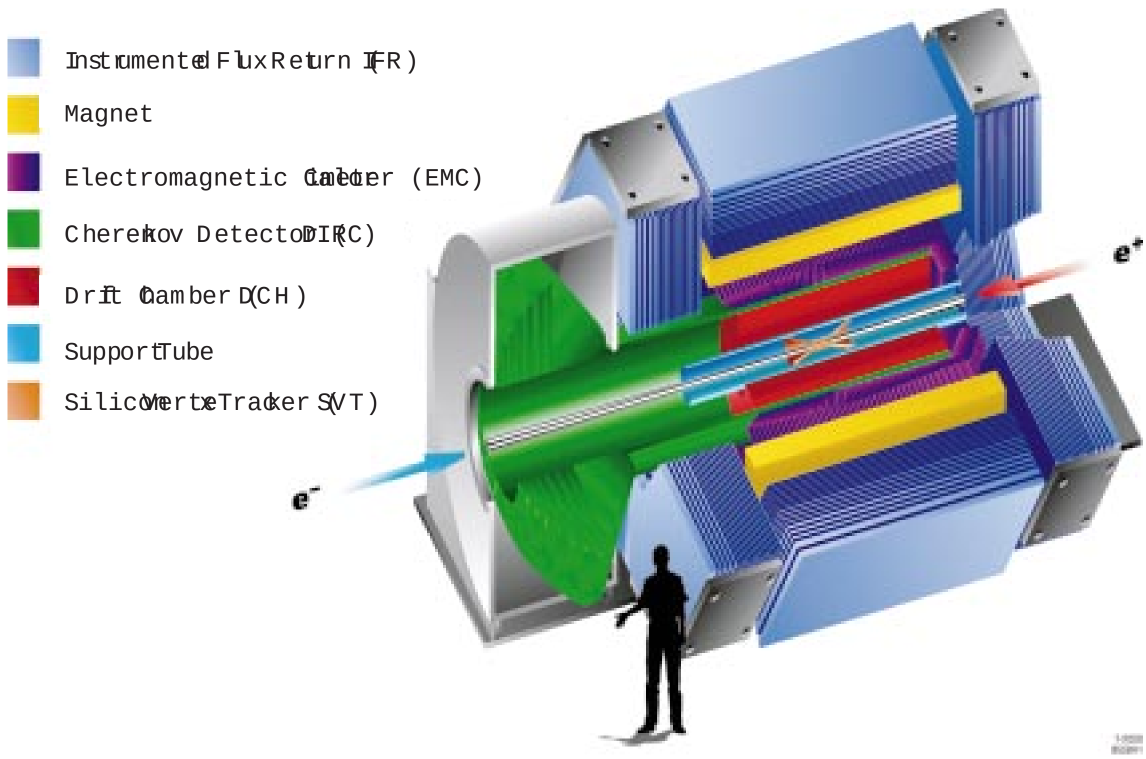

Figure 5: A schematic view of the *BABAR* detector showing the sub-detectors described in the text.

and kaons, and the energy of neutral particles such as photons. This is vital to be able to reconstruct the kinematics of the B meson from its decay products, which may be a mixture of charged and neutral particles. In addition, the detector must be able to provide measurements of quantities which can be used to discriminate between the various particle species (section 3.3). This is again useful in looking for specific decays of B mesons as well as being vital for the tagging of the flavour of the B decay (section 3.4). Finally, in order to be able to measure time-dependent CP violation, it must be possible to determine accurately the distance in z between the two B decay vertices (section 3.5).

A schematic diagram of the detector is shown in figure 5. There is more instrumentation in the forward (electron beam) direction because the asymmetric configuration of the beam energies means that more particles are produced moving in that direction. A vital component of the detector is the superconducting solenoid, which provides a magnetic field of 1.5 T, enabling the charge and the momentum of charged particles to be determined from their curvature in the field.

Within the solenoid are four nested sub-detectors. Moving outwards from the centre they comprise the following.

- **A Silicon Vertex Tracker (SVT)**. The SVT is made of five double-sided layers of silicon detectors giving, in general, ten points on the track of each charged particle. By extrapolating these points backwards towards the interaction point it is possible to obtain an accurate measurement of the z position of the B meson decay vertices, as well as the direction of the charged particles.

- **A Drift Chamber (DCH)**. This is the main detector for reconstructing charged particle tracks. It is a gas filled chamber containing several thousand wires maintained at voltages of about 1960 V. The passage of charged particles is detected by registering the current deposited on the wires from the ionization of the gas in the chamber. The momentum of a particle can be measured from the curvature of its trajectory in the magnetic field. In addition, information about the particle species can be obtained from studying its energy loss as it moves through the chamber. The centre of the chamber is somewhat forward in z of the collision point to improve the detection of charged particles moving in the forward direction.

- **The Detector of Internally Reflected Cherenkov Light (DIRC)**. This is a novel detector designed to provide information about the particle species, in particular to be able to separate pions from kaons at momenta of a few GeV. It uses the phenomena of *Cerenkov radiation*, the light emitted when a charged particle passes through a transparent medium at a speed greater than the speed of light in that medium. It is emitted in the form of a cone of light at an angle that depends on the speed of the particle. By combining the measurement of the Cerenkov angle with the measurement of the momentum of the particle from the DCH, it is possible to deduce the mass, and therefore the species, of the particle.

  The DIRC is made of 144 quartz bars, each nearly 5 m long. The Cerenkov radiation emitted as charged particles traverse the detector undergoes total internal reflection along the length of the bar, a process which preserves the Cerenkov angle. Mounted on the rear of the detector is a tank of water containing 10,752 photomultiplier tubes. The cone of Cerenkov light emerges from the ends of the quartz bars and is projected onto this array of photomultiplier tubes, allowing the Cerenkov angle to be measured.

- **An Electromagnetic Calorimeter (EMC)**. This detector is designed to detect photons and other neutral particles, which leave no signal in the tracking detectors. It is made of 6580 crystals of caesium iodide, a scintillating material, each about 31 cm in length and about 25 cm^2 in cross-section. Photons, electrons and positrons produce electromagnetic showers in this detector and the resulting scintillation light is detected by photodiodes on the rear of the crystals. The amount of light seen depends on the energy of the particle. In addition to photon identification electrons can be discriminated from pions on the basis of the way energy is shared between neighbouring crystals.

Surrounding the superconducting solenoid is the Instrumented Flux Return (IFR). This consists of 900 detectors interleaved with the iron plates that provide the flux return of the magnet. It is designed primarily to detect the passage of muons, which are highly penetrating particles. In addition, the IFR is used to detect any long lived neutral particles which pass through the EMC.

An electron and a positron do not interact every time two beam bunches cross (every 4.2 ns). A hardware and software trigger combines basic information from the detector, such as the number of charged particles observed and their most likely position of origin, and makes a decision on whether or not to record the data from the detector for this beam crossing. This process reduces the rate at which data is recorded to about 100 events a second, whilst being more than 99% efficient at keeping events useful for CP violation studies.

3.3 Particle identification

An important aspect in the experimental measurement of CP violation is the ability to identify particles of specific types, particularly muons, electrons and kaons. This enables the selection of different decay modes of the B meson and is a vital component in B flavour tagging, described in section 3.4.

Particle identification requires combining information from the various sub-detector components. Use is made of the way in which particles transfer their energy to the medium they are traversing via the process of ionization or excitation of the constituent atoms. This includes the energy deposited in the EMC, the number of layers of the IFR which have a signal induced by a given particle (which is a measure of its penetrating power), the Cerenkov angle measured in the DIRC and the mean rate of energy loss ($\mathrm{d}E/\mathrm{d}x$) of a particle measured in the SVT or DCH (using the fact that the $\mathrm{d}E/\mathrm{d}x$ of a charged particle of mass m and energy E has a minimum for $E \sim 3mc^2$ and increases logarithmically with E/mc^2).

By far the most abundant particle produced is the pion. Hence it is the ability to reject pions that dominates the purity of the particle-identification algorithms. Such algorithms can be optimised for efficiency or purity, depending on the analysis requirements. Typical performances of one such algorithm are listed in table 4.

Particle species	Efficiency	Pion rejection
Electrons	88%	99.7%
Muons	77%	97.5%
Kaons	90%	97.5%

Table 4: Typical performances of one of the particle identification algorithms. Efficiency refers to the fraction of particles correctly identified and pion rejection to the fraction of pions rejected.

- **Electron identification.** The primary means of identifying electrons makes use of the properties of the shower which an electron induces in the EMC, depositing all its energy in the first few centimeters of the EMC. This results in a relatively compact energy deposit spread over a small number of crystals with a well defined maximum. On the other hand, hadrons such as pions undergo nuclear interactions when passing through material. The showers they induce are in general more dispersed and all the energy of the particle may not be deposited in the EMC. Electrons can thus be distinguished from hadrons from the ratio of the energy deposited by a particle in the EMC to the momentum of the particle measured by the DCH. For electrons this ratio is very close to unity, but for hadrons it is in general lower. Further discriminating power comes from the distribution of energy within a shower, from the measurement of the $\mathrm{d}E/\mathrm{d}x$ of the particle in the DCH and, for low momentum electrons, from the Cerenkov angle in the DIRC.

- **Muon identification.** Muons are highly penetrating particles. A muon passes through the EMC depositing only a small amount of energy (typically 400 MeV, independent of momentum) and produces signals in a large number of layers of the IFR. Although some pions penetrate into the IFR, they normally deposit all their energy in the first few layers.

- **Kaon identification.** The ability to identify low momentum (less than about 2.7 GeV) kaons comes primarily from the measurement of the $\mathrm{d}E/\mathrm{d}x$ in the SVT and the DCH. At higher momentum, the Cerenkov angle measured in the DIRC and the number of photons found in the Cerenkov ring are the primary discriminating variables to separate kaons from pions.

3.4 B flavour tagging

To measure CP violation it is necessary to determine at a known time the flavour of the B meson (either B^0 or $\overline{\mathrm{B}}^0$) which subsequently decays to the final state of interest by examining the decay products of the other (*tagging*) B meson (section 2.3). The particle identification algorithms described in section 3.3 are used to find particles of a given species. The tagging algorithm employed by the *BABAR* experiment involves separating events into the following categories.

- **Lepton tag**. The decay products of the tagging B contains a high momentum (typically greater than about 1 GeV/c) lepton. This indicates a decay of the B, of the form $\mathrm{B} \rightarrow \mathrm{X}\ell\nu$, where X represents anything and ℓ is either an electron or muon. In these decays, positively charged leptons are only produced from decays of B^0 mesons and negatively charged leptons are only produced from decays of $\overline{\mathrm{B}}^0$ mesons.

- **Kaon tag**. The decay products of the tagging B contains at least one kaon. This indicates a cascade of quark decays $\mathrm{b} \rightarrow \mathrm{c} \rightarrow \mathrm{s}$. A positively charged kaon indicates a B^0 meson decay, whilst a negatively charged kaon indicates a $\overline{\mathrm{B}}^0$ decay. If the decay products include more than one kaon, the sign of the sum of the kaon charges is used to tag the decay. If the sum of the charges is zero, the event is assumed not to be tagged. If the event contains a high momentum lepton and one or more kaons, it is assumed to be tagged only if the identification of the flavour of the B is the same in both cases.

- **Neural network tag**. If the event cannot be tagged with leptons and kaons (about 45% of events) a neural network is used, combining many variables, each of which has some limited power of discriminating between B^0 and $\overline{\mathrm{B}}^0$ decays.

There are two important factors in characterising the performance of the algorithm used to tag the flavour of the B decay. The first is the efficiency of the tag, meaning what fraction of events fall into a given category. The second is the fraction of events where the flavour of the B meson is incorrectly identified. This is often referred to as the *mis-tag rate*. Both efficiency and mis-tag rate are different for each tagging category. The latter effect dilutes any measurement of asymmetries, as events which are really B^0 decays are treated as $\overline{\mathrm{B}}^0$ decays and vice versa. However, if the mis-tag rate is known, it can be accounted for in the measurement of the asymmetry. In practice, the tagging performance is measured in the study of $B^0 - \overline{B}^0$ mixing (section 4.1).

3.5 Decay length measurements

In measurements of CP violating asymmetries, typically one B meson is fully reconstructed by identifying all of its decay products and the distance between the two B decay vertices is determined. The difference in time between the two B decays (Δt) is directly proportional to this distance (Δz).

The decay vertex of the B which has been fully reconstructed is determined as the common point of origin of all the charged tracks from the B decay. This decay vertex can be reconstructed with a typical precision in z of $40\,\mu$m.

The other B vertex (the tagging B vertex) is reconstructed with the remaining charged tracks in the event. Complications arise since some of these tracks are produced from the decay of long lived particles (such as the K^0_S meson) or may be background particles not from the B meson decay. Such tracks do not originate from the decay vertex of the B meson. To account for this effect an iterative algorithm is employed that discards tracks successively if they do not appear to come from a common vertex. The precision to which the z position of the tagging B vertex can be determined is significantly worse than for the fully reconstructed B, with a typical resolution of $175\,\mu$m.

The precision with which Δz can be determined is therefore dominated by the resolution of the tagging B vertex. The resolution in Δz is typically $190\,\mu$m, which can be compared with the typical separation of the two B decay vertices of $250\,\mu$m. The finite resolution in Δz affects the measurement of any time-dependent asymmetry by smearing the true Δt distribution. However, since the resolution is known, it can be taken correctly into account. In practice, the Δz resolution is measured in the study of $B^0 - \overline{B}^0$ mixing described in section 4.1.

4 First results from *BABAR*

During its inaugural data taking period in 1999 – 2000, *BABAR* collected a total of 22.7 million $B^0\overline{B}^0$ events, the largest sample as yet recorded. Two of the many measurements made with this data sample are described here.

4.1 Measurement of mixing

Neutral B mesons can undergo mixing (section 1.2), where a B^0 meson can transform into a $\overline{B}^0$ meson or vice versa. Although initially the B mesons from the decay of the $\Upsilon(4S)$ particle must be a $B^0\overline{B}^0$ pair, after one B meson decays the other is free to mix before it in turn decays.

To study this effect, it is necessary to select a sample of events where one of the B mesons decays to a set of particles which unambiguously determines whether it was a B^0 or a $\overline{B}^0$ meson when it decayed. For example, a B^0 (quark content $d\overline{b}$) can decay to a D^- meson ($d\overline{c}$) and a π^+, while a $\overline{B}^0$ meson ($\overline{d}b$) decays to $D^+\pi^-$. Thus reconstructing a D meson and determining its charge identifies the B meson.

The algorithms described in section 3.4 is then applied to determine the flavour of the other B meson when it decayed. The sample can be divided into two categories: *unmixed* events, where the two B mesons had opposite flavour when they decayed, and *mixed* events, where they had the same flavour. By measuring the distance in z between the two B decay vertices (section 3.5), the time difference Δt between the two decays can be determined. It is then possible to construct the time-dependent asymmetry given by

$$A_{mixing}(\Delta t) = \frac{N_{unmixed}(\Delta t) - N_{mixed}(\Delta t)}{N_{unmixed}(\Delta t) + N_{mixed}(\Delta t)}.$$

This asymmetry is in principle equal to $\cos(\Delta m \Delta t)$, where Δm is the mass difference between the two B^0 mass eigenstates (section 2.3). However there are effects which need to be taken into account when measuring this asymmetry. Firstly the B flavour tagging algorithm sometimes gives the wrong answer. This means that in practice, the observed asymmetry is given by

$$A_{mixing}(\Delta t) = (1 - 2\omega)\cos(\Delta m \Delta t)$$

where ω is the mis-tag rate. Secondly, Δt is measured to a finite precision, thus smearing the asymmetry as a function of the true Δt. Thirdly, the data sample is not pure but contains events where the decay mode of the fully reconstructed B meson has been incorrectly identified. Although the fraction of background events can be determined by studying the distribution of the mass of the reconstructed B mesons, the fact that these events may have a different asymmetry in Δt than the true signal events needs to be taken into account.

In practice, the asymmetry reconstructed from the data is fitted to a function which has 34 free parameters to determine simultaneously Δm, the mis-tag rate for all the tagging categories, the resolution in Δt and the asymmetry in Δt for the background events in the sample. The fit is shown in figure 6 where the cosine dependence on Δt is clearly visible.

The tagging efficiency obtained from the fit is 69% and the mis-tag rate is about 20%. The value obtained for Δm is $0.519 \pm 0.020 \pm 0.016\,\mathrm{ps}^{-1}$, in agreement with the average of all previous measurements [8] of $0.478 \pm 0.017\,\mathrm{ps}^{-1}$.

The values of the mis-tag rates and the resolution in Δt determined from this fit are subsequently used in the measurement of $\sin 2\beta$ which is described in the next section.

4.2 Measurement of $\sin 2\beta$

The angle β of the CKM triangle can be measured by studying the time-dependent asymmetry for decays to the final states $J/\psi K^0_S$ and $\psi(2S)K^0_S$, which have CP$= -1$, and $J/\psi K^0_L$, which has CP$= +1$. For these decays the asymmetry $A_f(t)$ is proportional to $\sin 2\beta \sin \Delta m t$ (equation (5)).

The J/ψ and $\psi(2S)$ particles are identified through their decays to pairs of oppositely charged electrons or muons, and $\psi(2S)$ mesons also through the decay to $J/\psi \pi^+\pi^-$. K^0_S particles are reconstructed through their decay to a pair of oppositely charged pions or a pair of neutral pions. K^0_L particles are long lived and typically only deposit a fraction of their energy in traversing the various subdetectors of *BABAR* but their direction can be determined from the signal they leave in the EMC or IFR. The J/ψ, $\psi(2S)$ and K^0_S

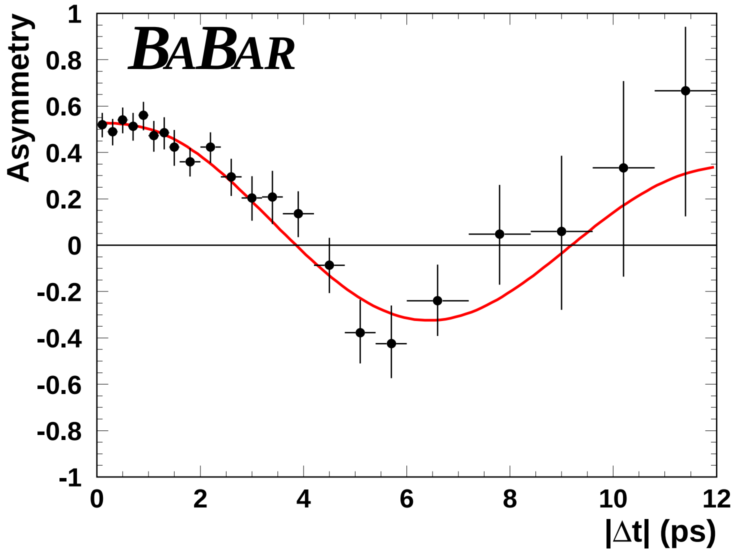

Figure 6: The fit to the asymmetry A_{mixing} as a function of Δt.

particles are combined to reconstruct the kinematics of the parent B meson. Only combinations with an invariant mass close to that of a B meson and with a small difference between the measured energy and the energy expected for a B meson (ΔE) are selected for the final sample. Figure 7 shows the mass and ΔE distributions for the events in this sample. For the $\mathrm{J}/\psi\mathrm{K^0_L}$ decay, as the energy of the $\mathrm{K^0_L}$ is not measured in the detector, it is calculated under the assumption that the $\mathrm{J}/\psi\mathrm{K^0_L}$ invariant mass is equal to that of a neutral B meson and B candidates are kept only on the basis of their measured ΔE.

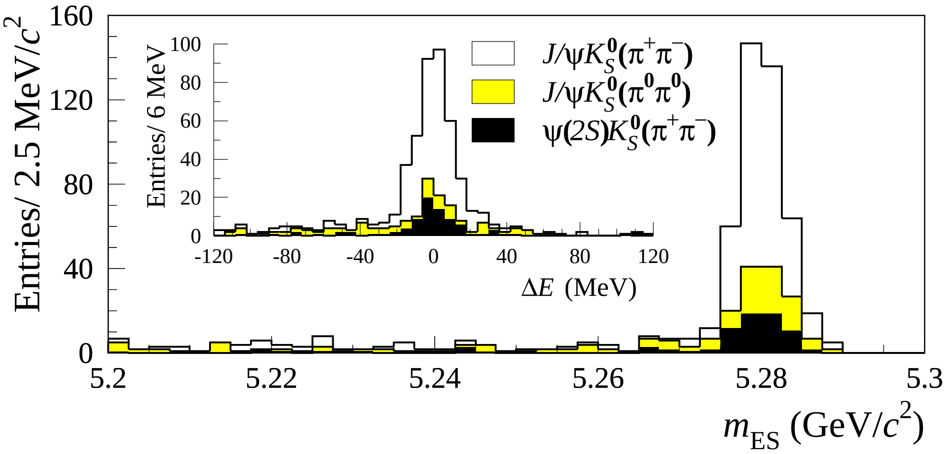

Figure 7: The distribution of the reconstructed B mass for events used in the $\sin 2\beta$ measurement. The insert shows the distribution of ΔE, the difference between the measured and expected energy of the B candidates (from [13]).

Having isolated the sample of events, the flavour of the other B is determined using the flavour tagging algorithm described in section 3.4, and the time difference between the two B decays measured (section 3.5). The final sample used for the measurement contains 273 $J/\psi K^0$ and $\psi(2S)K^0_S$ decays with a purity of about 96% and 256 $J/\psi K^0_L$ decays with a purity of about 39%.

In the same way as for the mixing analysis described in section 4.1, the value of $\sin 2\beta$ is determined from a fit. The mis-tag rate and the resolution in Δt are determined from a fit to the mixing sample. The asymmetry for the background events in the CP sample is allowed to vary in the fit.

Initially, the measurement was performed as a *blind analysis*, meaning that the value of $\sin 2\beta$ from the fit was not revealed. This enabled detailed studies to be performed of potential sources of error in the measurement without risk of biasing the value of $\sin 2\beta$. Prior to unveiling the value of $\sin 2\beta$, several consistency checks were performed. For example, the measurement was performed separately for the different decay modes in the CP sample and for the different tagging categories, and it was checked that the blind values of $\sin 2\beta$ obtained in each case were consistent. In addition, an identical analysis was carried out on samples of events which were kinematically similar to the CP sample, but which could not exhibit CP violation (for example, samples of charged B decays). For these samples, in every case the measured asymmetry was consistent with zero, indicating that the analysis procedure did not introduce a fake asymmetry.

Finally $\sin 2\beta$ was determined to be $0.34 \pm 0.20 \pm 0.05$ from the fit to the asymmetry shown in figure 8 [13].

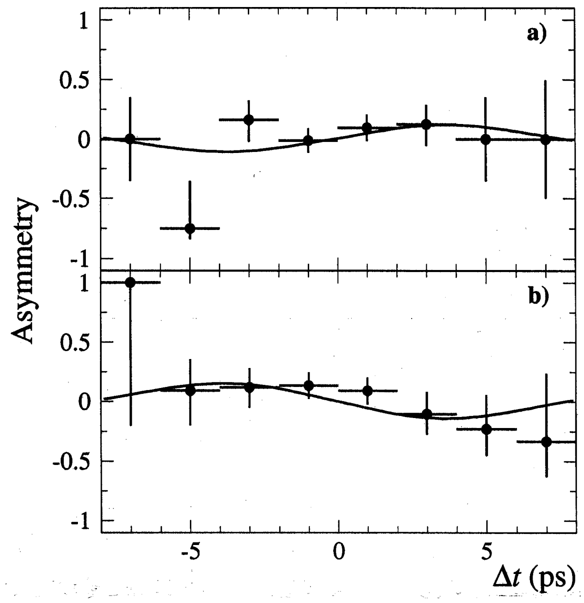

Figure 8: The fit to the CP violation asymmetry for (a) the $J/\psi K^0_S$ and $\psi(2S)K^0_S$ events (CP$= -1$) and (b) for the $J/\psi K^0_L$ events (CP$= +1$). The fitted curves have opposite sign because of the opposite sign of the CP eigenvalues (from [13]).

This result is consistent with previous measurements, but with a substantially improved error (figure 9). It is also consistent with theoretical estimates of the magnitudes of the CKM matrix elements. However, more data are required to improve the significance of this measurement. The Belle experiment at KEK has reported a similar measurement of $\sin 2\beta$ from similar decay modes [14].

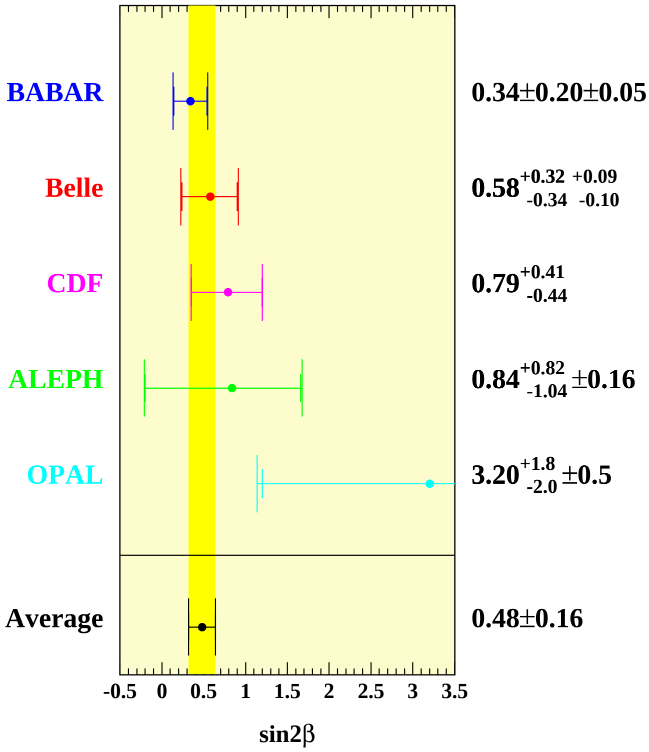

Figure 9: A summary of all $\sin 2\beta$ measurements.

5 The Future

The B factories have been taking data for about two years and already significant new measurements in the field of B physics and CP violation have been made. Two examples of measurements made by the *BABAR* experiment have been discussed in this article.

However, both the PEP-II and KEK accelerators have not yet reached their maximum possible luminosity. Although PEP-II has achieved its design targets, it is apparent that the accelerator is not running at its limit. It is expected that the *BABAR* detector will have recorded at least 10^9 B meson decays by the end of 2005, about twenty-five times more than in the first year. The KEK accelerator has already achieved a similar luminosity to PEP-II during its 2001 running period, but this is only one third of the design luminosity of this machine.

As well as improving the statistical significance of the measurement of $\sin 2\beta$, it is anticipated that the B factories will be able to make the first ever measurements of the other two angles of the CKM triangle, α and γ, using as many different decay modes of B mesons as possible. The precision to which the sides of the triangle are known can also be improved. It will be possible to check for consistency between measurements, for example to verify whether the sum of the three angles of the unitarity triangle is indeed 180° and whether the measurements of the angles obtained using different B decay modes agree with each other. Any inconsistencies will indicate flaws in our current model of CP violation. The high luminosity of the B factories will also make possible studies of very rare B decays.

In addition to the B factories, the $p\overline{p}$ accelerator at Fermilab (the Tevatron) has undergone a significant upgrade and will resume data taking this year. It is anticipated that the accelerator will produce $b\overline{b}$ quark pairs at the rate of 10^{11} a year. These data will be used to make both competitive and different measurements of CP violation to those made by the B factories. When the Large Hadron Collider begins operation at CERN in 2006 it will have the capability of further improving the precision of several of the CP triangle parameters.

It is an exciting time in the field of B physics and CP violation. In the next decade it will be possible to go further than ever before in our understanding of the asymmetry between matter and antimatter in the Universe.

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