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Physics of B mesons

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Abstract

In this report I discuss the physics of B mesons which were first observed directly in 1986 through their full reconstruction. Emphasis is put on the experimental results on exclusive and inclusive B decays obtained since then by the e^+e^- experiments ARGUS at DESY and CLEO at Cornell. The results are discussed in the framework of the standard model with three families, on which in particular the $B^0\bar{B}^0$ mixing observed in 1987 by ARGUS puts strong constraints.

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1. Introduction

The b quark was proposed as the fifth quark in 1973 by Kobayashi and Maskawa (1973), who introduced a six-quark model with three quark families as one possibility to describe the observed CP violation in K meson decays. The existence of the b quark was experimentally verified in 1977 with the discovery of the Υ resonances, which are bound states of a b quark and its antiquark $\bar{b}$ (Herb *et al* 1977). In the last ten years much has been learned about the properties of the b quarks, both through the investigation of the Υ resonances and expecially by studying the weak decays of B mesons which contain a $\bar{b}$ quark. In particular, 1987 was a very fruitful year with the observation of $B^0\bar{B}^0$ oscillations (Albrecht *et al* 1987d).

The study of b quarks and their decays can help to determine the parameters of the standard model, the present theory of electromagnetic, weak and strong interactions. The triumph of the standard model has been the discovery in 1983 at CERN of the predicted intermediate vector bosons, $W^{\pm}$ and the Z^0. However, one of its drawbacks is the large number of parameters which define the theory. Assuming the neutrinos to be massless, the standard model with three families is characterised by 18 parameters, namely three coupling constants, six quark masses, three lepton masses, three quark mixing angles and one phase, the weak mixing angle Θ_W and the mass of the Higgs particle. These parameters have to be determined by experiment. Before the discovery of the b quark in 1977 only the three coupling constants, four quark masses, three lepton masses, one quark mixing angle and the weak mixing angle were known more or less accurately.

A better understanding of the standard model is obtained by studying the physics of b quarks. The investigation of b hadrons allows the determination of five more parameters of the standard model, namely the masses of the b and t quarks, which together represent the third family, two quark mixing angles and the phase δ, which could be responsible for the CP violation. These quantities can be determined by measuring the lifetime and the semileptonic branching ratio of B hadrons, by studying flavour oscillations in the neutral B meson systems and by searching for rare B decays. For the determination of the mass of the t quark from B physics, theoretical input is needed so that the best way to determine this mass is the direct method of studying states with a t quark. Only the determination of the mass of the Higgs boson then remains to fix all the parameters of the standard model. Once a better knowledge is obtained for the standard model parameters, further insight could be gained by testing, for example, possible relations between the fermion masses and the quark mixing angles. If such relations exist, they would allow a substantial reduction of the number of parameters in the standard model.

The great importance of B physics lies further in the fact that its investigation allows valuable tests of the validity of the standard model. Certain processes, such as flavour oscillations in the neutral B system or rare decays of B mesons which are induced by loop diagrams, are also sensitive to physics beyond the standard model with three generations. The observation of CP violation in the B system will certainly shed light on this important phenomenon, which is so far not fully understood. In this respect, the physics of B mesons is complementary to that of the K mesons, which has contributed enormously to our understanding of elementary particles and their interactions.

Information on B mesons and their decays has been obtained mainly by studying B mesons from the decay of the Υ(4S) meson that is produced in e^+e^- annihilations at the CESR and DORIS e^+e^- storage rings. Lifetime measurements could only be made at the higher energy e^+e^- machines PETRA and PEP. $B\bar{B}$ oscillations have been studied at all e^+e^- machines and the CERN $p\bar{p}$ collider.

This review is organised as follows: § 2 will recall basic properties of the b quark and its description in the standard model. In §§ 3–6 exclusive and inclusive decay properties of the B mesons are given. Section 7 is devoted to the observation of flavour oscillations in the neutral B system. The experimental information on rare B decays is given in § 8 for loop-induced B decays. The implication of the observed phenomena is discussed in the framework of the standard model with three families.

2. The b quark

2.1. *The discovery of the b quark*

The existence of the b quark was experimentally established by the discovery of the Υ resonances in 1977 at Fermilab (Herb *et al* 1977). An enhancement near 9.5 GeV/c^2 was observed in the mass spectrum of $\mu^+\mu^-$ pairs produced in 400 GeV proton–nucleus collisions (figure 1). This was shown to consist of two peaks at $M_1 = 9.4$ GeV/c^2 and $M_2 = 10.0$ GeV/c^2, identified as the Υ and Υ′. The small observed width, unexpected for such heavy particles if they were composed of ordinary quarks, the sizable rate for electromagnetic decays, and the observed spacing between the two resonances, similar to that found in the charmonium system, led to the explanation of the Υ states as bound states of a new, massive quark b and its antiquark $\bar{b}$ in an atom-like configuration.

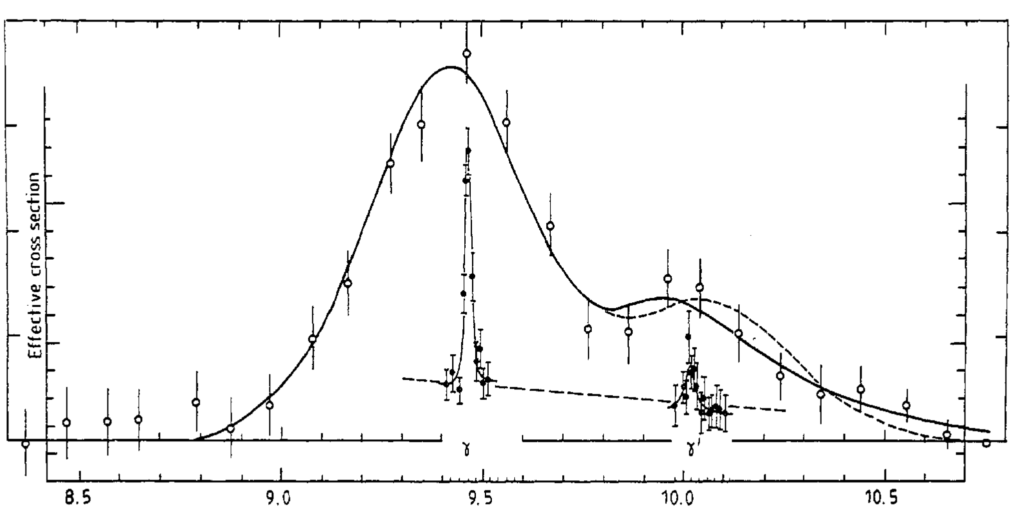

Figure 1. Open circles: dimuon mass spectrum above 8.5 GeV (background subtracted); full circles: visible cross section for $e^+e^- \rightarrow$ hadrons.

This interpretation of the Υ resonances as bound $b\bar{b}$ states was verified one year later by the DASP II and PLUTO collaborations. These experiments were carried out at the upgraded e^+e^- storage ring DORIS II at DESY in Hamburg (Darden *et al* 1978, 1979, Berger *et al* 1978, Bienlein *et al* 1979). Analysing e^+e^- annihilations into hadrons, the DORIS experiments observed two narrow resonances at 9.46 and 10.023 GeV/c^2 (figure 1) whose widths were consistent with the energy resolution of the DORIS storage ring. The Υ mesons must have the quantum numbers of the photon, $J^{PC}=1^{--}$ since they couple to the virtual photon created in e^+e^- annihilation (figure 2). The Υ and Υ' were identified as the lowest lying $b\bar{b}$ $^3S_1$ states $\Upsilon(1S)$ and its first radial excitation $\Upsilon(2S)$.

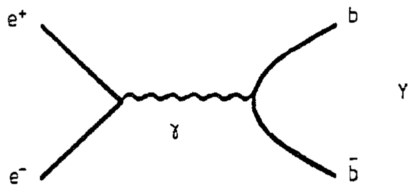

Figure 2. Formation of Υ mesons in e^+e^- annihilations.

In e^+e^- annihilations, the Υ resonances with mass M_Υ and decay width Γ are produced with a cross section

$$\sigma(e^+e^-\to\Upsilon\to\text{anything})=\frac{3\pi}{E_{cm}^2}\frac{\Gamma_{ee}\Gamma}{(E_{cm}-M_\Upsilon)^2+\Gamma^2/4}$$

where E_{cm} is the centre-of-mass energy and Γ_{ee} is the electronic width experimentally obtained from the resonance area

$$\int\sigma\,dE_{cm}=\frac{6\pi^2}{M_\Upsilon^2}\Gamma_{ee}$$

and is given theoretically by the VanRoyen–Weisskopf formula including first-order QCD corrections (VanRoyen and Weisskopf 1967, Barbieri *et al* 1975)

$$\Gamma_{ee}=\frac{16\pi Q_b^2\alpha^2}{M_\Upsilon}\left(1-\frac{16}{3\pi}\alpha_s\right)|\Psi(0)|^2$$

with Q_b the charge of the b quark, α and α_s the coupling constants of the electromagnetic and strong interactions respectively, and $\Psi(0)$ the wavefunction of the $b\bar{b}$ system at the origin.

From the measurement of the electronic widths Γ_{ee} of these resonances the charge of the new b quark was determined to be $|Q_b|=\frac{1}{3}$. The total width of the $\Upsilon(1S)$ meson is obtained from a measurement of Γ_{ee} and the branching ratio $B_{\mu^+\mu^-}$ for decays into $\mu^+\mu^-$ pairs, assuming lepton universality:

$$\Gamma_\Upsilon=\Gamma_{ee}/B_{\mu^+\mu^-}.$$

The narrow measured width, $\Gamma_\Upsilon=(51\pm3)$ keV (Buchmüller and Cooper 1987), results from the expected dominant decay of the Υ via annihilation of the $b\bar{b}$ system into three gluons (figure 3(*a*)): the rate for this decay is small since it depends on the third power of the strong coupling constant α_s. The measured value of Γ_Υ can be reproduced using $\alpha_s\simeq0.2$ in lowest-order QCD (Appelquist and Politzer 1975, Novikov *et al* 1978).

More recently the Υ system has been studied very intensively by groups working at the e^+e^- storage rings CESR at Cornell and DORIS II at DESY. As predicted, a

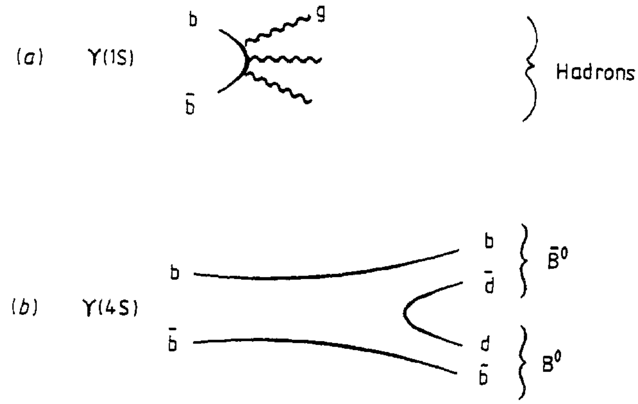

Figure 3. (*a*) Υ(1S) decay into three gluons; (*b*) Υ(4S) decay into a pair of B mesons.

series of b$\bar{\text{b}}$ states is observed with different quantum numbers, similar to those of the hydrogen atom. Hadronic transitions between the Υ(3S), Υ(2S) and Υ(1S) proved that these states have the same quark content. Radiative decays of the Υ(2S) and Υ(3S) have been used to show the existence of *p*-wave b$\bar{\text{b}}$ states. Together, all these measurements allowed details of the strong interactions to be studied so that the b$\bar{\text{b}}$ system is today well understood in terms of potential models, as reviewed elsewhere (for example, Buchmüller and Cooper 1987, Berkelmann 1983, Franzini and Lee-Franzini 1983).

Higher radial excitations of the Υ meson up to the Υ(6S) have been observed as peaks in the e^+e^- annihilation cross section (figure 4 (Giles *et al* 1984, Besson *et al*

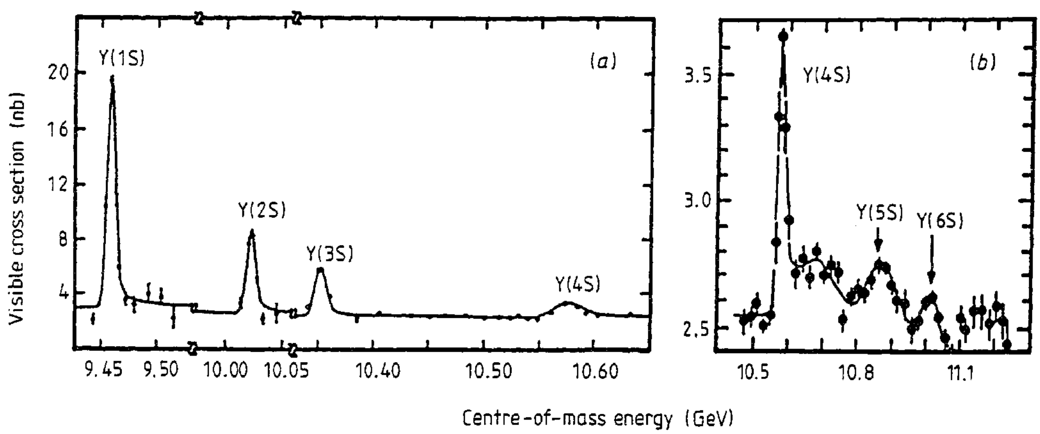

Figure 4. Cross section for $e^+e^- \rightarrow$ hadrons.

Table 1. Resonance parameters of Υ mesons (Buchmüller and Cooper 1987).

Resonance	Width (keV)	Mass (MeV/c^2)	Γ_{ee} (keV)
Υ(1S)	51 ± 3	9 460.3 ± 0.3	1.33 ± 0.06
Υ(2S)	37 ± 10	10 023.4 ± 0.3	0.60 ± 0.04
Υ(3S)	27 ± 6	10 355.5 ± 0.5 ± 0.2	0.43 ± 0.03
Υ(4S)	20 000 ± 4000	10 580.0 ± 4	0.23 ± 0.04

1985) and table 1). The Υ resonances above the Υ(3S) are much broader than the lower lying ones. This indicates that the Υ(4S) resonance is just above the threshold for decay into a pair of B mesons by the OZI favoured channel illustrated in figure 3(*b*).

2.2. The Υ(4S) and open beauty

B mesons are bound states of the heavy $\bar{b}$ antiquark and a lighter u, d, s or c quark forming B^+, B^0, B_s or B_c mesons†. Just as the $\psi(3770)$ meson is a source for charmed D^0 and D^+ mesons, the Υ(4S) meson is an excellent source for the b-flavoured B^0 and B^+ mesons and their antiparticles:

$$\Upsilon(4S)\to B^0\bar{B}^0 \qquad \text{or} \qquad \Upsilon(4S)\to B^+B^-.$$

The above decay modes of the Υ(4S) have been confirmed by direct reconstruction of the B mesons, as discussed in § 3. The B^0 and B^+ are the lightest B mesons. They have spin 0 and approximately the same mass. This mass has to lie in a narrow interval between half the mass of the narrow Υ(3S) meson and half the mass of the broad Υ(4S) meson respectively, namely $5.18 \leq M(B^0, B^+) \leq 5.29\ \text{GeV}/c^2$. B_s mesons are expected to be too heavy to be decay products of the Υ(4S) meson. B^* mesons with spin 1, the hyperfine partners to the B^0 and B^+ mesons, would be detected in Υ(4S) decays by the existence of a signal at around 50 MeV in the inclusive photon spectrum corresponding to the transition $B^* \to B\gamma$. Such a signal is not observed in Υ(4S) data but is seen in data taken above the Υ(4S) resonance (Schamberger *et al* 1982, Han *et al* 1985).

The Υ(4S) meson is visible as a peak in the e^+e^- annihilation cross section of (1.15 ± 0.05) nb at CESR (figure 4) and (0.95 ± 0.05) nb at DORIS II on a continuum cross section of (2.5 ± 0.2) nb. The difference in the Υ(4S) cross sections at CESR and DORIS reflects the different energy resolutions of the beams ($\sigma_{\text{beam}} = 3.2$ MeV for CESR and $\sigma_{\text{beam}} = 6.8$ MeV for DORIS II). Inclusive and exclusive Υ(4S) decays can be measured directly by subtracting the continuum contribution under the Υ(4S) meson. This continuum contribution is determined from data taken at energies just below the Υ(4S) mass and scaled to correct for differences in the accumulated luminosities and centre-of-mass energies.

The decay of the Υ(4S) into pairs of B mesons can be inferred from the measurement of the inclusive lepton yield since B mesons are weakly decaying particles with sizable semileptonic branching ratios (see § 5). Figure 5 shows the cross section for inclusive electron and muon production in e^+e^- annihilation (Besson *et al* 1985); a strong signal is observed at the Υ(4S) mass.

Throughout this paper we will assume that the Υ(4S) meson decays 100% of the time into $B^0\bar{B}^0$ or B^+B^- pairs. No evidence has been observed for other decay modes of the Υ(4S) meson. In particular, additional modes could show up in the momentum spectrum of the decay products of the Υ(4S) meson as a signal beyond the nominal cut-off at $p = p_{\text{beam}}/2$; no such effect is observed (Behrends *et al* 1987a) (figure 6).

2.3. Study of b quark properties

The physics of the b quark has been studied primarily at the e^+e^- storage rings CESR at Cornell, DORIS II and PETRA at DESY, and PEP at SLAC. At CESR and

† References in this paper to a specific charged state are to be interpreted as implying also the charge-conjugate state.

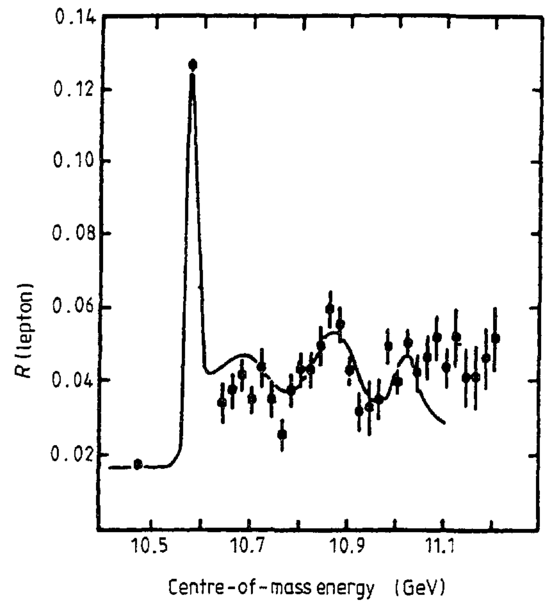

Figure 5. Cross section for $e^+e^- \to$ lepton + X.

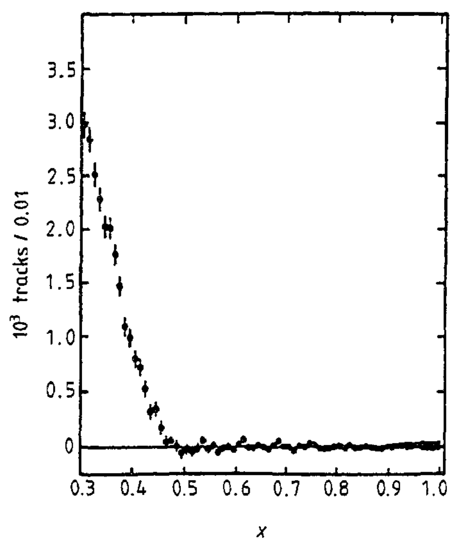

Figure 6. Momentum spectrum of charged particles from direct Υ(4S) decays (continuum subtracted).

DORIS II the Υ(4S) meson is the source for B^0 and B^+ mesons. At PETRA, PEP or the $p\bar{p}$ colliders all types of b hadrons are produced in the fragmentation of the b and $\bar{b}$ quarks, namely B^0, B^+, B_s or B_c mesons as well as their excited states or baryons containing b quarks. The relative production rates of the b hadrons are unknown. Events containing $b\bar{b}$ pairs cannot be isolated from other events, only enriched. Isolation of such events is desirable since the cross section $\sigma(e^+e^- \to b\bar{b})$ represents only about one eleventh of the total hadronic cross section, yielding $\sigma(e^+e^- \to b\bar{b}) \simeq$ 0.03 nb at $E_{cm} = 30$ GeV. With the same luminosities at the Υ(4S) resonance one obtains about 30 times more B mesons with much lower backgrounds.

As a consequence, most of the results on inclusive decays, and all results on exclusive decays, are obtained from investigation of B mesons produced in Υ(4S) decays. Lifetimes of b hadrons, however, can only be determined by measuring their decay length which is only possible at high e^+e^- energies where b hadrons are produced with high momenta.

The magnetic 4π spectrometers ARGUS at DORIS II (Albrecht *et al* 1988a) and CLEO at CESR (Andrews *et al* 1983) are well suited to the investigation of the decay of B mesons produced in Υ(4S) decays. This is especially true for the ARGUS detector, which can detect hadrons, leptons and photons over more than 90% of the full solid angle with high efficiency, good momentum resolution and excellent particle identification.

2.4. *The b quark in the standard model*

In the standard model with three families, the b quark plays an important role. As mentioned previously the b quark was introduced as the fifth quark, together with the as yet unobserved sixth quark, the t quark (Kobayasi and Maskawa 1973), in order to describe the observed CP violation in K meson decays. The six quarks were also needed in order to restore quark–lepton symmetry after the discovery of the τ lepton in 1975 (Perl *et al* 1975). In the standard model the left-handed leptons and quarks are arranged in three doublets (table 2).

Table 2. Left-handed leptons and quarks.

	Leptons		Quarks	
Charge Q	0	−1	$\frac{2}{3}$	$-\frac{1}{3}$
1st family	ν_e	e^-	u	d
2nd family	ν_μ	μ^-	c	s
3rd family	ν_τ	τ^-	t	b

The weak interaction eigenstates (d′ s′ b′) are mixtures of the flavour eigenstates (d s b). Such a mixture does not occur in the lepton sector if the neutrinos are massless. The transformation is described by the quark mixing matrix, the Kobayashi–Maskawa (KM) matrix **V**

$$\mathbf{V}=\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

This unitary 3×3 matrix with complex elements is determined by three angles θ, β and γ and one phase δ which possibly account for the observed CP violation. The KM matrix can be parametrised as (Chau and Keung 1984)

$$\mathbf{V}=\begin{pmatrix} c_\beta c_\theta & c_\beta s_\theta & s_\beta e^{-i\delta} \\ -c_\gamma s_\theta - s_\gamma c_\theta s_\beta e^{i\delta} & c_\gamma c_\theta - s_\gamma s_\theta s_\beta e^{i\delta} & s_\gamma c_\beta \\ s_\gamma s_\theta - c_\gamma c_\theta s_\beta e^{i\delta} & -s_\gamma c_\theta - c_\gamma s_\theta s_\beta e^{i\delta} & c_\gamma c_\beta \end{pmatrix}$$

where θ is the well measured Cabibbo angle. (The symbols c and s stand for cos and sin, respectively.) In this parametrisation, the first two families of quarks decouple from the third if $\beta = \gamma = 0$. These two angles β and γ as well as the phase δ still have to be determined precisely. The strength of the coupling between the $Q = -\frac{1}{3}$ and $Q = \frac{2}{3}$ quarks is given by the elements of the KM matrix. The coupling between the quarks is illustrated in figure 7 where only flavour-changing charged currents are allowed. Flavour-changing neutral currents are absent in lowest-order perturbation theory. This is guaranteed by the GIM mechanism (Glashow *et al* 1970) which is retained in the six-quark model by the unitarity of the KM matrix:

$$\sum_j V_{ij} V^*_{kj} = \sum_j V^*_{ji} V_{jk} = \delta_{ik}.$$

The couplings V_{ij} can in principle be measured by studying the weak decays of the quarks. The four V_{ij} matrix elements which describe the coupling between the quarks of the first two families are rather well known (Kleinknecht and Renk 1987): $|V_{ud}| = 0.9747 \pm 0.0011$ from the nuclear β decay, $|V_{us}| = 0.221 \pm 0.002$ from semileptonic hyperon or K meson decays and $|V_{cd}| = 0.21 \pm 0.03$ from single charm production in neutrino and antineutrino interactions. Information about the coupling of the c quark to the s quark, given by V_{cs}, is obtained from the investigation of semileptonic charm decays or the production of dimuon events in neutrino and antineutrino interactions. The measurement of the decay $D^0 \to K^- e^+ \nu$ yields $|V_{cs}| = 0.93 \pm 0.10$ (Anjos *et al* 1988) assuming for the D^0 form factor a value of $f_+(0) = 0.76$ (Wirbel *et al* 1986).

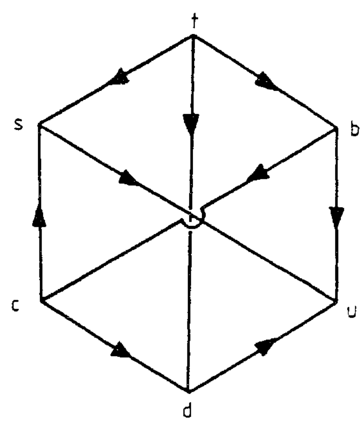

Figure 7. Allowed transitions between quarks.

The remaining five matrix elements can be studied by investigating the weak decays of the B^0 and B^+ mesons. The description of weak decays of hadrons is complicated by the fact that the decaying quarks are not free particles but are bound by the strong force. Therefore QCD effects have to be taken into account, making the weak decays of hadrons a testing ground for our understanding of the strong interaction as well.

For heavy mesons, such as the B^0 or B^+, an approximate description of their weak decays is given by the spectator model. In this model the initial hadron is represented by its valence quark configuration, for example $\bar{B}^0 = (b\bar{d})$. The heavy b quark decays into a lighter c (or u) quark by emission of a W^- boson while the $\bar{d}$ quark acts as a spectator having no influence on the decay rate (figure 8). The fragmentation of the c quark into charmed particles is discussed in detail in § 4.

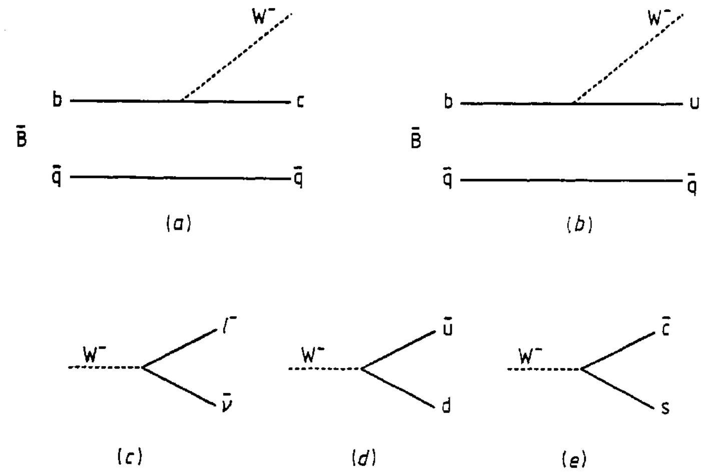

Figure 8. Spectator graph for B̄ decays.

Semileptonic decays of the B mesons are obtained when the W^- boson couples to a lepton l and its antineutrino, where the lepton l can be either an e^-, μ^- or τ^-. The semileptonic decay rate Γ_{sl} is calculated in close analogy to the muon decay rate:

$$\Gamma_{sl}=\frac{G_F^2 m_b^5}{192\pi^3}\left(|V_{ub}|^2 I\left(\frac{M_u}{M_b},\frac{M_l}{M_b},0\right)F_{sl}(b\to u)+|V_{cb}|^2 I\left(\frac{M_c}{M_b},\frac{M_l}{M_b},0\right)F_{sl}(b\to c)\right).$$

The function $I(x, y, z)$ describes the phase-space corrections due to finite quark and lepton masses and is given for $M_l \simeq 0$ by (Cabibbo and Maiani 1978)

$$I(x,0,0)=1-8x^2-24x^4\ln x+8x^6-x^8.$$

The factors $F_{sl}(b\to u)$ and $F_{sl}(b\to c)$ are 1 if the presence of gluons is neglected. Taking into account radiative gluonic corrections (Cabibbo and Maiani 1978, Ali and Pietarinnen 1979), analogous to the radiative electromagnetic corrections in μ decays, one obtains a suppression of the semileptonic decay rate by

$$F_{sl}(b\to u)\simeq 0.85 \qquad F_{sl}(b\to c)\simeq 0.89.$$

Non-leptonic Cabibbo-favoured B decays occur when the W^- boson couples mainly to $\bar{u}d$ or $\bar{c}s$. For non-leptonic B decays the presence of hard gluons must be taken into account, resulting in an increase of the decay rate which is given in the spectator model by (Altarelli *et al* 1981):

$$\Gamma_{nl}=\frac{G_F^2 M_b^5}{192\pi^3}F_{nl}\sum_{q_1q_2q_3}|V_{q_1b}|^2\left(|V_{q_2q_3}|^2 I\left(\frac{M_{q_1}^2}{M_b^2},\frac{M_{q_2}^2}{M_b^2},\frac{M_{q_3}^2}{M_b^2}\right)\right)$$

where the sum runs over the quarks: $q_1=u$, c, $q_2=u$, c and $q_3=d$, s. The non-leptonic enhancement factor F_{nl} is simply a colour factor of 3 if the presence of gluons is ignored. Taking into account the radiative gluon corrections as well as hard gluon effects, one obtains an enhancement of the non-leptonic decays: $F_{nl}\simeq 3.5$ for $M_b=5\ \mathrm{GeV}/c^2$.

From the expressions above, one obtains inclusive bottom decay rates in the spectator model approximation where gluonic effects are treated in next-to-leading order. Using current quark masses, the predicted semileptonic width Γ_{sl} is (Rückl 1984)

$$\Gamma_{sl}\simeq\frac{G_F^2 m_b^5}{192\pi^3}(0.86|V_{ub}|^2+0.48|V_{cb}|^2)$$

and for the total B decay width one obtains

$$\Gamma_{tot} \simeq \frac{G_F^2 M_b^5}{192\pi^3}(7.55|V_{ub}|^2 + 3.92|V_{cb}|^2).$$

If B mesons were to decay solely via the ($b \rightarrow c$) transition one would expect to find about 1.20 charmed particles per B decay in this version of the model. This will be discussed further in § 4.

If the spectator diagrams were the only possible decay diagrams, the lifetimes of charged and neutral B mesons should be the same. However, in B decays, as in charmed particle decays, non-spectator effects can take place. Possible interference effects due to the presence of identical quarks in the final state (for example, in the decay $B^- \rightarrow (c\bar{u})(d\bar{u})$), would decrease the decay rate of charged B mesons. On the other hand, flavour annihilation by W exchange (figure 9) would enhance the decay rate of the neutral B mesons.

The annihilation diagram (figure 10) can contribute to charged B meson decays. It is of special importance since it can only occur when a b quark couples to a u quark. Thus the rate for B decays through the annihilation diagram is proportional to $|V_{ub}|^2$.

If the quarks and antiquarks in the B meson are only weakly bound, the contributions from both flavour annihilation diagrams are helicity-suppressed, analogous to the $\pi^+ \rightarrow e^+\nu$ decay. However, as shown in the weak decays of charmed particles, this suppression might be overcome by the presence of soft gluons. Including such effects, one estimates that flavour annihilation can account for $\leqslant 5\%$ of the total decay rate (Shifman 1986). However, one should keep in mind that the role of flavour annihilation in heavy meson decays is not yet completely understood and surprises may occur in B decays, as in the case of charmed particle decays.

Generally, one expects that non-spectator effects would decrease the lifetime and the semileptonic branching ratio of the B^0:

$$\tau(B^-) > \tau(B^0) \qquad \text{and} \qquad \mathrm{BR}_{sl}(B^-) > \mathrm{BR}_{sl}(B^0).$$

However, a difference of more than 10% in these numbers is not expected. This is the justification for averaging lifetimes and semileptonic branching ratios for unknown mixtures of B particles.

Other possible types of B decays, such as $b \rightarrow sX$ transitions which are induced by so called 'Penguin diagrams', are expected to be rare and will be discussed in § 8.

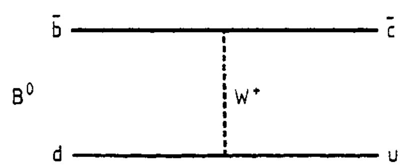

Figure 9. W-exchange in B^0 decays.

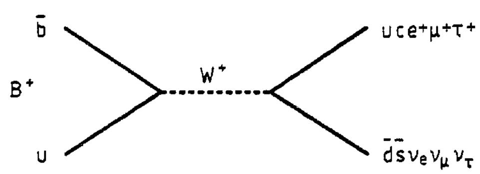

Figure 10. Flavour annihilation in B^+ decays.

In what follows we will use the spectator model and its predictions as a guide for interpreting the experimental data of the weak decays of b hadrons.

3. The reconstruction of B mesons

The reconstruction of B mesons not only explicitly demonstrates their existence but also allows the determination of their masses and branching ratios. A measurement of the masses provides information on the binding of heavy and light quarks. A knowledge of the masses of charged and neutral B mesons allows one to estimate the relative decay rates of the Υ(4S) meson into B^+B^- and $B^0\bar{B}^0$ pairs. The branching ratios for the decays of B mesons can be compared with theoretical estimates and used to test models for weak decays of heavy quarks. Furthermore, they are needed for planning future experiments involving t quark decays.

The main problem in reconstructing B mesons arises from the fact that the multiplicity in their decays is high. The charged and photon multiplicities in Υ(4S) decays are $N_{ch} = 10.99 \pm 0.06 \pm 0.2$ and $N_\gamma = 10.00 \pm 0.53 \pm 0.5$ (Ito *et al* 1986). This implies a large number of possible B decay channels with different decay chains resulting in small signal rates and substantial combinatorial background rates in most cases. The reconstruction of B mesons has been performed so far only by the ARGUS group (Albrecht *et al* 1987a, b, c, 1988b) in 16 different decay channels and by the CLEO (Bebek *et al* 1987) group in seven different decay channels. Both experiments use B mesons originating from Υ(4S) decays and reconstruct the B mesons in (b → c) transitions involving D^{*+}, D^0, D^+ or J/ψ mesons, where kinematical constraints can be used to keep the background sufficiently low.

3.1. Hadronic decay modes

In reconstructing B mesons produced in the reaction $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ one takes advantage of the fact that the energy of the B mesons, E_B, has to coincide with the beam energy, E_{e^+}. For B candidates with energies which are within three standard deviations of the beam energy, namely $|E_B - E_{e^+}| < 3\sigma$, a beam-energy constraint fit is performed. This fit translates good momentum resolution for the B candidate, σ_p, into good mass resolution, σ_{M_B}. With

$$M_B^2 = E_{e^+}^2 - \left|\sum_i \boldsymbol{p}_i\right|^2$$

where $\boldsymbol{p}_i$ are the momenta of the particles used in the reconstruction and M_B the mass of the B mesons, one obtains in the ARGUS experiment $\sigma_{M_B} = (4.5 \pm 1.0)\,\mathrm{MeV}/c^2$.

The mass spectrum for B candidates in the decays $\bar{B} \rightarrow D^{*+} n\pi$ ($n = 1, 3$) is shown in figure 11 as the hatched area (Albrecht *et al* 1987a). The $\bar{B}$ decays involving D^{*+} mesons are especially favourable since the D^{*+} are reconstructed with a gaussian width of about 1 MeV/c^2 in the ARGUS experiment which allows an efficient suppression of the combinatorial background. D^{*+} mesons are reconstructed in the decay chain $D^{*+} \rightarrow D^0\pi^+$, followed by $D^0 \rightarrow K^-\pi^+$ where the $K^+\pi^-$ mass is kinematically constrained to the D^0 mass.

The reconstruction of B mesons in the decays $B \rightarrow J/\psi K\, n\pi$ ($n = 0, 1, 2$) is shown as the shaded area in figure 11. The J/ψ is detected in its leptonic decay modes $J/\psi \rightarrow e^+e^-$, $\mu^+\mu^-$ (Albrecht *et al* 1987b) (see § 4).

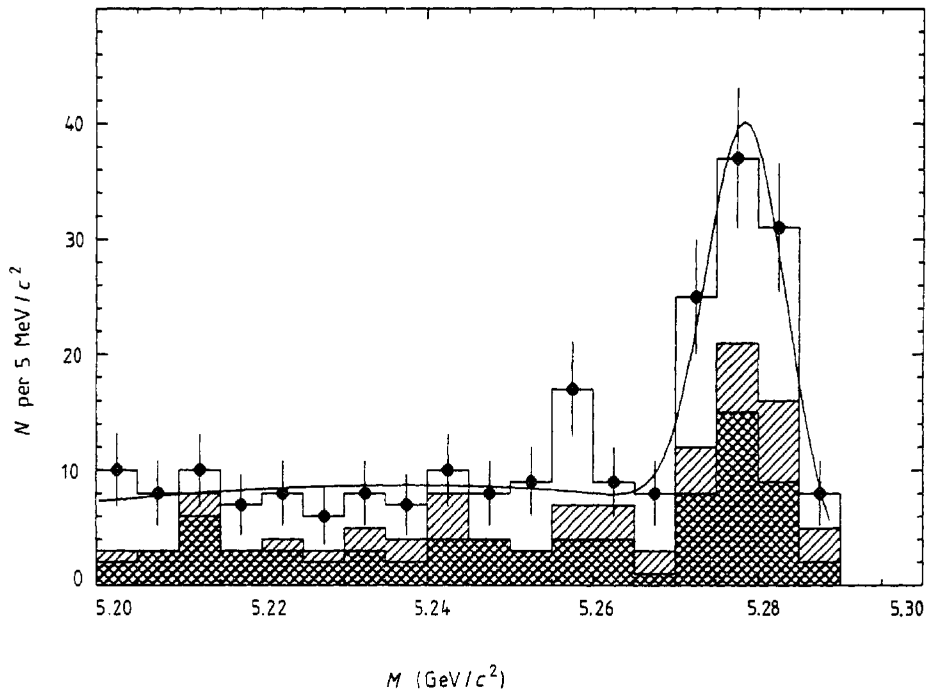

Figure 11. Mass distribution of B candidates in the decays $B \to D^{*+} n\pi$ ($n = 1$–3) (hatched area), $B \to J/\psi\ Kn\pi$ ($n = 1, 2$) (shaded area) and $B \to D^0$, $D^+ n\pi$ ($n = 1, 2$) (open area).

The reconstruction of B mesons in low multiplicity channels involving $\bar{D}^0$ or D^- mesons has been achieved by ARGUS (Albrecht *et al* 1988b). The mass distribution for the sum of the decays $B^- \to D^0\pi^-$, $B^- \to D^0\rho^-$, $\bar{B}^0 \to D^+\pi^-$ and $\bar{B}^0 \to D^+\rho^-$ channels is shown in figure 11 as the open histogram. The channels $B^- \to D^0\pi^-\pi^0$ and $\bar{B}^0 \to D^+\pi^-\pi^0$ can be interpreted as being completely due to $B^- \to D^0\rho^-$ and $\bar{B}^0 \to D^+\rho^-$. Figure 12(a) shows the $\pi^-\pi^0$ mass distribution if the mass of the B candidate lies in the signal region: $5.27 \leqslant M \leqslant 5.29$ GeV/c^2. A clear ρ^- signal of 16 events is observed. As a further check, for the decay $B^- \to D^0\rho^-$, and $\bar{B}^0 \to D^+\rho^-$, the helicity angle θ should exhibit a $\cos^2\theta$ distribution, where θ is the angle between the ρ^- helicity axis and the π^0 from the $\rho^- \to \pi^-\pi^0$ decay in the rest frame of the ρ^- meson. Figure 12(b) shows the measured angular distribution, together with the expected curve for a signal of 17 events in the decays $B^- \to D^0\rho^-$ and $\bar{B}^0 \to D^+\rho^-$. A background of 10 events, which are expected to have a flat distribution, is also included in the predicted curve. Reasonable agreement between data and expectation is observed.

The CLEO group uses a similar technique to reconstruct B mesons. The reconstructed mass distribution for seven final states is shown in figure 13.

In order to determine branching ratios, one has to know the relative frequency of $\Upsilon(4S)$ decays into B^+B^- and $B^0\bar{B}^0$ pairs. The relative rate can be inferred from the measured masses (table 3). Both experiments find that the charged state is lighter than the neutral, which is expected from their different light-quark content. The mass values are obtained by using an energy scale which is set by fixing the mass of the $\Upsilon(4S)$ to 10 580 MeV/c^2.

From the measured B^0 and B^+ masses one finds variations between 50% (50%) and 60% (40%) for the $\Upsilon(4S)$ decay fraction into B^+B^- ($B^0\bar{B}^0$) pairs using different models. In the following we will assume that 55% of $\Upsilon(4S)$ mesons decay into B^+B^- pairs and

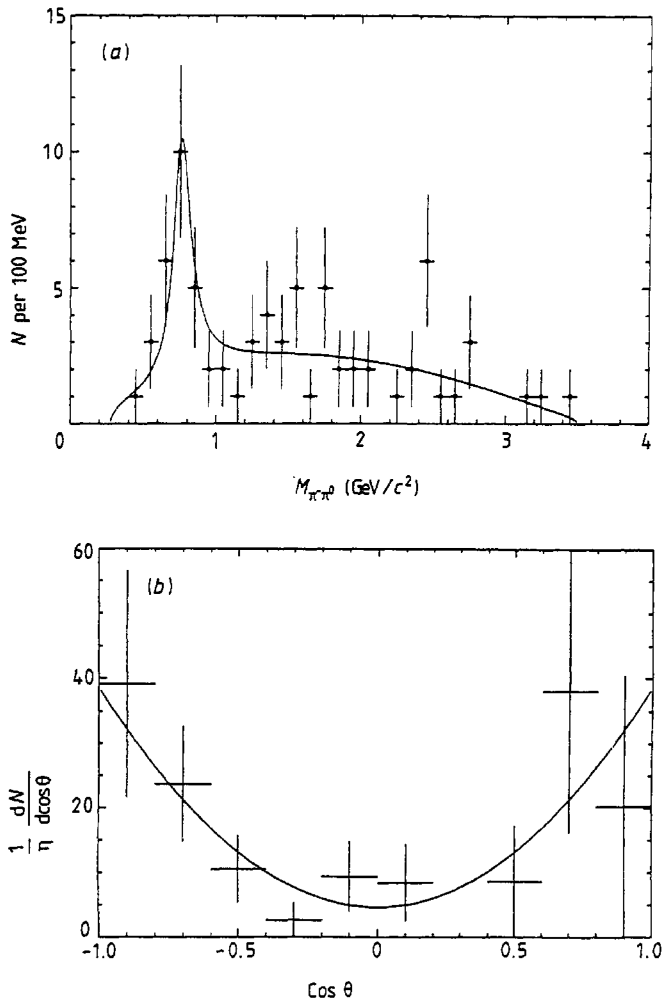

Figure 12. (*a*) $M_{\pi^-\pi^0}$ distribution in $\bar{B}\to D\pi^-\pi^0$ decays. (*b*) Acceptance-corrected angular distribution of π^0 mesons in $B\to D\rho$ decays, $\rho^-\to\pi^-\pi^0$ (Albrecht *et al* 1988b).

45% into $B^0\bar{B}^0$ pairs. The branching ratio of the decay $D^{*+}\to D^0\pi^+$ and the branching ratios of the D^0, D^+ decay channels are taken from Aguilar-Benitez *et al* (1986) and Adler *et al* (1988) respectively. The resulting branching ratios for B decays are given in table 4. The branching ratios measured by ARGUS and CLEO agree within the large errors. Some of the systematic errors are common to both experiments.

The measured branching ratios can be compared with theoretical estimates. In the valence quark model (Fakirov and Stech 1978, Bauer *et al* 1987) one expects to describe the exclusive two-body decays of B mesons to a good approximation with only a few quark diagrams. A comparison with the measured branching ratios shows reasonable agreement (see table 4).

3.2. *The decay* $\bar{B}^0\to D^{*+}l^-\bar{\nu}$

The exclusive semileptonic decay $\bar{B}^0\to D^{*+}l^-\bar{\nu}$ has been reconstructed by ARGUS (Albrecht *et al* 1987c). The reconstruction of this channel, where l^- is either an e^- or a μ^-, is possible for $\bar{B}^0$ mesons produced in $\Upsilon(4S)$ decays since they are nearly at rest.

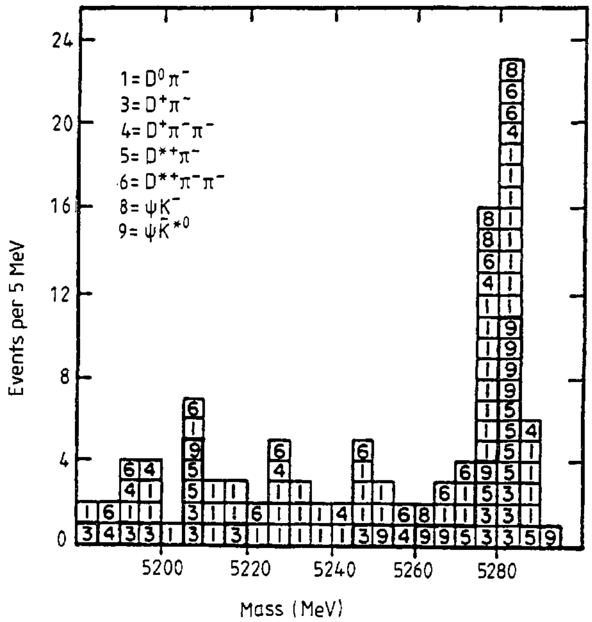

Figure 13. Mass distribution of B meson candidates in seven final states from CLEO.

Table 3. B meson masses. The $\Upsilon(4S)$ mass is set to $10.58\ \mathrm{GeV}/c^2$.

	$M(B^0)$ (MeV/c^2)	$M(B^-)$ (MeV/c^2)	$\Delta(M)$ (MeV/c^2)
ARGUS	$5279.9 \pm 0.9 \pm 3.0$	$5278.0 \pm 0.8 \pm 3.0$	$1.9 \pm 1.2 \pm 1.0$
CLEO	$5281.3 \pm 0.8 \pm 2.0$	$5279.3 \pm 0.8 \pm 2.0$	$2.0 \pm 1.1 \pm 0.3$

Table 4. Branching ratios of B mesons. The ratio of $\Upsilon(4S)$ decays into charged and neutral B mesons is taken to be 55:45.

	Branching ratio (%)		
Decay	ARGUS	CLEO	Theory
$\bar{B}^0 \to D^{*+}\pi^-$	$0.35 \pm 0.18 \pm 0.13$	$0.46 \pm 0.12 \pm 0.10$	0.45
$\bar{B}^0 \to D^{*+}\pi^-\pi^0$	$2.0 \pm 1.0 \pm 1.0$		
$\bar{B}^0 \to D^{*+}\pi^-\pi^-\pi^+$	$4.3 \pm 1.2 \pm 2.0$	$2.6 \pm 0.9 \pm 1.1$	2.0
$\bar{B}^0 \to D^+\pi^-$	$0.33 \pm 0.12 \pm 0.10$	$0.60^{+0.32+0.15}_{-0.28-0.12}$	
$\bar{B}^0 \to D^+\rho^-$	$2.3 \pm 1.0 \pm 0.9$		1.5
$\bar{B}^0 \to J/\psi K^{*0}$	0.33 ± 0.18	0.06 ± 0.03	0.15
$\bar{B}^0 \to J/\psi \bar{K}^0$		0.04 ± 0.03	
$\bar{B}^0 \to D^+D_s^-$		1.1 ± 1.0	1.0
$B^- \to D^{*+}\pi^-\pi^-$	$0.6 \pm 0.3 \pm 0.4$		
$B^- \to D^{*+}\pi^-\pi^-\pi^0$	$5.6 \pm 1.7 \pm 3.4$		
$B^- \to D^0\pi^-$	$0.21 \pm 0.10 \pm 0.06$	$0.51^{+0.17+0.11}_{-0.15-0.07}$	0.41
$B^- \to D^+\pi^-\pi^-$	$0.29 \pm 0.19 \pm 0.11$	$0.25^{+0.41+0.24}_{-0.23-0.07}$	
$B^- \to J/\psi K^-$	0.07 ± 0.04	0.05 ± 0.02	0.06
$B^- \to J/\psi K^-\pi^+\pi^-$	0.11 ± 0.07		
$B^- \to \psi' K^-$	0.22 ± 0.17		
$B^- \to D^0\rho^-$	$2.1 \pm 0.8 \pm 0.9$		1.3
$\bar{B}^0 \to D^{*+}l^-\nu$	$7.0 \pm 1.2 \pm 1.9$		6.6

The neutrino is unobserved, but can be inferred if the recoil mass squared against the $D^{*+}l^-$ system, M^2_{rec}, is consistent with zero. M^2_{rec} is defined by

$$M^2_{rec} = (E_{beam} - (E_{D^{*+}} + E_{l^-}))^2 - (p_{D^{*+}} + p_{l^-})^2.$$

The identification of electrons and muons, as well as the reconstruction of D^{*+} mesons, is performed in the ARGUS detector with high efficiency and low misidentification probability (Albrecht *et al* 1987d).

The M^2_{rec} spectrum for D^{*+} candidates with $x_p < 0.5$ and a positive lepton of momentum greater than 1.0 GeV/c is shown in figure 14. There is a prominent peak visible at $M^2_{rec} = 0$, with little background. The position and shape of the signal is well described by the Monte Carlo prediction for $\Upsilon(4S) \to B^0\bar{B}^0$ followed by the semileptonic decay $\bar{B}^0 \to D^{*+}l^-\bar{\nu}$ (histogram in figure 14). Background contributions to the observed signal can be estimated quantitatively in size and shape.

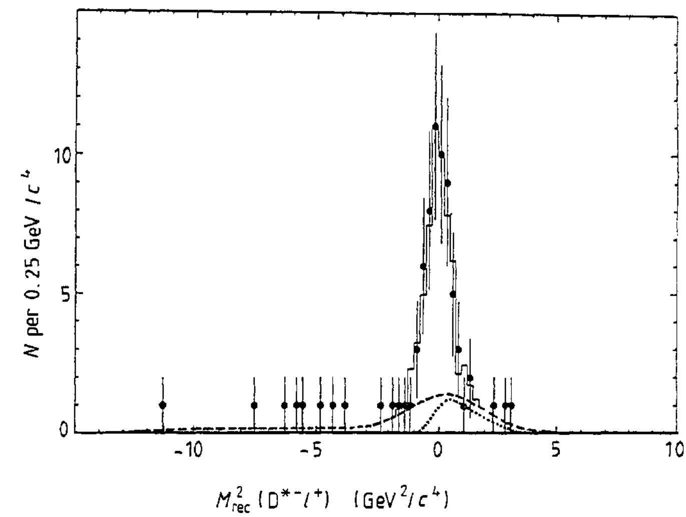

Figure 14. Recoil mass squared spectrum.

The M^2_{rec} spectrum is fitted with a gaussian for the signal on the known background. From this analysis one finds a signal of (47 ± 8) events divided about equally between the decays $\bar{B}^0 \to D^{*+}e^-\bar{\nu}$ and $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}$. The branching ratios determined separately for the decays $\bar{B}^0 \to D^{*+}e^-\bar{\nu}$ and $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}$ are the same within errors, as expected from electron-muon universality. Assuming equality, and using the combined data, one obtains

$$\text{BR}(\bar{B}^0 \to D^{*+}e^-\bar{\nu}) = \text{BR}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}) = (7.0 \pm 1.2 \pm 1.9)\%$$

where the first error is statistical and the second systematic. The decay $\bar{B}^0 \to D^{*+}l^-\bar{\nu}$ is, so far, the strongest exclusive decay channel for B mesons.

The decay $\bar{B}^0 \to D^{*+}l^-\bar{\nu}$ has been studied theoretically by several authors (Close *et al* 1984, Suzuki 1985, Wirbel *et al* 1986, Grinstein *et al* 1986, Shifman and Voloshin 1987, Körner and Schuler 1988, Altomari and Wolfenstein 1987). The D^{*+} meson in this decay can be either in a $m = 0$ state (longitudinally polarised) or in a $m = \pm 1$ state (transversely polarised). The rate for the decay $\bar{B}^0 \to D^{*+}l^-\bar{\nu}$ is therefore given by three contributions corresponding to the three helicity states

$$\Gamma = \Gamma_L + \Gamma_{T_-} + \Gamma_{T_+}$$

which can be rewritten as

$$\Gamma(\bar{B}^0 \to D^{*+} l^- \nu) = |V_{cb}|^2 \tilde{\Gamma}_T (1 + \Gamma_L/\Gamma_T)$$

with $\Gamma_T = \Gamma_{T_-} + \Gamma_{T_+}$. The quantity $\tilde{\Gamma}_T$ is predicted by different authors (Wirbel *et al* 1986, Grinstein *et al* 1986, Körner and Schuler 1988, Altomari and Wolfenstein 1987) to be in the range $\tilde{\Gamma}_T = 1.0\text{–}1.4 \times 10^{13}\ s^{-1}$. A measurement of the D^{*+} polarisation yields the ratio Γ_L/Γ_T and therefore, in combination with the known branching ratio for the decay $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ and the B lifetime, allows the determination of the KM matrix element $|V_{cb}|$. Moreover, the magnitude of this ratio fixes the lepton spectrum as well as the q^2 dependence.

The polarisation of D^{*+} mesons can be measured by using the strong decay $D^{*+} \to \pi^+ D^0$ as an analyser. The distribution in the angle θ^*, where θ^* is the decay angle of the π^+ in the D^{*+} rest frame with respect to the D^{*+} direction, is given by

$$dN/d\cos\theta^* \propto 1 + \alpha \cos^2\theta^*$$

where α measures the ratio of longitudinal to transverse polarisation:

$$\alpha = (2\Gamma_L/\Gamma_T) - 1.$$

The $\cos\theta^*$ distribution is extracted from the events in the signal region ($|M^2_{rec}| < 1\ GeV^2/c^4$) by subtracting the background contributions in this M^2_{rec} range. The acceptance corrected and normalised $\cos\theta^*$ distribution in the decay $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ is shown in figure 15. This distribution is fitted to a $(1 + \alpha \cos^2\theta^*)$ form which results in $\alpha = 0.7 \pm 0.8$ (full curve in figure 15) (Gläser 1988).

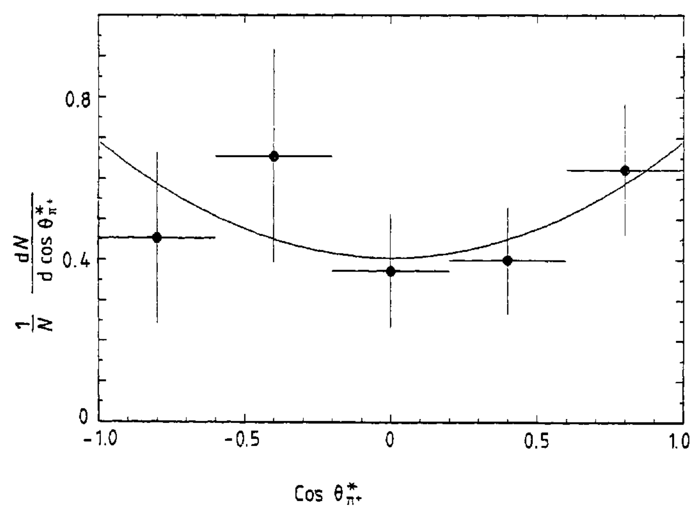

Figure 15. Cos θ distribution for the decay $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ from ARGUS.

The value of α has to be corrected for the limited phase space due to the cut on the lepton momentum and the vanishing acceptance for D^{*+} mesons with $x_p < 0.2$. Both effects tend to cancel each other, leading to

$$\alpha = 0.7 \pm 0.9$$

where systematic errors are also included. From this value of α one deduces the ratio of the longitudinal and transverse component Γ_L/Γ_T:

$$\Gamma_L/\Gamma_T = 0.85 \pm 0.45.$$

Using $\tilde{\Gamma}_T = 1.2 \times 10^{13}\ \text{s}^{-1}$, $\text{BR}(\bar{B}^0 \to D^{*+} l^- \bar{\nu}) = (7.0 \pm 1.2 \pm 1.9)\%$ and $\tau_B = 1.14 \times 10^{-12}$ s (see § 5) one obtains

$$|V_{cb}| = 0.052 \pm 0.011.$$

The measured polarisation of the D^{*+} mesons in the $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ decay should also be reflected in the shapes of the lepton spectrum and the q^2 distribution. The endpoint region of the lepton spectrum in the decay $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ is dominated by the T_- component. This leads to a harder lepton spectrum for the decay $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ than for the decay $\bar{B} \to D l^- \bar{\nu}$. The observed electron momentum spectrum from the decay $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ (figure 16(*a*)) is well described by the theoretical models of Körner and Schuler (1988) (full curve) which predict $\alpha \simeq 1$.

The q^2 spectrum was obtained by reconstruction of the decay $\bar{B}^0 \to D^{*+} e^- \nu$, with a cut on the electron momentum of $p_{e^-} > 0.4$ GeV/*c*. The q^2 distribution can be inferred from the energy spectrum of the D^{*+} mesons by using

$$q^2 = (p_B - p_{D^{*+}})^2 = (E_B - E_{D^{*+}})^2 - (\mathbf{p}_B - \mathbf{p}_{D^{*+}})^2$$
$$\simeq (E_B - E_{D^{*+}})^2 - p^2_{D^{*+}}.$$

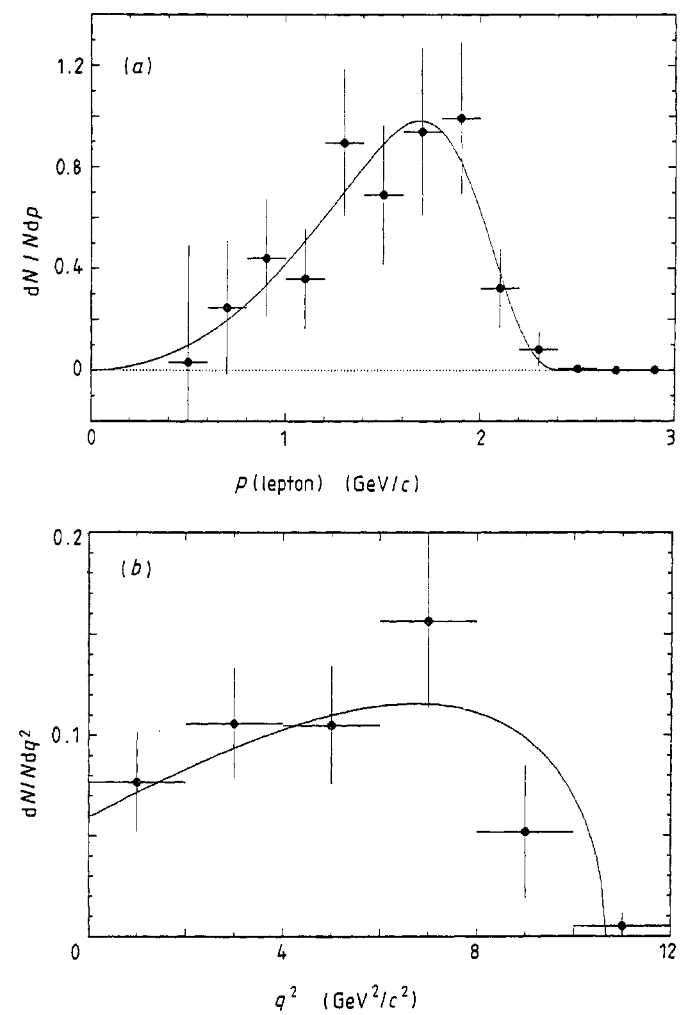

Figure 16. (*a*) Momentum spectrum of leptons from the decay $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$. (*b*) q^2 distribution of D^{*+} mesons from the decay $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$.

The acceptance-corrected and background-subtracted q^2 spectrum is displayed in figure 16(b). The presence of a strong T_- component at large q^2 is clearly demonstrated by the data, which are fitted reasonably well by the theoretical model of Körner and Schuler (1988) (full curve in figure 16(b)). In conclusion, the investigation of the $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ decay by ARGUS shows that its basic features are reproduced by the models of weak decays of heavy quarks.

4. The decay of B mesons into charmed particles

The investigation of inclusive production of charmed particles at the Y(4S) is a means of studying the weak decays of B mesons. ($b \to c$) transitions lead ultimately to D^0, D^+, D_s^+ mesons, stable charmed baryons ('Λ_c') or charmonium states ('J/ψ') as the lowest-lying charmed particles. Measurements of their inclusive rates allow one to determine the strength of the ($b \to c$) transition. The momentum spectrum of hadrons containing charmed quarks provides information on the weak decay mechanism. The charmed particles are reconstructed through their long-lived decay products, e.g. $D^0 \to K^- \pi^+$ the branching ratio of which is obtained by other measurements (Adler *et al* 1988).

The number, N_c, of charmed quarks per B decay is given by

$$N_c / N_B = \mathrm{BR}(B \to D^0 X) + \mathrm{BR}(B \to D^+ X) + \mathrm{BR}(B \to D_s^+ X)$$
$$+ \mathrm{BR}(B \to \text{`}\Lambda_c\text{'} X) + 2\mathrm{BR}(B \to \text{`}J/\psi\text{'} X).$$

If B decays proceed only via the spectator diagram, for ($b \to c$) transitions one would expect:

$$N_c / N_{(b \to c)} \simeq 1.20$$

where the additional 20% is due to charm production in the fragmentation of $W^- \to \bar{c}s$. One also expects for ($b \to u$) transitions

$$N_c / N_{(b \to u)} \simeq 0.20.$$

The total yield of charmed quarks per B decay is a measure for the relative strengths of the ($b \to u$) and the ($b \to c$) transitions, $\alpha = \Gamma(b \to u)/\Gamma(b \to c)$, assuming that only these two processes contribute to B decays:

$$\frac{N_c}{N_B} \simeq \frac{1.2 + 0.2\alpha}{1 + \alpha}.$$

Charmed particles from Y(4S) decays can be distinguished from those produced in the e^+e^- continuum by their different momentum dependence. Continuum production yields a hard momentum spectrum which peaks at around $x_p = 0.7$ where $x_p = p/p_{\max}$ is the scaled momentum with $p_{\max} = (E_B^2 - M^2)^{1/2}$. This x_p spectrum can be measured directly in the e^+e^- continuum and can be parametrised by quark fragmentation models. In contrast, the momentum spectrum of charmed particles from Y(4S) decays cuts off at $x_p \leqslant 0.5$. Enhancements of charmed particle yields in Y(4S) data at low x_p values are thus due to B decays and can be extracted by comparing with data taken in the continuum below the Y(4S). The measurements of the inclusive decays of B mesons into the lowest-lying charmed particles were performed by ARGUS and CLEO.

4.1. *The decays $B \to D^0X$ and $B \to D^+X$*

In the spectator model, D^0 and D^+ mesons in B decays are expected to be predominantly produced in the fragmentation of the c quark from the $b \to cW^-$ decay (see figure 8). These decays have been measured by ARGUS (Harder 1988) and CLEO (Bortoletto *et al* 1987) where the D^0 and D^+ mesons were detected in the decay channels $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ respectively. The $K^-\pi^+$ invariant mass spectrum as obtained by the ARGUS group is shown in figure 17 for data taken at the $\Upsilon(4S)$ energy for the interval of the scaled momentum $x_p(K^-\pi^+) < 0.5$ (upper data points). The spectrum shows a D^0 peak at the correct mass with the expected resolution. Figure 18(*a*) shows the acceptance-corrected x_p spectrum of D^0 mesons originating from $\Upsilon(4S)$ decays. The contribution from the continuum under the $\Upsilon(4S)$ meson has been determined from data taken at centre-of-mass energies below the $\Upsilon(4S)$ mass (figure 17) and subtracted (figure 18(*b*)).

The decay $B \to D^+X$ is measured by reconstructing the D^+ mesons in the decay $D^+ \to K^-\pi^+\pi^+$. The x_p distribution of D^+ mesons originating from $\Upsilon(4S)$ decays is similar to that of the D^0 mesons (figure 19). The resulting branching ratios are listed in table 5, where for the branching ratios of D mesons are used: $\mathrm{BR}(D^0 \to K^-\pi^+) = (4.2 \pm 0.4 \pm 0.4)\%$ and $\mathrm{BR}(D^+ \to K^-\pi^+\pi^+) = (9.1 \pm 1.3 \pm 0.4)\%$ (Adler *et al* 1988).

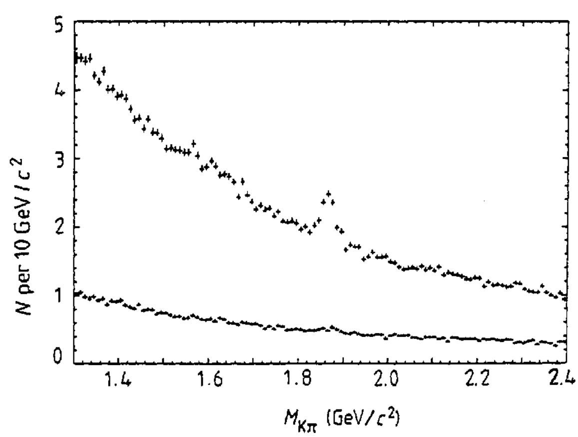

Figure 17. $K^-\pi^+$ invariant mass spectrum in $\Upsilon(4S)$ data (upper trace) and continuum data (lower trace) for $x_p \leq 0.5$.

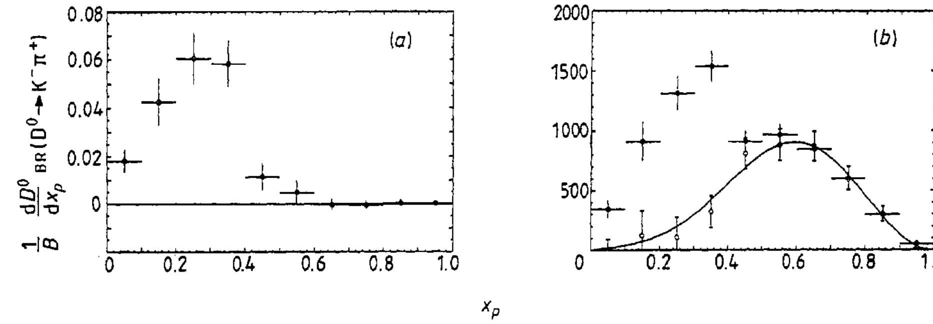

Figure 18. (*a*) $x_p(D^0)$ spectrum in $\Upsilon(4S)$ decays; (*b*) $x_p(D^0)$ spectrum from $\Upsilon(4S)$ decays and continuum.

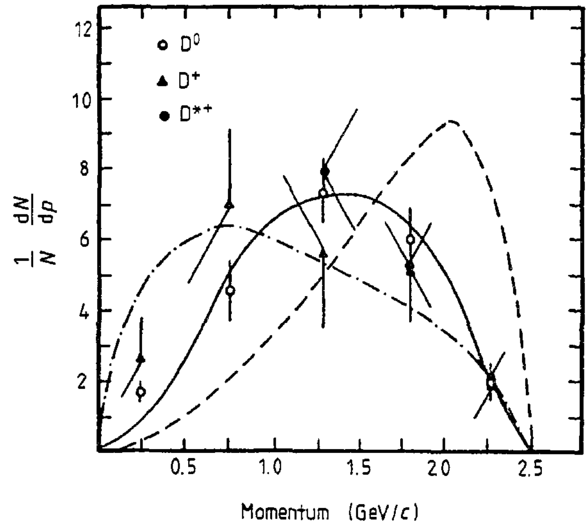

Figure 19. D^0, D^+ and D^{*+} momentum spectra.

Table 5. Inclusive branching ratios of B decays into charmed particles.

	Branching ratio (%)	
	CLEO	ARGUS
$B \to D^0X$	$50.0 \pm 6.1 \pm 6.7$	$46.6 \pm 7.1 \pm 6.3$
$B \to D^+X$	$20.9 \pm 4.9 \pm 3.1$	$23.2 \pm 5.3 \pm 3.5$
$B \to D_sX$	$19 \pm 5 \pm 4$	$16 \pm 4 \pm 3$
$B \to$ 'Λ_c' X	$8.2 \pm 1.4 \pm 2.0$	$7.6 \pm 1.4 \pm 1.8$
$2 \times B \to$ 'J/ψ' X	4.2 ± 1.0	4.2 ± 1.0
Σ	$102 \pm 10 \pm 9$	$98 \pm 10 \pm 8$

Together the B decays into a D^0 or D^+ meson saturate about 60% of the B meson decay rate. This observation implies the dominance of $(b \to c)$ over $(b \to u)$ transitions.

The relative rates of D^0 and D^+ mesons in B decays can be qualitatively understood if B mesons decay dominantly into D^{*+} and D^{*0} mesons. If the latter are produced with the same rates one expects to observe D^0 and D^+ mesons from the decay of the D^{*+} and D^{*0} mesons with a ratio

$$N_{D^0}/N_{D^+} \simeq 3:1.$$

The production of D^{*-} mesons in B decays has been measured by CLEO (Bortoletto *et al* 1987) to be

$$\mathrm{BR}(B \to D^{*+}X) \times \mathrm{BR}(D^{*+} \to D^0\pi^-) \times \mathrm{BR}(D^0 \to K^-\pi^+) = 0.0073 \pm 0.0012 \pm 0.0007.$$

Using the measured branching ratios for D^{*-} (Aguilar-Benitez *et al* 1986) and D^0 mesons (Adler *et al* 1988) decays one obtains

$$\mathrm{BR}(B \to D^{*+}X) = 0.35 \pm 0.07^{+0.11}_{-0.06}.$$

Assuming the same rate for the decay $B \to D^{*0}X$ would imply that B mesons decay with an inclusive branching ratio of about 70% into D^{*+} or D^{*0} mesons. This would result in 0.53 D^0 mesons and 0.17 D^+ mesons per B decay from D^{*+} or D^{*0} mesons which are about the observed D^0 and D^+ rates.

The observed momentum spectra of the D^0, D^+ and D^{*+} mesons are similar (figure 19). The spectra are best described by a model where a decay $b \to cW^-$ takes place and the c quark forms either a D or D* meson with the spectator quark. The virtual W^- boson couples to an appropriate mixture of quark-antiquark and lepton-antineutrino pairs. The quark and antiquark from the virtual W^- boson fragment independently of the c quark. The resulting D momentum is shown in figure 19 as the full curve. All three spectra exhibit only a small two-body component from decays such as $\bar{B}^0 \to D^0\pi^-$. These contribute at momenta $p \geqslant 2$ GeV/c^2 (corresponding to $x_p \geqslant 0.4$).

4.2. *The decay $B \to D_sX$*

In the spectator model, D_s mesons in B decays can be produced in different ways as illustrated in figure 20. In the first diagram the W^- couples to a $\bar{c}s$ quark pair which forms a D_s^- meson. This process will yield a hard momentum spectrum with a substantial two-body component $\bar{B} \to D_s^-(c\bar{q})$, where the $c\bar{q}$ quarks form either D or D* mesons. In the second diagram, a D_s^+ meson is formed in the fragmentation of the c quark and the W^- couples to a lepton pair. This process $\bar{B} \to W^-D_s^+X$ results in a soft momentum spectrum of the D_s mesons.

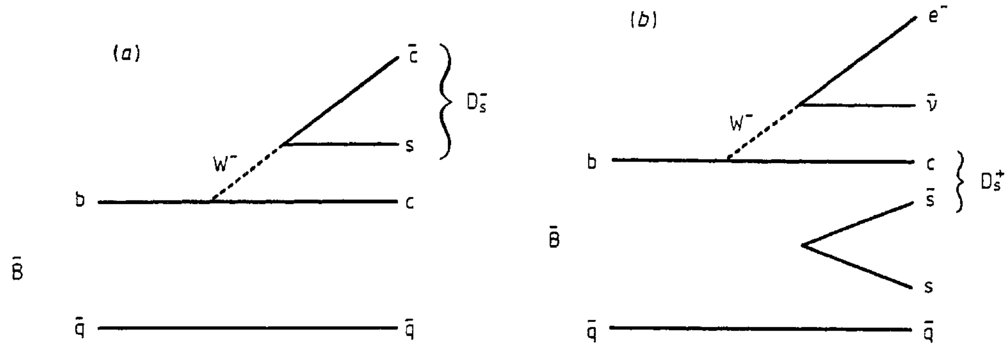

Figure 20. D_s production in B decays.

The decay $B \to D_s^+X$ has been studied by CLEO (Haas *et al* 1986) and ARGUS (Albrecht *et al* 1987e, Gingrich 1988) where the D_s^+ is detected in its decay $D_s^+ \to \phi\pi^+$ with $\phi \to K^+K^-$. The measured branching ratios from the two groups are in good agreement (table 5) and similar to the predicted rate for $b \to c\bar{c}s$ transitions of about 20%. For the decay $D_s^+ \to \phi\pi^+$ a branching ratio of $\mathrm{BR}(D_s^+ \to \phi\pi^+) = (2.0 \pm 0.4)\%$ is used which can be inferred from the D_s production in the e^+e^- continuum which is assumed to contribute to 15% of the cross section $e^+e^- \to c\bar{c}$ at $\sqrt{s} = 10.55$ GeV (Bortoletto *et al* 1988).

The scaled momentum spectrum of D_s^+ mesons from $\Upsilon(4S)$ decays is shown in figure 21. It peaks at high x_p values which implies that the total $B \to D_s^+X$ yield has a large $\bar{B} \to D_s^-D$ or $\bar{B} \to D_s^-D^*$ component of $(64 \pm 22)\%$ (CLEO) and $(54 \pm 12)\%$ (ARGUS) (full curve in figure 21). The broken curve gives the expected spectrum for a three-body phase-space decay $\bar{B} \to D_s^-D\pi$ which might account for the low-momentum

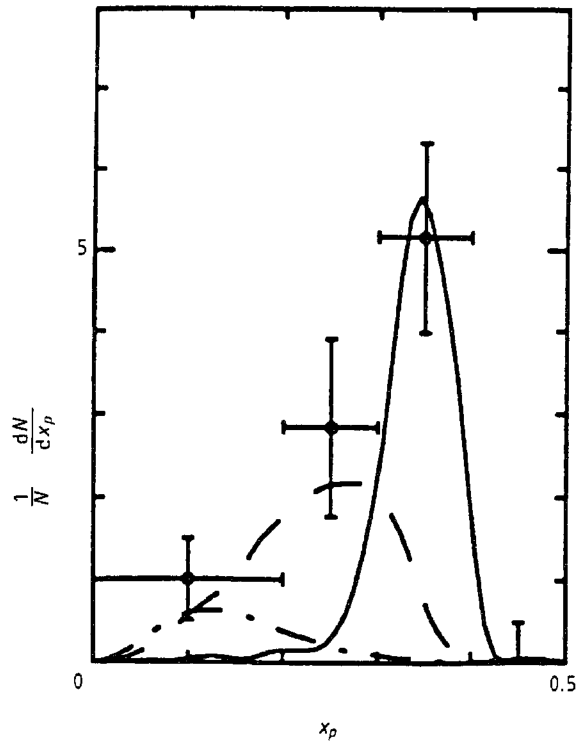

Figure 21. $B \to D_s X$, $x_p(D_s)$. See text for details.

part of the spectrum. Contributions to the inclusive $\bar{B} \to W^- D_s^+ X$ rate from the diagram in figure 20(*b*) cannot be very large (chain curve in figure 21).

4.3. *The decay $B \to J/\psi\ X$*

The decay $B \to J/\psi X$ is of particular interest for the understanding of the interplay between strong and weak interactions in heavy quark decays (Fritzsch 1979, Kühn *et al* 1980, Wise 1980, DeGrand and Toussaint 1980, Bigi and Sanda 1981, Kühn and Rückl 1984, Cox 1985, Bauer *et al* 1987). It is expected to proceed dominantly through the 'colour-suppressed' diagram in which colour matching is required between the c quark from the $(b \to c)$ transition and the $\bar{c}$ from the $W^- \to \bar{c}s$ decay (figure 22).

The inclusive production rate of J/ψ mesons in B decays can be estimated in the following way: first, we assume the branching ratio for the $b \to c\bar{c}s$ decay to be about 20% (see § 2). Secondly, since only one out of three $c\bar{c}$ pairs produced in the decay $b \to c\bar{c}s$ is in a colour singlet state, charmonium production is expected to be suppressed

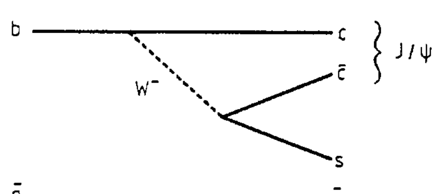

Figure 22. Diagram for the decay $B \to J/\psi\ X$.

by a factor $\frac{1}{9}$. Thirdly, one has to know how often J/ψ are produced out of a c$\bar{c}$ singlet. This probability is predicted to be about 60% (Kühn *et al* 1980, Kühn and Rückl 1984):

$$\eta_c : J/\psi : \chi_1 : \psi' \simeq 0.57 : 1 : 0.27 : 0.31.$$

With these three ingredients, one estimates an inclusive branching ratio of BR(B → J/ψX) ≃ 1.3%, if colour suppression is at work. The presence of soft gluons in this weak decay, however, could overcome this suppression by their ability to transport colour 'at no cost'. The colour suppression factor of $\frac{1}{9}$ would not exist and the resulting branching ratio could then be as large as 10%. The presence of hard gluons, on the other hand, would lead to a branching ratio much smaller than 1.3%.

The measurement of the inclusive decay B → J/ψX was performed by CLEO (Haas *et al* 1985, Alam *et al* 1986) and ARGUS (Albrecht *et al* 1985, 1987b). In both experiments the J/ψ is detected in its leptonic decay mode J/$\psi \to e^+e^-$ or J/$\psi \to \mu^+\mu^-$. The observed signals in Υ(4S) data are shown in figure 23. No corresponding signals are found in continuum data, which implies that all J/ψ are from B decays.

The measured branching ratios (table 5) are close to the prediction from the spectator model with colour suppression and without hard gluon corrections. The observed

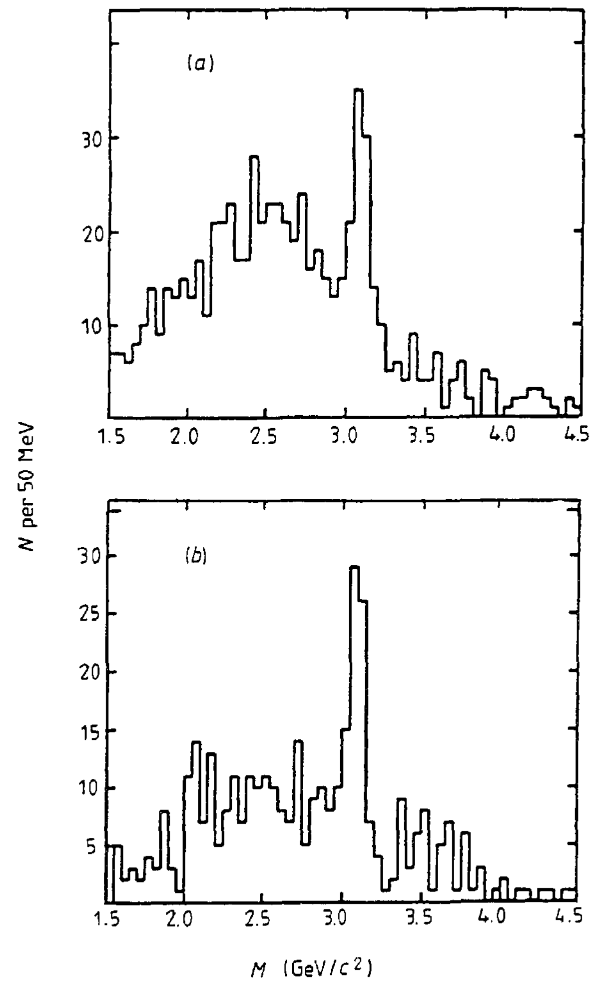

Figure 23. (*a*) e^+e^- and (*b*) $\mu^+\mu^-$ mass spectra in Υ(4S) decays.

momentum spectrum of J/ψ mesons, shown in figure 24, provides information on how the J/ψ mesons were produced. The high-momentum part of the J/ψ spectrum can in fact be described by the reaction $B\to J/\psi X$ in which $X = K$ or K^*, using the observed rates for $B^-\to J/\psi K^-$ and $\bar{B}^0\to J/\psi K^{*0}$, and assuming equal $\mathrm{BR}(B^-\to J/\psi K^-) = \mathrm{BR}(\bar{B}^0\to J/\psi K^0)$ and $\mathrm{BR}(\bar{B}^0\to J/\psi K^{*0}) = \mathrm{BR}(B^-\to J/\psi K^{*-})$. These exclusive two-body decays contribute about 40% to the total inclusive J/ψ rate (full curve in figure 24). The low-momentum part of the J/ψ momentum spectrum is partly explained by the production of other $c\bar{c}$ states, such as the ψ' or χ_c, which cascade down to the J/ψ by emitting pions or photons.

The gross features of the decay $B\to J/\psi X$ are therefore reasonably well explained by direct J/ψ production from $c\bar{c}$ singlets or from cascade decays. The measured branching ratio lies close to the theoretical estimates which include colour suppression, thus suggesting the importance of this phenomenon. More precise measurements are needed in order to judge whether other decay processes, such as those involving gluons, are necessary to explain the J/ψ momentum spectrum, especially at low momenta.

4.4. *The decay B→baryons X*

B mesons can decay into final states containing baryon–antibaryon pairs by a simple mechanism. In the decay $b\to cd\bar{u}$, for example, a cd diquark can be formed (figure 25). Only *one* $q\bar{q}$ loop has to be pulled out of the vacuum so that the cd diquark can hadronise into a charmed baryon and likewise the $\bar{u}\bar{q}$ diquark, together with the spectator antiquark, forms an ordinary antibaryon.

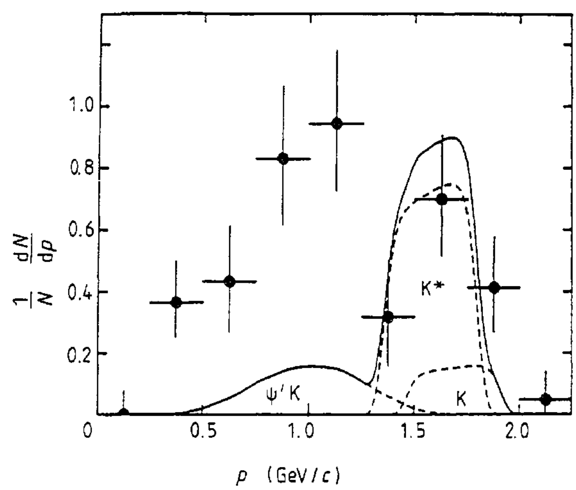

Figure 24. Momentum spectra of J/ψ mesons in $\Upsilon(4S)$ decays.

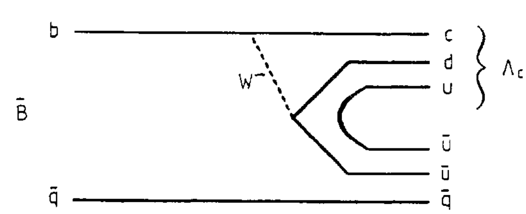

Figure 25. Baryon–antibaryon production in B decays.

The baryon-antibaryon production rate in B decays is estimated in this simple approach, neglecting QCD effects (Bigi 1981), to be

$$\mathrm{BR}(b \to (cd)\bar{u})/\mathrm{BR}(b \to c) \simeq 5\text{-}10\%$$

for $M_{cd} \simeq 2\text{-}2.5\ \mathrm{GeV}/c^2$.

For $(b \to c)$ transitions one expects to have predominantly Λ_c baryons in the final state. Λ_c production in B decays is directly observed by ARGUS (Albrecht *et al* 1988c) where the Λ_c is reconstructed in its decay $\Lambda_c^+ \to pK^-\pi^+$. ARGUS measures a product branching ratio of

$$\mathrm{BR}(B \to \Lambda_c^+ X)\mathrm{BR}(\Lambda_c^+ \to pK^-\pi^+) = 0.0030 \pm 0.0012 \pm 0.0006.$$

The momentum spectrum of the Λ_c baryons from B decays is shown in figure 26. It exhibits a soft momentum distribution with no pronounced structure, which might be due to two-body decays like $\bar{B} \to \Lambda_c^+ \bar{N}$ (dotted curve in figure 26). Three-body phase-space decays like $\bar{B} \to \Lambda_c^+ \bar{N}\pi$ give a qualitatively better description (full curve in figure 26).

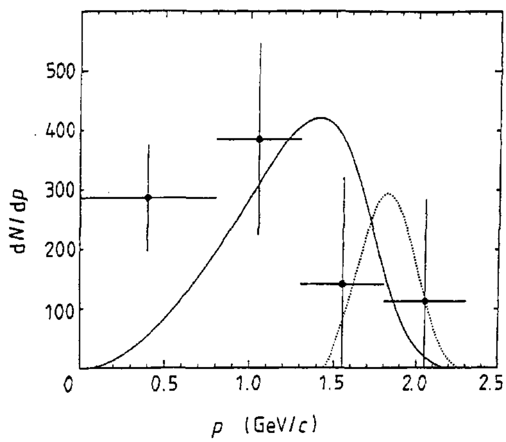

Figure 26. Momentum distribution of Λ_c baryons from B decays. See text for details.

The branching ratio $\mathrm{BR}(B \to \Lambda_c X)$ can be deduced from the inclusive B decays into protons and Λs which are well established (Alam *et al* 1987, Albrecht *et al* 1988d). The proton and Λ momentum spectra are very soft (figure 27) which reflects the softness of the Λ_c spectrum. The proton and Λ momentum spectra are adequately described by assuming that they are produced in B decays involving Λ_c baryons. The measured inclusive branching ratios for protons and Λs (table 6) can then be translated into a rate for $B \to \Lambda_c X$, assuming that all baryons in B decays are from a decay $B \to \Lambda_c \bar{N} X$ and that $\mathrm{BR}(B \to pX) = \mathrm{BR}(B \to nX)$. The resulting branching ratio for $B \to \Lambda_c X$ is listed in table 5.

In summary, the first baryonic decay of flavoured mesons has been observed in the decay of B mesons. The substantial rate is qualitatively explained by the prediction of the simple spectator model (Bigi 1981). The softness of both the Λ_c, and proton or Λ spectra, indicate that highly excited baryonic resonances are produced in $(b \to c)$ decays.

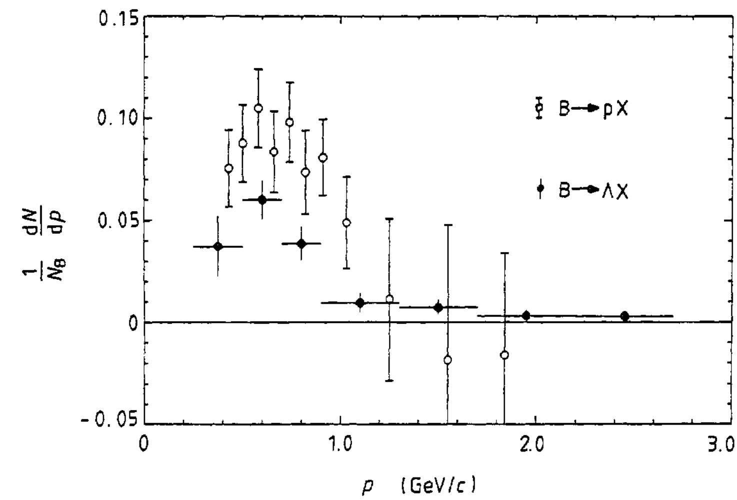

Figure 27. Momentum spectra of protons and Λs in Υ(4S) decays.

Table 6. Inclusive baryon branching ratios of B decays. The branching ratio B→pX does *not* include protons from Λ decays.

	Branching ratio (%)	
	CLEO	ARGUS
$B\to\Lambda X$	$4.2\pm0.6\pm0.4$	$4.2\pm0.5\pm0.6$
$B\to pX$	$6.1\pm0.8\pm1.0$	$5.5\pm0.6\pm1.5$
$B\to\Lambda_c^- X$	$8.2\pm1.4\pm2.0$	$7.6\pm1.4\pm1.8$

4.5. Charm counting in B decays

Counting the number of charmed particles per B decay is one possible method of determining the relative frequency of (b→c) transitions in B decays. This method is limited by the uncertainties in the branching ratios of the charmed particles, since one measures a product of branching ratios, e.g. $\text{BR}(B\to D^0X)\times\text{BR}(D^0\to K^-\pi^+)$, and by theoretical uncertainties in the expected number of charmed quarks in (b→c) and (b→u) transitions.

From the measurements of charmed particle yields one can conclude that (b→c) transitions are the dominant B decays (see table 5). The observed average of the ARGUS and CLEO number of charmed quarks in B decays of $(100\pm11)\%$ leads to an inclusive branching ratio $\text{BR}(b\to cX)\simeq(83\pm14)\%$. This still leaves some room for non-negligible contributions from (b→u) transitions, from 'rare' B decays (see §§ 6 and 8) or other non-spectator transitions. From charm counting alone, no sensitive limit for the ratio of KM matrix elements of V_{ub}/V_{cb} can be deduced.

5. Semileptonic decays and lifetimes of B mesons

The semileptonic decay of B mesons is expected to proceed via the spectator diagram (figure 8) with a semileptonic decay rate

$$\Gamma_{sl} = \frac{\mathrm{BR}_{sl}}{\tau_b} \simeq \frac{G_F^2 M_b^5}{192\pi^3}(0.86|V_{ub}|^2 + 0.48|V_{cb}|^2).$$

This rate is determined experimentally by measuring the semileptonic branching ratio $\mathrm{BR}_{sl} = \mathrm{BR}(B \to X l^+ \nu)$ and the lifetime τ_b of B mesons and is a measure of the KM matrix elements V_{ub} and V_{cb}.

5.1. *The semileptonic branching ratio* BR_{sl} *of B mesons*

The measured momentum distributions of leptons originating from $\Upsilon(4S)$ decays as obtained by the different experiments (Behrends *et al* 1987b, Schubert *et al* 1986, Wachs *et al* 1987) are shown in figure 28. Contributions from events containing no b quarks, denoted as $S_{cont}(p)$, are determined by using measurements in the e^+e^- continuum below the $\Upsilon(4S)$ resonance. The measured spectra obtained at $\Upsilon(4S)$ energies can be described by (see figure 28(*d*))

$$dN/dp = \alpha S_{bc}(p) + \beta S_{bu}(p) + \gamma S_{BC}(p) + \delta S_{B\tau}(p) + S_{back}(p) + S_{cont}(p)$$

with fit parameters α, β, γ, δ and the contributions as follows:

- S_{bc} from $B \to X_c l^+ \nu$ for the $(b \to c)$ transition
- S_{bu} from $B \to X_u l^+ \nu$ for the $(b \to u)$ transition
- S_{BC} from $B \to X_c X$, $X_c \to l^- X$ for the cascade decays of $X_c = D^0, D^+, D_s, \Lambda_c$ or J/ψ.
- $S_{B\tau}$ from $B \to X\tau^+\nu_\tau$, $\tau^+ \to l^+ \bar{\nu}_\tau \nu$
- S_{back} from background due to lepton misidentification, which can be determined by the known fake rates.

For the spectra $S_{bc}(p)$, $S_{bu}(p)$ and $S_{B\tau}(p)$ one must appeal to theoretical models for the $b \to c l^- \bar{\nu}$ and $b \to u l^- \bar{\nu}$ transitions. The theoretical descriptions are based on spectator models (Cabibbo and Maiani 1978, Ali and Pietarinnen 1979, Suzuki 1978, Cabibbo *et al* 1979, Bigi and Ewertz 1982, Altarelli *et al* 1982, Angelini *et al* 1986) or on form-factor models (Ali and Yang 1976, Wirbel *et al* 1986, Grinstein *et al* 1986, Körner and Schuler 1988). The predictions for the lepton spectrum depend basically on the mass distribution of the recoil system X, as well as on the momentum distribution of the b quarks inside the b hadrons. These variables are treated as free parameters in the models and are adjusted to fit the observed lepton spectra. The spectrum $S_{BC}(p)$ is obtained by using the measured semileptonic spectra from the decay $D \to X l^+ \nu$ (Bacino *et al* 1979, Baltrusaitis *et al* 1985).

Fits to the lepton spectra using the described contributions are shown in figure 28. The data are well described using only contributions from the decay $B \to l^+ \nu X_c$ with $M_{X_c} \simeq 2\ \mathrm{GeV}/c^2$ and from the cascade decay $B \to X_c X$, $X_c \to l X$. Averaging the results from $\Upsilon(4S)$ decays (Klopfenstein *et al* 1983, Levman *et al* 1984, Schubert *et al* 1986, Behrends *et al* 1987b, Wachs *et al* 1987), one obtains

$$\mathrm{BR}(B \to l^+ X \nu) = (11.4 \pm 0.4 \pm 0.7)\%$$

where the first error represents the statistical and systematic errors in the branching ratio $\mathrm{BR}(B \to l^- X)$. The second error accounts for model-dependent uncertainties which are common to all experiments.

The measured semileptonic branching ratio for the mixture of charged and neutral B mesons from $\Upsilon(4S)$ decays may be compared with predictions of the spectator model using current quark masses and next-to-leading order QCD corrections which yield $\mathrm{BR}(B \to l^- X) \simeq 12\%$ (Rückl 1984).

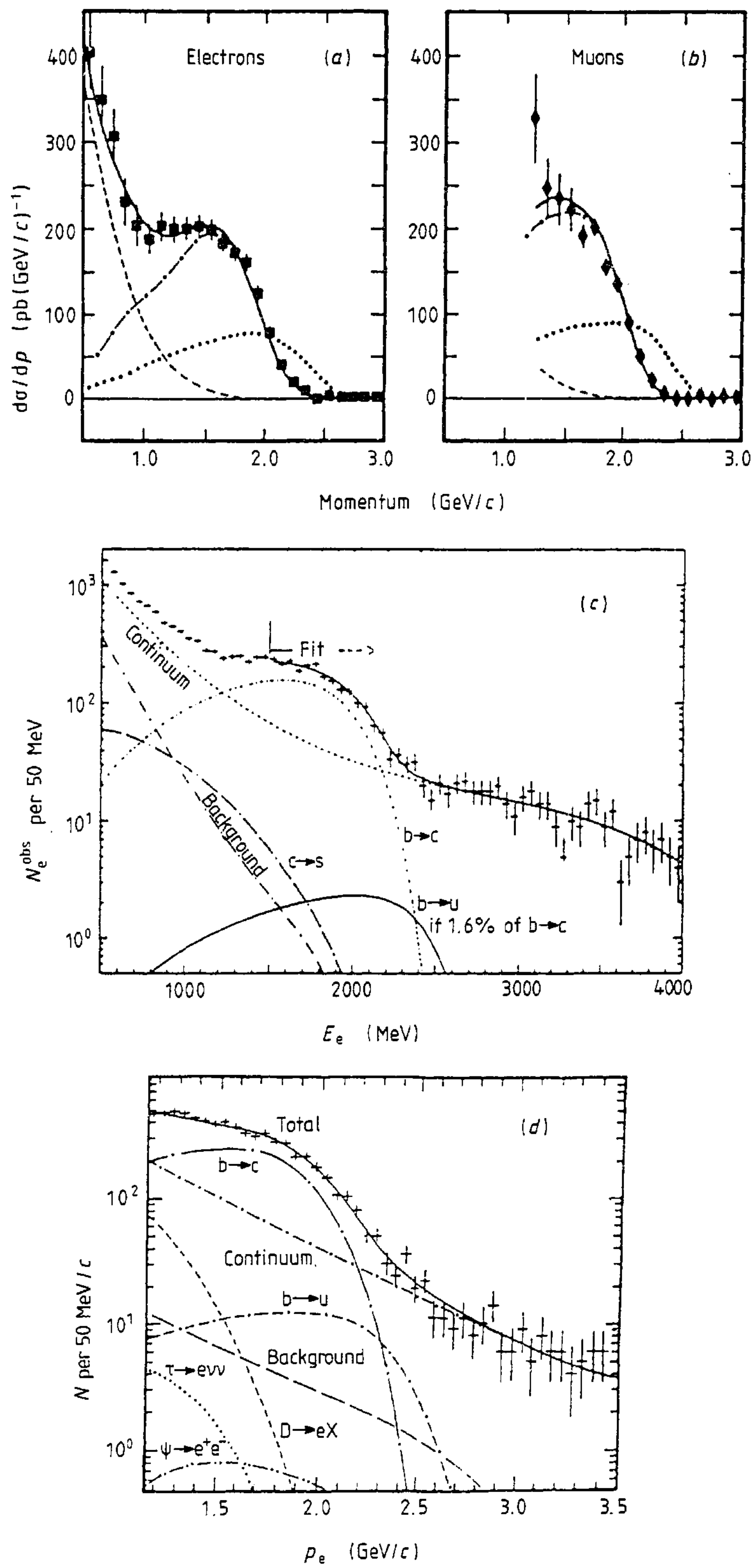

Figure 28. Lepton spectra from Υ(4S) decays.

The high-momentum part of the lepton spectrum is sensitive to ($b \to u$) transitions. In ($b \to c$) decays one has $M_X \geqslant M(D^0)$, whereas in ($b \to u$) decays, the condition is $M_X \geqslant M(\pi)$. Thus the lepton spectrum in ($b \to u$) decays extends to higher momenta than in ($b \to c$) decays. No significant contribution to the lepton momentum spectrum is found above $p_l \simeq 2.4$ GeV/c, the kinematic limit for ($b \to c$) transitions if the b quark is nearly at rest as in $\Upsilon(4S)$ decays. Therefore, only limits can be obtained for the ratio $\text{BR}(b \to u)/\text{BR}(b \to c)$. These limits depend strongly on how the endpoint region of the ($b \to c$) transition is modelled and by how much the ($b \to u$) decay is saturated by the lowest-lying non-strange mesons, namely by the decays $B \to \pi l^+ \nu$ or $B \to \rho l^+ \nu$. The theoretical predictions for these partial decay widths differ significantly (Wirbel *et al* 1986, Grinstein *et al* 1986). Accordingly, only conservative limits are quoted in table 7.

Table 7. Branching ratios for $B \to lX$ and $B \to X_cX$, $X_c \to lX$ (CLEO: Thorndyke and Poling 1988; CUSB: Klopfenstein *et al* 1983, Levman *et al* 1984; ARGUS: Schubert 1986; CB: Wachs *et al* 1987). The errors for $\text{BR}(B \to l^- \bar{\nu} X)$ contain the statistical and systematic errors for each experiment but not model-dependent uncertainties which are common to all experiments.

	$\text{BR}(B \to e^- \bar{\nu} X)$ (%)	$\text{BR}(B \to \mu^- \bar{\nu} X)$ (%)	$\text{BR}(B \to X_cX) \times \text{BR}(X_c \to lX)$ (%)	$\frac{\text{BR}(b \to ul\nu)}{\text{BR}(b \to cl\nu)}$ (90% CL)
CLEO	11.0 ± 0.8	11.0 ± 1.1	$9 \pm 1 \pm 2$	<0.08
CUSB	13.2 ± 1.6	11.2 ± 1.3	9 ± 3	
ARGUS	12.0 ± 0.9		$12 \pm 2 \pm 1$	<0.12
CB	11.7 ± 0.8			<0.13

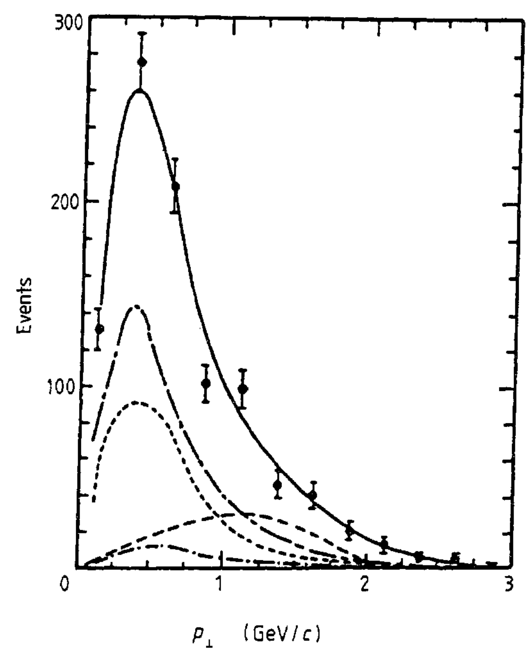

Figure 29. p_T distribution of muons in $e^+e^- \to$ hadrons events (Bartel *et al* 1987a). — — — —, background; · · ·, $c \to \mu$; - - -, $b \to \mu$; - · - ·, $b \to c \to \mu$ plus $b \to \tau \to \mu$; ——, total; ●, data points.

Using the relation

$$\frac{\text{BR}(b\to ul\nu)}{\text{BR}(b\to cl\nu)}=\frac{0.86|V_{ub}|^2}{0.48|V_{cb}|^2}$$

one obtains

$$\frac{|V_{ub}|}{|V_{cb}|}<0.21$$

for the best limit of $\text{BR}(b\to ul\nu)/\text{BR}(b\to cl\nu)\leqslant 8\%$.

A determination of the semileptonic branching ratio for B mesons produced in e^+e^- annihilations at energies above that of the $\Upsilon(4S)$ resonance is more difficult than on the $\Upsilon(4S)$ resonance because the B mesons represent only a small fraction of the particles produced in the continuum. The dominant source of leptons is the $c\bar{c}$ events which must be accounted for by exploiting their different behaviour in the p_T distribution, where p_T is the lepton momentum transverse to the thrust axis of the event (figure 29).

The measured branching ratios from the groups at PEP and PETRA are listed in table 8 and are, within large errors, compatible with the measurements made at the $\Upsilon(4S)$. As an average for the semileptonic branching ratio of b hadrons one obtains in the continuum (Bartel *et al* 1987a)

$$\text{BR}(b\to l^-X)=(11.8\pm1.1)\%.$$

The near equality of the semileptonic branching ratios for b hadrons from $\Upsilon(4S)$ decays and from continuum production, unless due to a fortuitous mixture of b hadrons from the $\Upsilon(4S)$ and in the continuum, could be explained if all B particles have about the same lifetime. Averaging the results for the measurements of the semileptonic branching ratio of b hadrons from the $\Upsilon(4S)$ meson and the continuum, one obtains

$$\text{BR}(B\to l^+X)=(11.5\pm0.9)\%.$$

5.2. *Lifetime of b hadrons*

Lifetime measurements for B mesons which are decay products of the $\Upsilon(4S)$ have not been possible because their small velocity ($\beta\simeq0.06$) produces decays too close to the

Table 8. Semileptonic branching ratios of b quarks and c quarks in the e^+e^- continuum above 28 GeV.

	$\text{BR}(b\to l^-\bar{\nu}X)$ (%)	$\text{BR}(c\to l^+\nu X)$ (%)	l	Reference
TASSO	$11.7\pm2.8\pm1.0$	$8.2\pm1.2^{+2}_{-1}$	μ	Althoff *et al* (1984a)
TASSO	$11.1\pm3.4\pm4.0$	$9.2\pm2.2\pm4.0$	e	Althoff *et al* (1984b)
MARKJ	$8.8\pm0.7\pm1.1$	$12.4\pm1.3\pm2.0$	μ	Adeva *et al* (1983)
CELLO	$8.8\pm3.4\pm3.5$	$12.3\pm3.4\pm3.5$	μ	Behrends *et al* (1983)
CELLO	$14.1\pm5.8\pm3.0$		e	Behrends *et al* (1983)
JADE	$11.7\pm1.6\pm1.5$	$7.8\pm1.6\pm1.5$	μ	Bartel *et al* (1987a)
MAC	$12.3\pm1.8(\pm0.8^{+1.7}_{-1.3})$	9 ± 3	μ	Fernandez *et al* (1983)
MAC	$11.3\pm1.9\pm3.0$	8 ± 3	e	Piccolo *et al* (1983)
MARK II	$12.6\pm5.2\pm3.0$	$8.3\pm1.3\pm3.0$	μ	Lockyer *et al* (1983)
MARK II	$13.5\pm2.6\pm2.0$	$6.6\pm1.4\pm2.0$	e	Nelson *et al* (1983)
DELCO	$14.9^{+2.2}_{-1.9}$	$11.6^{+1.1}_{-0.9}$	e	Pal *et al* (1986)
TPC	$15.2\pm1.9\pm1.2$	$6.9\pm1.1\pm1.1$	μ	Aihara *et al* (1985a)
TPC	$11.0\pm1.8\pm1.0$	$9.1\pm0.9\pm1.3$	e	Aihara *et al* (1985b)

production vertex. Lifetime measurements of b hadrons have only been performed by the PEP and PETRA groups. In these experiments the decay length distribution is measured for a sample of $b\bar{b}$ enriched events. The detection of individual B decay vertices or the reconstruction of single B mesons has therefore not been possible, so that only average lifetimes of b hadrons have been determined from the decay length distributions.

As a measure of the proper decay length one determines the lepton impact parameter δ. This impact parameter is determined by the thrust axis, which describes the average direction of a b hadron, the mean beam position, as obtained by Bhabha scattering, and the lepton track. It is close to zero for particles decaying close to the production vertex. A typical distribution of the lepton impact parameter is shown in figure 30 where for the leptons one measures an average value $\langle\delta\rangle = (112.7 \pm 12.3)\ \mu\text{m}$ in a b-enriched sample (Ong *et al* 1987). Again, as for the determination of the semileptonic branching ratios, Monte Carlo simulations of the signal must be performed using as input b fragmentation functions, branching ratios and spatial distributions for the decay $B \to lX$. Likewise, for the background the input comprises charm fragmentation functions, semileptonic charm and cascade decays $B \to C \to l$, and charm lifetimes. The derived lifetimes for b hadrons are listed in table 9. The mean value obtained is (Wu 1987)

$$\tau_b = (1.18 \pm 0.14) \times 10^{-12}\ \text{s}.$$

Assuming that all b hadrons have the same lifetime, one can combine the results for the lifetime and semileptonic branching ratios of b hadrons to obtain the following relation between V_{ub} and V_{cb}:

$$(0.86|V_{ub}|^2 + 0.48|V_{cb}|^2) \simeq 0.0011 \pm 0.0003. \qquad (5.1)$$

The main uncertainty in this relation is the poor knowledge of the mass of the b quark, for which a value of $M_b = (4.8 \pm 0.25)\ \text{GeV}/c^2$ is taken. For $V_{ub} \simeq 0$, one obtains $|V_{cb}| \simeq 0.048 \pm 0.008$ which compares well with the values for $|V_{cb}|$ derived in § 3.

The value for V_{cb} is of considerable importance, since it also constrains, through unitarity of the KM matrix, the other unknown matrix elements. Comparing the value

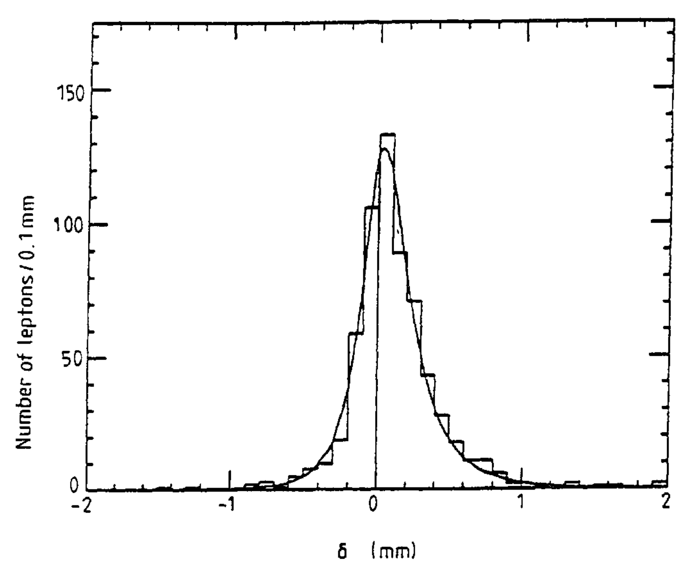

Figure 30. Lepton impact parameter δ distribution. 634 leptons; $\langle\delta\rangle = 112.7 \pm 12.3\ \mu\text{m}$.

Table 9. Lifetimes of b hadrons. Different methods are used to extract the lifetimes (Wu 1987).

	τ_B(ps)	Reference
MARK II	$0.98 \pm 0.12 \pm 0.13$	Ong *et al* (1987)
DELCO	$1.17^{+0.27+0.17}_{-0.22-0.16}$	Klem *et al* (1986)
JADE	$1.8^{+0.5}_{-0.4} \pm 0.4$	Bartel *et al* (1986)
HRS	$1.02^{+0.41}_{-0.37}$	Blockus *et al* (1987)
MAC	1.29 ± 0.20 ● 0.21	Ash *et al* (1987)
TASSO	$1.52 \pm 0.18 \pm 0.24$	Braunschweig *et al* (1987)
TASSO	$1.37 \pm 0.14 \pm 0.32$	Braunschweig *et al* (1987)
JADE	$1.46 \pm 0.19 \pm 0.30$	Bartel *et al* (1987b)
TASSO	$1.39 \pm 0.10 \pm 0.25$	Braunschweig *et al* (1987)
TASSO	$1.35 \pm 0.16 \pm 0.27$	Braunschweig *et al* (1987)
Combined	1.18 ± 0.14	Wu (1987)

for V_{cb} with $V_{us} = 0.221 \pm 0.002$, one observes that the third family is more decoupled from the second family than the second family is from the first one. This accounts for the relatively long lifetime of the b hadrons.

6. Charmless B decays via b→u transitions

Measurement of a B decay mode, which can only proceed via a (b→u) transition, provides information about the Kobayashi–Maskawa element V_{ub}. CP violation occurs in the standard model only if this matrix element is non-zero. This is easily seen by using for example the Chau parametrisation of the Kobayashi–Maskawa matrix for which one obtains (see § 2)

$$V_{ub} = s_\beta e^{-i\delta}.$$

CP conservation is violated if the quantity (Jarlskog 1986)

$$J \propto s_\theta s_\beta s_\gamma c_\theta c_\beta^2 c_\gamma \sin\delta$$

is non-zero, which implies

$$\theta, \beta, \gamma \neq 0, \pi/2 \qquad \text{and} \qquad \delta \neq 0, \pi$$

and therefore $V_{ub} \neq 0$.

(b→u) transitions can be detected by reconstructing exclusive B decays containing neither charm nor strangeness in the final state, e.g. $B \rightarrow n\pi$. Although a signal in such decays will demonstrate that $V_{ub} \neq 0$, there exists considerable theoretical uncertainty in extracting a value for V_{ub} from measurements of rates for such exclusive decay modes.

6.1. Search for decays $B \rightarrow n\pi$

The reconstruction of these charmless B decays is performed in a similar way to that described in § 3. Due to the large combinatorial background in decays involving high multiplicities only decays with $n = 2$, 3, 4 have been studied. No significant signals have been observed and the limits of such decays are summarised in table 10. These results can be compared with theoretical models which give branching ratios as a

Table 10. Limits on charmless B decays (Bebek *et al* 1987, Weseler 1986, Schröder 1988). Theoretical predictions from Bauer *et al* (1987) and Wirbel *et al* (1986).

Decay mode	90% CL upper limits (%) CLEO	ARGUS	Predicted branching ratio (%)
$B^0 \to \pi^+\pi^-$	0.03	0.04	$0.21\ (V_{ub}/0.05)^2$
$B^0 \to \rho^+\pi^-$	0.61		$0.56\ (V_{ub}/0.05)^2$
$B^- \to \pi^0\pi^-$	0.23		$0.06\ (V_{ub}/0.05)^2$
$B^- \to \rho^0\pi^-$	0.02	0.07	$0.06\ (V_{ub}/0.05)^2$
$B^0 \to \rho^0\rho^0$	0.05		$0.01\ (V_{ub}/0.05)^2$
$B^0 \to \pi^+ a_1(1270)^-$	0.12		$0.59\ (V_{ub}/0.05)^2$
$B^0 \to \pi^+ a_2(1320)^-$	0.16		
$B^- \to \rho^0 a_1(1270)^-$	0.32		$0.33\ (V_{ub}/0.05)^2$
$B^- \to \rho^0 a_2(1320)^-$	0.23		
$B^0 \to p\bar{p}$	0.02	0.013	
$B^- \to \rho^0 l^- \nu$	0.25	0.22	$3.9\ (V_{ub}/0.05)^2$

function of V_{ub} for various non-leptonic (Bauer *et al* 1987) and semileptonic (Wirbel *et al* 1986) decays (table 10).

The predicted rates for the studied low-multiplicity charmless B decays are therefore too small to improve our knowledge of the ratio $|V_{ub}|/|V_{cb}|$.

6.2. *Search for the decay* $B^+ \to \rho^0 l^+ \nu$

The most sensitive limit for exclusive $(b \to u)$ transitions is obtained from the measurement of the decay $B^+ \to \rho^0 l^+ \nu$. The endpoint of the lepton spectrum for events containing $B^+ \to \rho^0 l^+ \nu$ candidates is shown in figure 31 (Bean *et al* 1987a). In the lepton momentum range between 2.4 and 2.6 GeV/c, which contains about 11% of the $\bar{B}^- \to \rho^0 l^- \nu$ decay rate, CLEO finds -5.1 ± 25.5 candidates for this decay. This yields an upper limit for the branching ratio of the semileptonic decay $\bar{B}^- \to \rho^0 l^- \nu$ of 0.25% taking the model of Wirbel *et al* (1986).

The ARGUS analysis of the decay $B^+ \to \rho^0 l^+ \nu$ (Schröder 1988) is performed in a manner similar to that used for the decay $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$. No signal is observed for the decay $B^+ \to \rho^0 l^+ \nu$ which suffers from a large background.

A direct comparison with the decay $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ in the same data yields the result

$$\frac{\mathrm{BR}(B^+ \to \rho^0 l^+ \nu)}{\mathrm{BR}(B^0 \to D^{*-} l^+ \nu)} < 3.2\%.$$

Some experimental errors cancel in the determination of R. It is also expected that this ratio can be reasonably well predicted by theoretical models. Assuming equal lifetimes for charged and neutral B mesons and $\Gamma(B^0 \to \rho^- l^+ \nu)/\Gamma(B^+ \to \rho^0 l^+ \nu) \simeq 2$ and using models that give reasonable descriptions for the decay $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$ (Wirbel *et al* 1986, Körner and Schuler 1988) (see § 3.2) one obtains

$$\frac{\Gamma(B^+ \to \rho^0 l^+ \nu)}{\Gamma(B^0 \to D^{*-} l^+ \nu)} \simeq 0.63 \times \frac{|V_{ub}|^2}{|V_{cb}|^2}.$$

This relation yields the limit

$$|V_{ub}|/|V_{cb}| < 0.22.$$

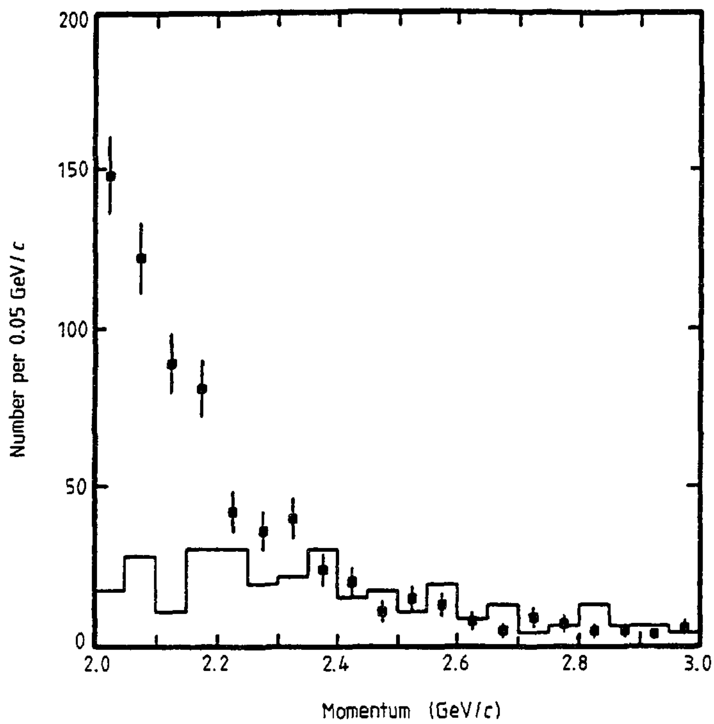

Figure 31. Lepton spectrum from events containing $B^+ \to \rho^0 l^+ \nu$ candidates. Data points, $\Upsilon(4S)$; histogram, continuum contribution.

6.3. Evidence for B decays into $p\bar{p}\pi^-$ and $p\bar{p}\pi^+\pi^-$

The motivation to search for non-charm final states containing baryons derives from the higher masses of the decay particles absorbing more of the available phase space. Therefore it is possible that low-multiplicity channels involving baryons could have larger branching ratios.

Following this line of thought, ARGUS has investigated the channels (Albrecht *et al* 1988e) $B^- \to p\bar{p}\pi^-$ and $B^0 \to p\bar{p}\pi^+\pi^-$. The analysis is performed analogous to the reconstruction of hadronic B decays through $(b \to c)$ channels (§ 3). In addition, one requires $\cos\Theta_{p\bar{p}} \leq -0.98$, where $\Theta_{p\bar{p}}$ is the opening angle between the proton and antiproton candidates.

The resulting mass spectrum for the $\Upsilon(4S)$ data shows a pronounced peak in the B mass region on a small background (figure 32). From a fit with a gaussian plus background (full curve) one observes a signal of 25 events at a mass of $(5278.3 \pm 1.1 \pm 3.0)$ MeV/c^2 with a width, consistent with expectation, of $\sigma_M = (4.2 \pm 1.0)$ MeV/c^2.

The sample can be divided into neutral and charged B mesons. The masses obtained for these agree nicely with previous measurements in the $(b \to c)$ decay channels (see § 3). For the branching ratios one finds

$$\text{BR}(B^- \to p\bar{p}\pi^-) = (5.2 \pm 1.4 \pm 1.9) \times 10^{-4}$$

$$\text{BR}(B^0 \to p\bar{p}\pi^+\pi^-) = (6.0 \pm 2.0 \pm 2.2) \times 10^{-4}$$

where the first is the statistical and the second the systematic error, including a contribution introduced by the assumed background function.

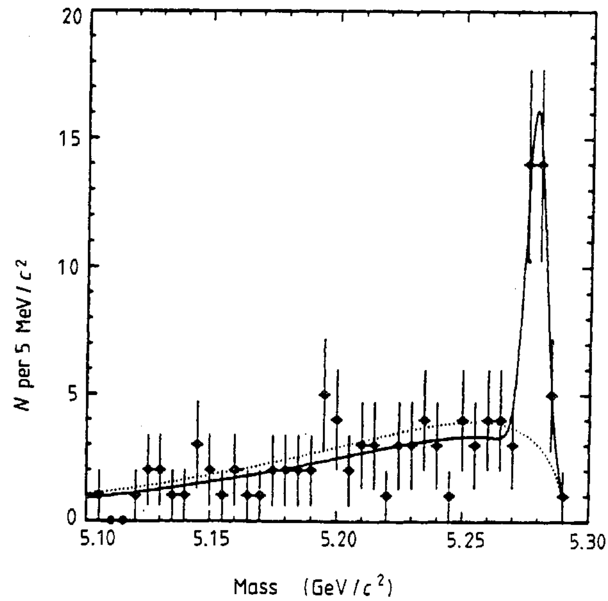

Figure 32. Mass distribution of B meson candidates for Υ(4S) data (points with error bars). The dotted line corresponds to continuum data, fitted and normalised.

The observation of these charmless B decay modes, if confirmed†, represents the first evidence that the Kobayashi–Maskawa matrix element V_{ub} is non-zero. From the measured branching ratios, one can estimate a lower limit on the strength of the $b \to u$ coupling of $V_{ub}/V_{cb} \geq 0.08$ (Gronau and Rosner 1987, Deshpande *et al* 1987a, Barshay *et al* 1988). Such an estimate is, however, subject to large theoretical uncertainties.

7. $B\bar{B}$ oscillations

The study of oscillations in the neutral B meson systems, that is $B^0\bar{B}^0$ and $B_s\bar{B}_s$, provides basic information on the parameters and validity of the standard model (Kobayashi and Maskawa 1973, Gaillard and Lee 1974, Ellis *et al* 1977, Ali and Aydin 1978, Bigi and Sanda 1984, Paschos and Tuerke 1984). In particular, in the standard model with three families it allows a determination of the Kobayashi–Maskawa matrix elements V_{td} and V_{ts}. Since massive or exotic virtual states can also contribute to the mixing phenomenon it is potentially a sensitive probe for new physics (Bose and Paschos 1980, Gavela *et al* 1985a, Anselm *et al* 1985, Gronau and Schechter 1985, Ecker and Grimus 1986, Altarelli and Franzini 1988, Bertolini *et al* 1987a, Paschos *et al* 1987).

7.1. Phenomenology of $B\bar{B}$ oscillations

Oscillations between particle and antiparticle were predicted for the K^0-$\bar{K}^0$ system in 1955 (Gell-Mann and Pais 1955) and observed in 1956 (Landé *et al* 1956). Sizable effects are also expected in the $B^0\bar{B}^0$ and $B_s\bar{B}_s$ systems. $B^0\bar{B}^0$ oscillations proceed by

† A recent measurement by Bebek *et al* (1988) yields no signal in these B decay modes in a sample of 332 000 produced $B\bar{B}$ pairs. The upper limit of 3.6×10^{-4} for the sum of the two branching fractions is in disagreement with the ARGUS result.

a second-order weak interaction, as described by the 'box diagrams' (figure 33) (Gaillard and Lee 1974). The $B^0\bar{B}^0$ system is given by the phenomenological Hamiltonian matrix

$$H\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} M-\frac{1}{2}i\Gamma & M_{12}-\frac{1}{2}i\Gamma_{12} \\ M_{12}^*-\frac{1}{2}i\Gamma_{12}^* & M-\frac{1}{2}i\Gamma \end{pmatrix}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}.$$

The diagonal terms describe the decay of the neutral B mesons with M being the mass of the flavour eigenstates B^0 and $\bar{B}^0$ and Γ their decay width. The off-diagonal terms are responsible for $B^0\bar{B}^0$ mixing and represent the $B^0\bar{B}^0$ transition amplitudes

$$M_{12}-\tfrac{1}{2}i\Gamma_{12}=\langle B^0|H|\bar{B}^0\rangle.$$

M_{12} and Γ_{12} can be determined from theory by evaluating the box diagram. Diagonalisation of this matrix leads to the mass eigenstates B_1 and B_2 which are linear combinations of the flavour eigenstates. Neglecting CP violation one obtains:

$$|B_1\rangle=\frac{1}{\sqrt{2}}(|B^0\rangle+|\bar{B}^0\rangle)$$

$$|B_2\rangle=\frac{1}{\sqrt{2}}(|B^0\rangle-|\bar{B}^0\rangle)$$

with masses $M_{1,2}$ and width $\Gamma_{1,2}$ where

$$M_{1,2}=M\pm\Delta M/2$$

$$\Gamma_{2,1}=\Gamma\pm\Delta\Gamma/2.$$

The mass difference between the two mass eigenstates

$$\Delta M=M_2-M_1$$

is a measure of the oscillation frequency to change from a B^0 to a $\bar{B}^0$ and vice versa. For the mass difference ΔM one obtains (Kobayashi and Maskawa 1973, Gaillard and Lee 1974, Ellis *et al* 1977, Ali and Aydin 1978, Bigi and Sanda 1984)

$$\Delta M=\frac{G_F^2}{6\pi^2}B_B f_B^2 M_b |V_{tb}^* V_{td}|^2 M_t^2 F\left(\frac{M_t^2}{M_W^2}\right)\eta_{QCD}$$

where B_B is the 'bag' parameter, f_B the B decay constant and M_t the mass of the t quark. F and η_{QCD} are correction factors, $F\simeq 0.75$ for $M_t=M_W$ and $\eta_{QCD}\simeq 0.85$.

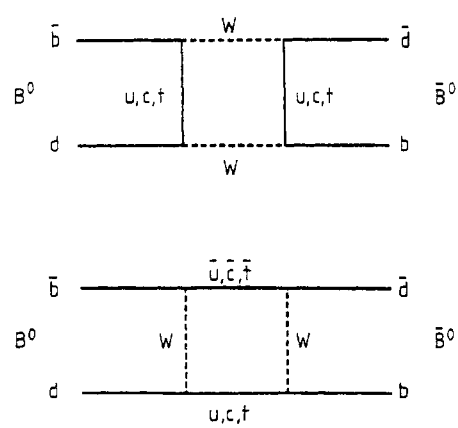

Figure 33. Box diagrams for $B^0\bar{B}^0$ transitions.

$B^0\bar{B}^0$ oscillations are measured by determining the mixing parameter

$$r = \frac{\text{PROB}(B^0 \to \bar{B}^0)}{\text{PROB}(B^0 \to B^0)} = \frac{x^2}{2+x^2}$$

which is defined as the rate that an originally produced B^0 decays as a $\bar{B}^0$ meson over the rate that it decays as a B^0 meson. The quantity x is defined as $x = \Delta M/\Gamma$ for which one obtains in the case of $B^0\bar{B}^0$ mixing:

$$x = \frac{G_F^2}{6\pi^2} B_B f_B^2 M_b \tau_b |V_{tb}^* V_{td}|^2 M_t^2 F\left(\frac{M_t^2}{M_W^2}\right) \eta_{QCD}$$

where τ_b is the measured lifetime of B hadrons.

7.2. *Methods of observing $B\bar{B}$ mixing*

Searches for $B^0\bar{B}^0$ and $B_s\bar{B}_s$ mixing have been carried out using e^+e^- or $p\bar{p}$ annihilation events where B hadrons are produced in pairs. Mixing manifests itself by the presence of two B hadrons each containing either a b or a $\bar{b}$ quark. In order to observe $B^0\bar{B}^0$ or $B_s\bar{B}_s$ mixing one first has to obtain a clean sample of events containing the B hadron pair. Secondly, one has to determine the b flavour of both B hadrons.

The cleanest source for $B^0\bar{B}^0$ pairs is the $\Upsilon(4S)$ meson which decays about 45% of the time into $B^0\bar{B}^0$ pairs:

$$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0.$$

The existence of mixing will lead in $\Upsilon(4S)$ decays to events consisting of B^0B^0 or $\bar{B}^0\bar{B}^0$ pairs.

In the decay of the $\Upsilon(4S)$ resonance the $B^0\bar{B}^0$ pair is produced coherently in a $l=1$ state since the $\Upsilon(4S)$ resonance has the quantum numbers $J^{PC} = 1^{--}$. The ratio R of mixed events to unmixed events in $\Upsilon(4S)$ decays

$$R = \frac{N_{B^0B^0} + N_{\bar{B}^0\bar{B}^0}}{N_{B^0\bar{B}^0}}$$

coincides exactly with the mixing parameter r (Okun *et al* 1975)

$$R_{l=\text{odd}} = r = \frac{x^2}{2+x^2}.$$

In the continuum the B mesons are produced incoherently. In this case the ratio of mixed to unmixed events is given by

$$R_{\text{incoh}} = \frac{2r}{1+r^2} = \frac{2x^2+x^4}{2+2x^2+x^4}.$$

Mixing in the continuum will lead to events which contain a B^0 ($\bar{B}^0$) or B_s ($\bar{B}_s$) meson together with a B ($\bar{B}$) hadron of the same $\bar{b}$ (b) quark content. It is convenient to define the quantity χ as the ratio of mixed events to all $b\bar{b}$ events:

$$\chi = \frac{N_{BB} + N_{\bar{B}\bar{B}}}{N_{b\bar{b}}}.$$

The quantity χ is then a linear combination of χ_d and χ_s for $B^0\bar{B}^0$ and $B_s\bar{B}_s$ mixing:

$$\chi = p_d \frac{r}{1+r} + p_s \frac{r_s}{1+r_s} = p_d\chi_d + p_s\chi_s$$

where r_s is the mixing parameter for $B_s\bar{B}_s$ mixing. The quantity p_d (p_s) is the relative fraction of B^0 and $\bar{B}^0$ (B_s and $\bar{B}_s$) mesons produced in $b\bar{b}$ events. From measurements of strange particle production in e^+e^- annihilation the quantity p_s is expected to be $p_s \simeq 0.15$ (Bartel *et al* 1983) and, assuming further the b-flavoured baryons to be produced with a fraction of 10% and $p_d = p_u$, one expects $p_d \simeq 0.38$. Therefore χ is given in the e^+e^- continuum by $\chi = 0.38 \times \chi_d + 0.15 \times \chi_s$.

The standard method for studying $B^0\bar{B}^0$ mixing exploits the fact that B mesons are most efficiently tagged through their leptonic decays. A B^0 or B_s meson will decay semileptonically into an e^+ or μ^+ plus an antineutrino and hadrons. Likewise a $\bar{B}^0$ or $\bar{B}_s$ meson will yield an e^- or μ^- in its semileptonic decays. Mixing can therefore be studied by searching for events containing like-sign lepton pairs.

7.3. *Experimental results on $B\bar{B}$ mixing*

Positive experimental results on $B^0\bar{B}^0$ mixing exist only from ARGUS studies of $\Upsilon(4S)$ decays (Albrecht *et al* 1987d). The CLEO collaboration has reported on a search for $B^0\bar{B}^0$ in $\Upsilon(4S)$ decays (Bean *et al* 1987b). Further searches for $B^0\bar{B}^0$ and $B_s\bar{B}_s$ mixing have been performed by the UA1 collaboration at the CERN $p\bar{p}$ collider (Albajar *et al* 1987) and the MARK II (Schaad *et al* 1985) and MAC collaborations (Band *et al* 1988) at PEP.

7.3.1. Observation of $B^0\bar{B}^0$ mixing by ARGUS. The mixing study of the ARGUS experiment is made with B mesons produced in 96 000 $\Upsilon(4S)$ decays. Evidence for substantial $B^0\bar{B}^0$ mixing is obtained by using three different analysis methods. The first approach is to search for fully reconstructed $\Upsilon(4S)$ decays into B^0B^0 or $\bar{B}^0\bar{B}^0$ pairs.

ARGUS succeeded in completely reconstructing a decay $\Upsilon(4S) \to B^0B^0$, which represents the first observation of $B^0\bar{B}^0$ mixing. The two B^0 mesons decay in the following way:

$$B_1^0 \to D_1^{*-}\mu_1^+\nu_1 \qquad \text{and} \qquad B_2^0 \to D_2^{*-}\mu_2^+\nu_2$$
$$\hookrightarrow \bar{D}^0\pi_{1s}^- \qquad\qquad \hookrightarrow D^-\pi^0$$
$$\hookrightarrow K_1^+\pi_1^- \qquad\qquad \hookrightarrow K_2^+\pi_2^-\pi_2^-.$$

The event is shown in figure 34 and its kinematical quantities are listed in table 11. The masses of the intermediate states agree well with the known values (Aguilar-Benitez *et al* 1986). Both D^{*-} mesons contain positive kaons of momenta $p(K_1) = 0.548$ GeV/c and $p(K_2) = 0.807$ GeV/c which are uniquely identified by the measurements of specific ionisation loss (dE/dx) and time of flight. The two positive muons are the fastest particles in the event with momenta $p(\mu_1) = 2.186$ GeV/c and $p(\mu_2) = 1.579$ GeV/c, and have dE/dx and shower counter information consistent with the muon hypothesis. One muon, μ_1, is clearly identified in the muon chambers whereas the second one, μ_2, points in a direction of the detector not covered by muon chambers.

This event has a kinematic peculiarity which leads to the conclusion that B_2^0 decays semileptonically, and that therefore μ_2 must be a muon, providing further proof that this event contains two B^0 mesons. The momenta of D_1^{*-} and μ_1^+ are such that they restrict the momentum vector of the B_1^0 meson onto a small cone around the direction of the $D_1^{*-}\mu_1^+$ system. Knowing the direction of B_1^0 and, opposite to it, of B_2^0, the event can then be fully reconstructed in spite of the fact that two neutrinos are present.

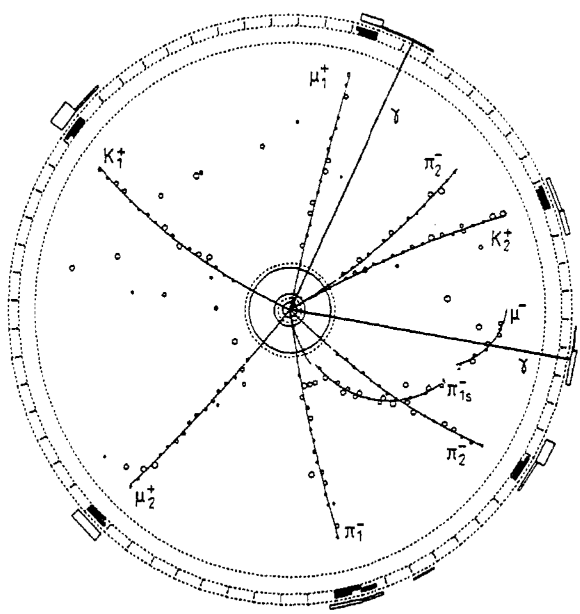

Figure 34. Completely reconstructed event consisting of the decay $\Upsilon(4S) \to B^0B^0$.

Table 11. Kinematical quantities of the observed $\Upsilon(4S) \to B^0B^0$ event.

Decay	Mass (GeV/c^2)	p (GeV/c)	M^2_{rec} (GeV^2/c^4)
$B^0 \to D_1^{*-}\mu_1^+(\nu_1)$	4.393 ± 0.088†	1.090 ± 0.108†	-0.609
$D_1^{*-} \to \pi_1^-\bar{D}^0$	2.008 ± 0.001	1.196 ± 0.013	
$\bar{D}^0 \to K_1^+\pi_1^-$	1.873 ± 0.021	1.091 ± 0.012	
$B^0 \to D_2^{*-}\mu_2^+(\nu_2)$	3.969 ± 0.032†	1.244 ± 0.015†	-0.275
$D_2^{*-} \to \pi^0 D^-$	2.008 ± 0.005	1.611 ± 0.017	
$\pi^0 \to 2\gamma$	0.180 ± 0.028	0.136 ± 0.019	
$D^- \to K_2^+\pi_2^-\pi_2^-$	1.886 ± 0.015	1.478 ± 0.007	

† Mass and momentum without neutrino.

Specifically, the missing mass in the decay of B_2^0 is compatible only with zero or the π^0 mass. Since no additional signal for a single photon or a π^0 is seen in the detector, the neutrino hypothesis alone is acceptable which agrees perfectly with the above interpretation.

For a mixing strength of $r = 0.2$, one expects to reconstruct 0.3 events of this type where both B mesons decay as $B^0 \to D^{*-}l^+\nu$. In order to estimate the background for such an event, a Monte Carlo simulation was performed. Among 22 000 $B^0\bar{B}^0$ pairs where the B_1^0 is reconstructed in the observed channel and the multiplicities of the detected remaining charged and neutral particles are the same as in the above event, no fake candidate for mixing was found. This one event demonstrates that the phenomenon of $B^0\bar{B}^0$ mixing must exist.

A determination of the $B^0\bar{B}^0$ mixing strength was obtained by a second analysis method, where ARGUS investigated events containing lepton pairs originating from $\Upsilon(4S)$ decays. Exactly two of the particles in the events have to be well identified leptons with momenta greater than 1.4 GeV/c. The momentum cut suppresses most of the secondary leptons orginating from charmed mesons in B decays. Further requirements are made in order to reduce specific background sources of lepton pairs. The distribution of the opening angle θ_{ll} between the leptons is shown in figure 35 for events passing the cuts. For leptons originating from two different B mesons, this distribution should be isotropic. Lepton pairs from the continuum or originating from the same B meson tend to be back-to-back. These contributions are suppressed by requiring $\cos\theta_{ll} > -0.85$. Table 12 gives the number of dilepton events surviving the cuts both on the Y(4S) resonance and in the continuum below the Y(4S). The number of dilepton events from Y(4S) decays is determined by subtracting the continuum contribution scaled by a factor of 2.5 according to the ratio of accumulated luminosities.

The remaining dilepton events still include contributions from backgrounds due to lepton–hadron misidentification, secondary leptons from charm decays, J/ψ decays and converted photons. The background due to lepton–hadron misidentification is evaluated from data. Decay-in-flight and punch-through result in a π/μ misidentification probability of $(2.2\pm0.2)\%$ per pion. For K/μ misidentification the fake rate is $(1.9\pm0.5)\%$ per kaon. The fake rates due to π/e and K/e misidentification are both $(0.5\pm0.1)\%$. The number of faked dilepton events is extracted from the observed hadron momentum spectrum in the events containing like-sign and unlike-sign lepton–hadron pairs.

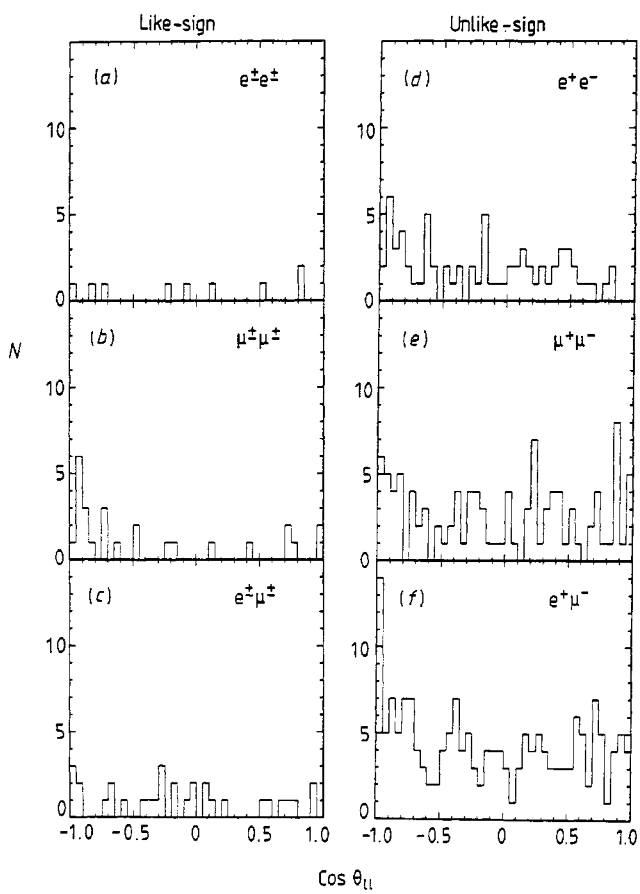

Figure 35. Distribution of the opening angle between the leptons for (*a*)–(*c*) like-sign and (*d*)–(*f*) unlike-sign pairs.

Table 12. Dilepton rates.

	$e^{\pm}e^{\pm}$	$\mu^{\pm}\mu^{\pm}$	$e^{\pm}\mu^{\pm}$	$e^{+}e^{-}$	$\mu^{+}\mu^{-}$	$e^{\pm}\mu^{\mp}$
Υ(4S) + continuum	8	16	26	60	92	149
Continuum	0	0	0	3	1	2
Υ(4S) direct	8.0	16.0	26.0	52.6	89.5	144.1
Corrected for J/ψ cut	8.0 ± 3.9	16.0 ± 4.8	26.0 ± 5.8	58.5 ± 9.8	99.6 ± 11.3	144.1 ± 12.4
Background						
Fakes	0.7	5.7	4.9	1.4	12.1	10.2
Conversion	0.5	—	0.5	0.5	—	0.5
Secondary decays	2.3	2.9	4.6	0.7	1.5	1.6
J/ψ decays	0.7	0.9	1.5	1.0	0.9	1.5
Signal	3.8 ± 3.9	6.5 ± 4.8	14.5 ± 5.8	54.9 ± 9.8	85.1 ± 4.8	130.3 ± 5.8
Background		$25.2\pm5.0\pm3.8$				
Signal		$24.8\pm7.6\pm3.8$			$270.3\pm19.4\pm5.0$	
r (%)	17 ± 19	19 ± 16	28 ± 14			
Combined mixing parameter $r=(22\pm9\pm4)\%$						

The background due to secondary leptons is determined by a Monte Carlo simulation of B decays. The simulation was checked by comparison with ARGUS measurements of the inclusive spectra for leptons, D^0 mesons, pions and kaons from B decays, and with the inclusive electron spectrum for D^0 and D^+ decays from MARK III (Baltrusaitis *et al* 1985). The background from J/ψ and ψ' decays or converted photons where only one of the two leptons is observed in the detector is also determined by Monte Carlo simulation.

The number of events is given in table 12. Out of the 50 like-sign dilepton events, $25.2\pm5.0\pm3.8$ events are attributed to the background sources as described above. The first error is the statistical and the second the systematic uncertainty in the background determination. The probability for the 50 measured events to be a fluctuation of the background corresponds to 4.0 standard deviations. Thus, a signal of $24.8\pm7.6\pm3.8$ events remains which is attributed to $B^0\bar{B}^0$ mixing. The signal for unlike-sign pairs is $270.3\pm19.4\pm5.0$ events.

In calculating the mixing parameter r for $B^0\bar{B}^0$ mixing, one assumes equal semileptonic branching ratios for charged and neutral B mesons and that the Υ(4S) meson decays 55% (45%) of the time into a B^+B^- ($B^0\bar{B}^0$) pair. Combining the results for ee, $\mu\mu$ and $e\mu$ events one obtains

$$r=0.22\pm0.09\pm0.04.$$

This result is not sensitive, within the statistical errors, to a variation of the lepton momentum cut between 1.4 and 1.6 GeV/c.

A third analysis method involved the reconstruction of one of the B^0 mesons originating from the Υ(4S) decay, as described in § 3, and tagging the second B^0 with a fast lepton. This method is considerably less sensitive to background from lepton misidentification.

The most efficient reconstruction of B^0 mesons is performed in the channel $B^0\to D^{*-}l^+\nu$ where the undetectable neutrino is inferred from the recoil mass squared against the $D^{*-}l^+$ system, M^2_{rec}, which has to be consistent with zero for B^0 mesons originating in Y(4S) decays (Albrecht *et al* 1987c) (see § 3). D^{*-} mesons are reconstructed in the decay chain $D^{*-} \to \bar{D}^0\pi^-$, followed by $\bar{D}^0 \to K^+\pi^-$, $\bar{D}^0 \to K^+\pi^-\pi^0$, $\bar{D}^0 \to K^0\pi^+\pi^-$ or $\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$. One obtains the recoil-mass-squared spectrum shown in figure 36 where the prominent peak at $M^2_{rec} = 0$ corresponds to a B^0 signal on a relatively low background.

By requiring an additional lepton with momentum larger than 1.4 GeV/c in the events, ARGUS obtained 26 events with a B^0 candidate reconstructed in the decay $\bar{B}^0 \to D^{*+}l^-\bar{\nu}$ and the second neutral B mesons tagged by a fast lepton (figure 37). Adding two events where the B^0 mesons are reconstructed in the hadronic channels, one obtains a total of 23 candidates for unmixed events and five candidates for mixed

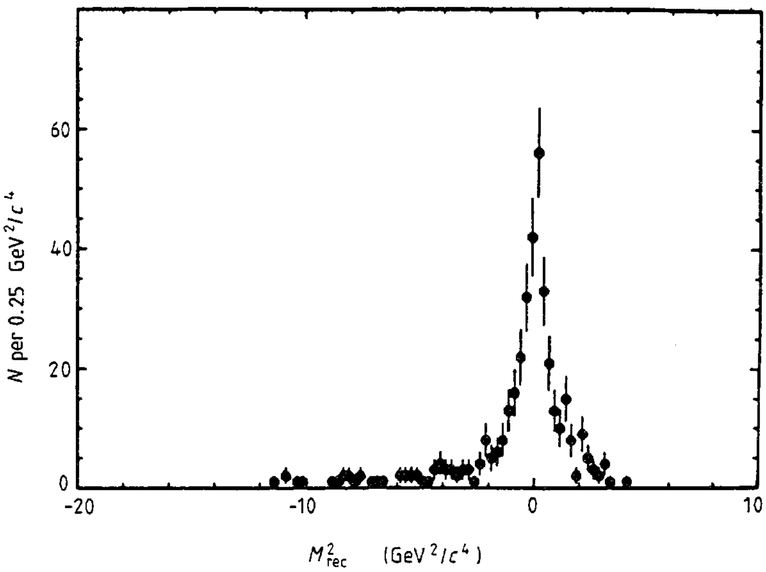

Figure 36. Recoil-mass squared M^2_{rec} spectrum.

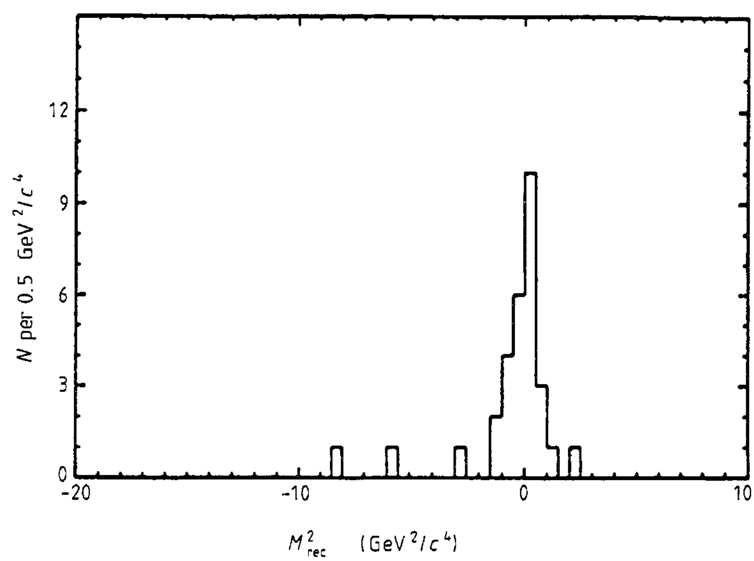

Figure 37. Recoil mass squared M^2_{rec} spectrum in events with one additional lepton.

events. These five events are composed of two B^0e^+, two $\bar{B}^0e^-$ and one $\bar{B}^0\mu^-$ events. The background for the mixed sample, determined in a way similar to that used for the second method, is expected to be 0.9 ± 0.3 due to fakes and secondary leptons. Therefore one is left with 4.1 events from $B^0\bar{B}^0$ mixing. The background to the unmixed events is 2.2 ± 1.1 events. Thus, one finds for the mixing parameter r

$$r = \frac{N(B^0 l^+) + N(\bar{B}^0 l^-)}{N(B^0 l^-) + N(\bar{B}^0 l^+)} = 0.20 \pm 0.12.$$

Two like-sign and 11 unlike-sign events from this sample are also contained in the dilepton sample. Taking this correlation into account, one obtains a combined result of

$$r = 0.21 \pm 0.08.$$

The parameter $\chi_d = r/(1+r)$ is found to be $\chi_d = 0.17 \pm 0.05$.

7.3.2. Searches for $B^0\bar{B}^0$ and $B_s\bar{B}_s$ mixing. The ARGUS result can be directly compared with results obtained by the CLEO collaboration (Bean *et al* 1987b) who also searched for $B^0\bar{B}^0$ mixing in $\Upsilon(4S)$ decays by studying like-sign lepton pairs. The CLEO analysis is similar to that made by ARGUS. The results obtained by studying 84 000 $\Upsilon(4S)$ decays yield after background subtraction 5.1 ± 5.9 events with a like-sign lepton pair and 117 ± 17 unlike-sign dileptons. From these a value for r of 0.10 ± 0.12 is derived. The two experiments are seen to be consistent with each other†.

The results from the MARK II (Schaad *et al* 1985) and MAC groups (Band *et al* 1988) on $B^0\bar{B}^0$ and $B_s\bar{B}_s$ mixing are obtained from continuum e^+e^- annihilations at 29 GeV by studying lepton pairs. Events of the type $e^+e^- \to b\bar{b}$ are enriched by requiring the leptons to have a momentum $p > 2$ GeV/c and a momentum transverse to the thrust axis of the events of $p_T > 1$ GeV/c. The cut at $p_T > 1$ GeV/c enhances the $e^+e^- \to b\bar{b}$ contribution over the $e^+e^- \to c\bar{c}$ contribution. For events containing two leptons these requirements lead to a nearly pure sample of $b\bar{b}$ events.

Both experiments observe a slightly larger number of like-sign lepton pairs than would be expected in the absence of mixing (table 13). The amount of $B^0\bar{B}^0$ and $B_s\bar{B}_s$ mixing as determined from the like-sign and unlike-sign lepton pairs yields for the MARK II experiment an upper limit of $\chi < 0.12$ (90% CL) and for the MAC experiment a value $\chi = 0.21^{+0.29}_{-0.15}$, corresponding to the limit $\chi > 0.02$ (90% CL).

Table 13. Comparison between $B^0\bar{B}^0$ mixing results from MARK II and MAC.

	Like-sign dilepton candidates		Unlike-sign dilepton candidates	
	MARK II	MAC	MARK II	MAC
Observed	4	5	10	7
Expected for no mixing	2.5 ± 0.7	1.9 ± 0.8	10.0 ± 2.0	8.6 ± 1.2
Sum	9 on 4.4 ± 1.1 background		17 (expected 18.6 ± 2.3)	

† Meanwhile the ARGUS result has been confirmed by the CLEO collaboration (Artuso *et al* 1988). Based on 220 000 $B\bar{B}$ events CLEO obtained from the observed like-sign to unlike-sign dileptons a mixing parameter $r = 0.182 \pm 0.055 \pm 0.056$.

The UA1 experiment (Albajar *et al* 1987) investigates events with two muons produced in $p\bar{p}$ annihilation at $\sqrt{s} = 546$ and 630 GeV. It is expected that semileptonic decays of b and $\bar{b}$ quarks are the dominant source of pairs of high p_T muons ($p_T^{\mu} > 3$ GeV/c) where p_T is defined as the muon momentum component transverse to the beam direction. The experiment finds 84 like-sign and 199 unlike-sign μ pairs with a mass $M_{\mu\mu} > 6$ GeV/c^2. The ratio R is then given by

$$R = \frac{N_{\mu^\pm\mu^\pm}}{N_{\mu^+\mu^-}} = 0.42 \pm 0.07 \pm 0.03$$

where the second error reflects the uncertainty in the background subtraction. The predicted value for R in the absence of flavour mixing is $R_{pred} = 0.26 \pm 0.03$, obtained from detailed QCD Monte Carlo calculations, which includes the known decay properties of B and D mesons and matches within 30% the UA1 data on heavy flavour production in size and shape. The difference between the measured value of $R = 0.42 \pm 0.07 \pm 0.03$ and the predicted one is attributed to $B^0\bar{B}^0$ and $B_s\bar{B}_s$ mixing and yields $\chi = 0.121 \pm 0.047$. This value can be compared with the values obtained by MAC and MARK II. Table 14 summarises the results from all groups.

Table 14. Mixing results from five different experiments.

	χ_d	$\chi = (BR_{sl}^0/BR_{sl})\, p_d \chi_d + (BR_{sl}^s/BR_{sl})\, p_s \chi_s$
ARGUS	0.17 ± 0.05	
CLEO	< 0.20	
MARK II		< 0.12
MAC		$0.21^{+0.29}_{-0.15}$
UA1		0.121 ± 0.047

All data are consistent with each other. A combined fit to extract χ_d and χ_s from all data yields the allowed region shown shaded in figure 38 which reflects the dominance of the ARGUS result. There is currently no experimental restriction on the value of χ_s, which can lie anywhere in the range from 0 to 0.5. However, as we will see in the next section, the standard model with three families, in conjunction with the ARGUS result discussed above, restricts χ_s to large values.

7.4. Implications from the observed mixing

The ARGUS result on $B^0\bar{B}^0$ mixing with the mixing parameter $r = 0.21 \pm 0.08$ yields

$$x = 0.73 \pm 0.18 = \Delta M/\Gamma.$$

For the mass difference ΔM between the CP eigenstates B_1 and B_2 one obtains by inserting the measured lifetime of B hadrons of $\tau_b = (1.18 \pm 0.14) \times 10^{-12}$ s

$$\Delta M = (4.1 \pm 1.1) \times 10^{-4} \text{ eV}$$

which is about one hundred times larger than in the case of the $K^0\bar{K}^0$ system.

The prediction for x, as given by the standard model with three families, depends on the following three unmeasured quantities.

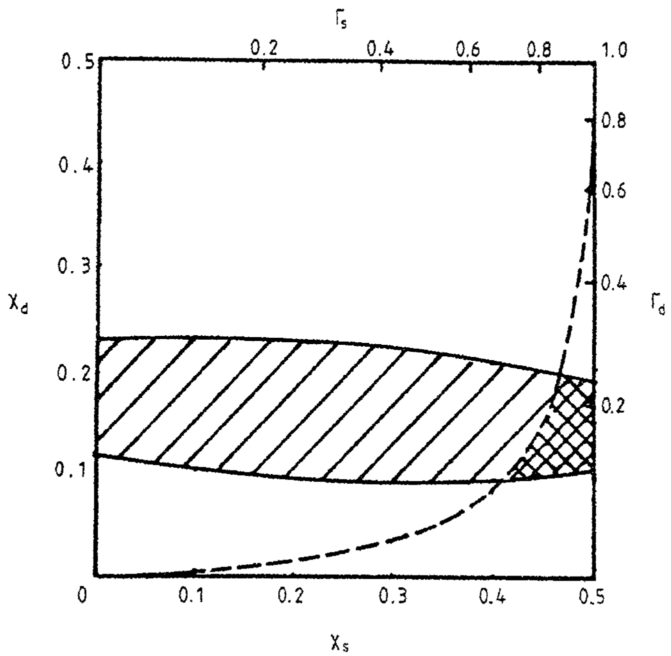

Figure 38. Combined fit to χ_d and χ_s. The shaded region is the allowed range in the $\chi_d - \chi_s$ plane with 90% CL. The broken curve corresponds to the limit $|V_{td}|^2/|V_{ts}|^2 < 0.21$ which is derived from the unitarity of the KM matrix with three families and determines the allowed region for χ_d and χ_s, shown hatched.

(i) The mass of the top quark, M_t for which only limits exist: $M_t > 26\ \mathrm{GeV}/c^2$ from the non-observation in e^+e^- annihilation at $\sqrt{s} = 52$ GeV (Takasaki 1987).

(ii) The Kobayashi-Maskawa matrix element $|V_{td}|$ which is limited by the unitarity constraint of the Kobayashi-Maskawa matrix to $|V_{td}| < 0.018$ (Aguilar-Benitez *et al* 1986).

(iii) The quantity $B_B f_B^2$ for which a 'reasonable' guess was given by (Altarelli 1987, Ali 1987)

$$B_B^{1/2} f_B \simeq (150 \pm 50)\ \mathrm{MeV}.$$

The measurement of x from ARGUS can be used to put constraints on the parameters of the standard model. Specifically, ARGUS finds that the mass of the top quark must satisfy

$$M_t > 50\ \mathrm{GeV}/c^2$$

using the measured value of $x > 0.44$ (90% CL) and the estimates $|V_{td}| < 0.018$, $B_B^{1/2} f_B <$ 180 MeV and $\eta_{QCD} < 0.86$ (see figure 39). From the upper bound of the mass of the top quark, $M_t < 190\ \mathrm{GeV}/c^2$, as derived from the size of the electroweak radiative corrections (Costa *et al* 1988) a lower bound on V_{td} of $|V_{td}| > 0.006$ is obtained. Similar results are given by other authors (Ellis *et al* 1987, Barger *et al* 1987, Khoze and Uraltsev 1987, Bigi and Sanda 1987a, Chau and Keung 1987, Du and Zhao 1987, Maalampi and Roos 1987, Tanimoto 1987, Harari and Nir 1987, Datta *et al* 1987, Donoghue *et al* 1987, Hoogeveeen and Leung 1987).

The discovery of a top quark with a mass below 40 GeV/c^2 would imply an extension of the standard model to more than three families (Paschos 1986) or new physics with new particles (Datta *et al* 1987), namely (i) charged Higgs particles, (ii) right-handed W boson or (iii) SUSY particles like gluinos and squarks. These particles could contribute to the box-diagram amplitudes and enhance $B^0\bar{B}^0$ mixing.

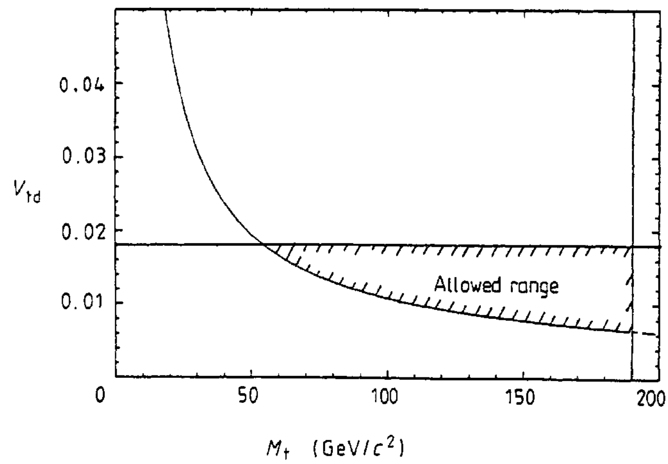

Figure 39. V_{td} as a function of M_t.

The ratio of the mixing frequencies of B^0 and B_s mesons,

$$\frac{x}{x_s}=\frac{[2\chi_d/(1-2\chi_d)]^{1/2}}{[2\chi_s/(1-2\chi_s)]^{1/2}}\simeq\frac{|V_{td}|^2}{|V_{ts}|^2}$$

is independent of the mass of the top quark, M_t. From the measurement of χ_d and the limit for $|V_{td}|^2/|V_{ts}|^2<0.21$ derived from the unitarity of the KM matrix, it is possible to obtain a strong constraint on χ_s (figure 38). Only a small region (hatched in figure 38) is allowed for χ_d and χ_s, requiring nearly complete mixing in the $B_s\bar{B}_s$ system: $\chi_s>0.4$ with 90% CL.

So far all experimental data are consistent with the standard model. Precise measurements of χ_d, and especially of χ_s, will provide a stringent test of the validity of the standard model. The main importance of the observation of the $B^0\bar{B}^0$ lies in the fact that together with the results on the b lifetime measurements (see § 5) and the measurements of (b→u) transitions (see § 6) it is possible to determine the KM angles γ, β and δ and thus fix the standard model parameters as is discussed in § 9.

8. Rare B decays induced by loop diagrams

Loop-induced decay modes of K mesons have been of great interest, since their observation provides insight into higher-order weak and electromagnetic interactions, which was useful for the development of the standard model. The suppression of flavour-changing neutral currents was observed by studying the $K^0\to\mu^+\mu^-$ decay and explained by the GIM mechanism. The $\Delta I=\frac{1}{2}$ rule, an empirical expression of the observed ratio $\Gamma(K^+\to\pi^+\pi^0)/\Gamma(K^0\to\pi^+\pi^-)\simeq 1/450$, is possibly explained by the introduction of so called 'penguin diagrams' (see figure 40) involving the presence of strong interaction effects due to gluon exchange. Contributions from penguin diagrams can, in principle, be calculated in the framework of the standard model. However, quantitative estimates in the case of the K mesons are not reliable, since strong interaction effects can only be computed in a perturbative framework, which is not applicable in this case. Due to the small available phase space, there exist no decays of K mesons, which can only occur through penguin-type diagrams, and can thus provide direct proof of their existence and significance.

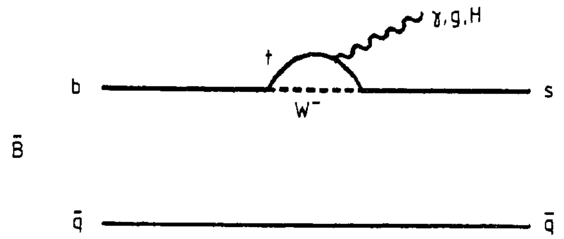

Figure 40. Penguin diagrams for B decays.

Penguin-type decays are more easily studied with B mesons, for the following reasons.

(i) A larger number of rare B decays than K decays is possible, since B mesons are more than ten times heavier than K mesons.

(ii) Perturbative QCD analysis is expected to be applicable in the case of rare B decays, so standard model predictions can be tested.

(iii) Special exclusive B decays, such as the decay $B^0 \to \phi K^0$ (figure 41), are possible only through the penguin diagram if flavour-changing neutral currents are absent.

(iv) In B decays the penguin diagram involves the KM matrix elements $V_{ts}^* V_{tb}$, which are much larger than their counterparts $V_{td}^* V_{ts}$, in the K system. Comparing the relevant couplings one finds for the B system

$$|V_{ts}^* V_{tb} / V_{cb}|^2 \simeq 1$$

whereas, for the K system, one obtains

$$|V_{td}^* V_{ts} / V_{us}|^2 \simeq 10^{-5}.$$

Since the exchanged quarks can couple to gluons, photons or Higgs bosons, there exist three different types of penguin diagrams which can be studied experimentally. Moreover, the contribution from the heaviest quark dominates the loop amplitude and so a measurement is potentially sensitive to the existence of a fourth family of quarks. In the standard model with three families the transition amplitudes depend on the mass of the t quark and the coupling of the t quark to the s quark, V_{ts}.

8.1. The transitions $b \to s + gluon$

The inclusive rate for the transitions $b \to s\,gluon$ (figure 40) is predicted to be

$$\text{BR}(b \to s\ \text{gluon}) \simeq 1\text{–}2\%$$

in the standard model with three families (Bander *et al* 1979, Guberina *et al* 1980, Eilam 1982, Guberina 1984, Hou *et al* 1987). The dependence on the mass of the top

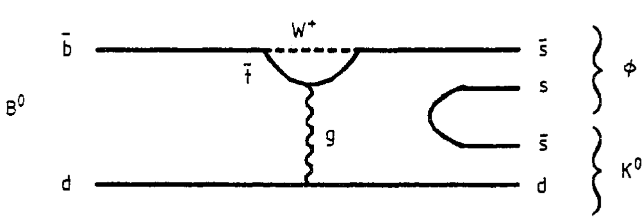

Figure 41. The decay $B^0 \to \phi K^0$.

quark is shown in figure 42. The existence of a fourth family could enhance this rate by an order of magnitude. The calculation of the inclusive rate should be relatively safe and should not suffer too much from QCD corrections. However, experimentally one is only able to measure branching ratios for exclusive decays, for which the theoretical estimates depend strongly on the poorly known hadronisation process. Rough estimates for specific channels, assuming three families, are (Gavela *et al* 1985b, Chau and Cheng 1986)

$$\text{BR}(B \to \phi K) \simeq 0.5 \times 10^{-4}$$

and

$$\text{BR}(B^0 \to K^- \pi^+) \simeq 10^{-4}.$$

No significant signals have been observed for exclusive decays of the penguin type. Only upper limits have been obtained (Avery *et al* 1987, Swain 1988) which are, however, not too far away from expectations (table 15) in the three-family case. In any case, the upper limits are much smaller than the branching ratios obtained for

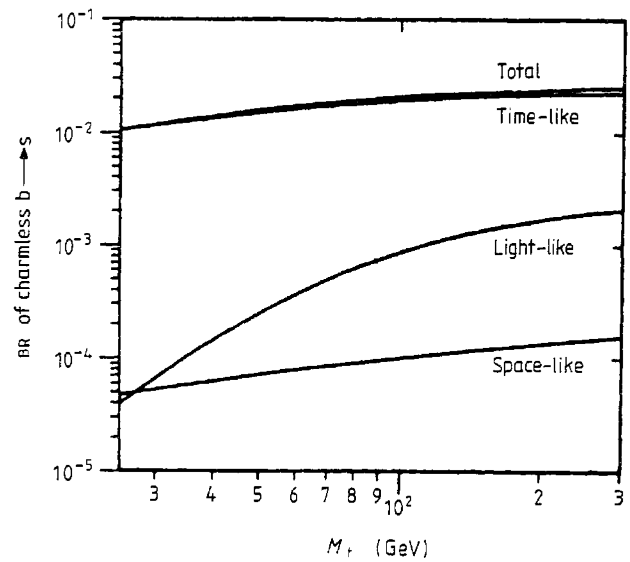

Figure 42. Theoretical prediction for b → s gluon (Hou *et al* 1987).

Table 15. Limits on branching ratios for rare B decays (Avery *et al* 1987, Swain 1988, Albrecht *et al* 1988f).

Decay mode	Expected branching ratios	90% CL upper limits CLEO	ARGUS
$B^0 \to K^- \pi^+$	10^{-4}	3.2×10^{-4}	2.7×10^{-4}
$B^0 \to \phi K^0$	0.5×10^{-4}	13.0×10^{-4}	3.3×10^{-4}
$B^- \to \phi K^-$	0.5×10^{-4}	2.1×10^{-4}	1.8×10^{-4}
$B^0 \to K^{*0} \gamma$	0.6×10^{4}	20.5×10^{-4}	2.9×10^{-4}
$B^+ \to K^+ \mu^+ \mu^-$		3.2×10^{-4}	
$B^+ \to K^+ e^+ e^-$		2.1×10^{-4}	
$B^0 \to K^0 \mu^+ \mu^-$		4.5×10^{-4}	
$B^0 \to K^0 e^+ e^-$		6.5×10^{-4}	

decays allowed by spectator diagrams (see table 3), indicating that penguin-type diagrams contribute only little to the total decay rate of the B mesons.

8.2. The transitions $b \to s\gamma$

The rate for the transition $b \to s\gamma$ (Campbell and O'Donnell 1982) depends strongly on QCD corrections (Deshpande *et al* 1987b, Bertolini *et al* 1987b). The reason for this unexpected behaviour arises from the fact that the transition amplitude for the process $b \to s\gamma$ is, in zeroth order, proportional to (M_t^2/M_W^2), whereas the first-order QCD corrections are proportional to $\alpha_s \log (M_t^2/M_c^2)$. The correction term can thus be comparable with the zeroth-order term. Figure 43 illustrates the M_t dependence of the branching ratio for the inclusive decay $b \to s\gamma$ and the exclusive channel $B \to K^*(890)\gamma$ with and without QCD corrections. With QCD corrections the inclusive branching ratio can go up to about 10^{-3}, and depends little on the mass of the top quark if $M_t \geqslant 50\ \mathrm{GeV}/c^2$. The predicted rate for the exclusive channel $B \to K^*(890)\gamma$ accounts in this model for about 10% of the inclusive rate. The present limits on exclusive decays are already close to this rate (table 15).

8.3. The transitions $b \to sH$

The Higgs particle H, a necessary ingredient in the standard model, has been searched for without success in radiative decays of the J/ψ and $\Upsilon(1S)$ mesons (Davier 1986).

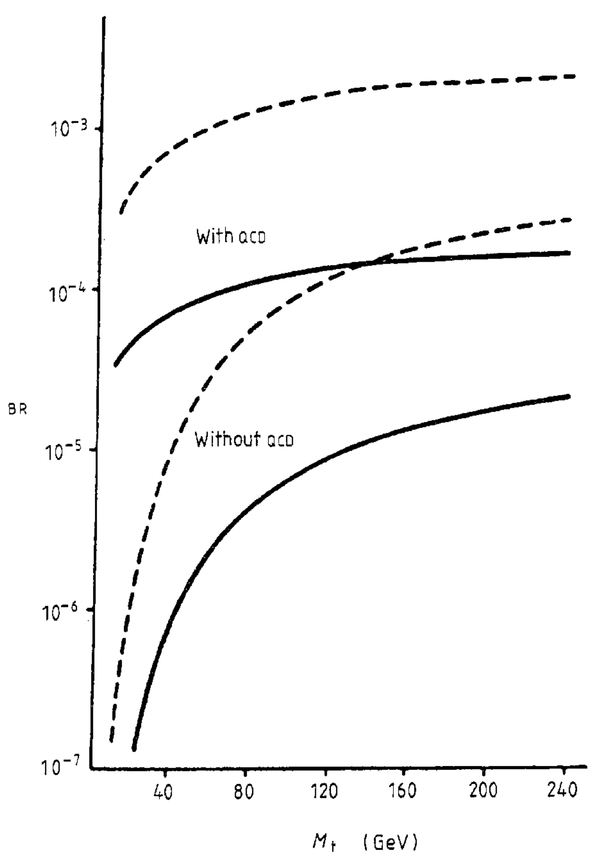

Figure 43. Decays $b \to s\gamma$ (- - -) and $B \to K^*\gamma$(——) as function of M_t (Deshpande *et al* 1987b).

Since no solid experimental or theoretical limits on the mass of the Higgs particle exist, a light Higgs is still allowed, and a decay $b \to sH$ with a real Higgs is still possible (figure 40). The decay rate for this inclusive process $b \to sH$ is given by (Willey and Yu 1982)

$$\frac{\Gamma(B \to HX_s)}{\Gamma(B \to l\nu X)} \simeq \frac{|V_{ts}^* V_{tb}|^2}{0.4|V_{cb}|^2} \frac{27\sqrt{2}}{64\pi^2} G_F M_b^2 \left(\frac{M_t}{M_b}\right)^4 \left(1 - \frac{M_H^2}{M_B^2}\right)$$

where M_H is the mass of the Higgs particle. QCD corrections have been estimated and are found to be small (Hall and Wise 1981, Frère *et al* 1983). Using $|V_{ts}| \simeq |V_{cb}|$, $M_b = 4.8\ \text{GeV}/c^2$ and $\text{BR}(B \to l\nu X) = 11.6\%$, one obtains

$$\text{BR}(B \to HX_s) \simeq 0.30 \left(\frac{M_t}{M_W}\right)^4 \left(1 - \frac{M_H^2}{M_B^2}\right).$$

For a heavy top quark ($M_t \geq M_W$) a light minimal Higgs boson is already excluded by the measurement of the inclusive rate of the B→charm X decays (§ 4.5).

8.4. *Flavour-changing neutral currents in B decays*

Flavour-changing neutral currents in B decays can be detected by observing the decays $\bar{B}^0 \to \mu^+\mu^-$ or $\bar{B}^0 \to e^+e^-$. The decay rates can be calculated by evaluating the box diagram (figure 44) and are expected to be very small (see table 16). In fact, they are orders of magnitudes too small to be observable with the present samples of B mesons. However, the discovery of such decays would be of tremendous importance, since rates much larger than expected would be a hint of new physics at higher energies. The experimental limits on these decays are shown in table 16 (Avery *et al* 1987, Ammar *et al* 1987), together with the limit for the decay $B^0 \to \mu^+e^-$, which is not allowed in the standard model. Its existence would be the manifestation of a new interaction.

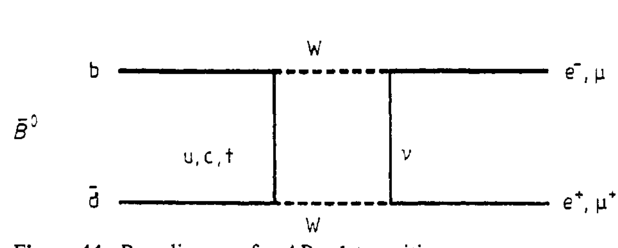

Figure 44. Box diagram for $\Delta B = 1$ transitions.

Table 16. Limits on branching ratios for leptonic B decays (Avery *et al* 1987, Ammar *et al* 1987).

Decay mode	Expected branching ratios	90% CL upper limits: CLEO	ARGUS
$B^0 \to e^+e^-$	10^{-12}	0.8×10^{-4}	0.85×10^{-4}
$B^0 \to \mu^+\mu^-$	10^{-8}	0.9×10^{-4}	0.5×10^{-4}
$B^0 \to \mu^+e^-$	—	0.5×10^{-4}	0.5×10^{-4}

In conclusion, the searches for any rare decay of B mesons induced by loop diagrams have so far proved fruitless. Data samples containing at least one order of magnitude more B mesons are probably needed in order to observe penguin-type decays at the expected rate. The search for flavour-changing neutral currents, in the context of the standard model, would require 10^5 times more data.

9. Conclusions

9.1. *Summary*

The large number of new experimental results on the properties of B mesons obtained in the last few years has given further insight into the weak decays of heavy quarks and the underlying standard model. All data so far can be accommodated by the standard model with three families and can be used to determine its parameters. The most importance result in 1987 was the observation of $B^0\bar{B}^0$ oscillations by the ARGUS group which has significant implications for the parameters of the standard model. Specifically, the large measured rate of $r = 0.21 \pm 0.08$ implies that the t quark, which has yet to be observed, must have a mass greater than $50\,\text{GeV}/c^2$ and that the KM matrix element $|V_{td}|$ has a value between 0.006 and 0.018. Furthermore, mixing in the $B_s\bar{B}_s$ system has to be maximal: $r_s \geq 0.7$. Important experimental checks of the standard model with three families will come from precision measurements of M_t and r_s, which might be possible in the near future.

As expected, the third family is more decoupled from the first than from the second, as demonstrated by the dominance of $(b \to c)$ transitions over $(b \to u)$ transitions. This is observed in B decays into charmed particles as well as in the leptonic spectra in B decays which yield $|V_{ub}/V_{cb}| \leq 0.21$. Measurements of semileptonic branching ratios and the decay $\bar{B}^0 \to D^{*+} l^- \bar{\nu}$, together with the B lifetime, can be used to determine the KM matrix element $|V_{cb}| \simeq 0.049 \pm 0.007$. The evidence for the charmless decays $B^- \to p\bar{p}\pi^-$ and $B^0 \to p\bar{p}\pi^+\pi^-$ indicates a non-zero value for V_{ub}.

The three KM matrix elements V_{td}, V_{ub} and V_{cb} are related by (see § 2.4):

$$V_{td} + c_\theta c_\gamma V_{ub}^* = \frac{s_\theta}{c_\beta} V_{cb}$$

which represents a triangle in the complex plane (see figure 45). Using the experimentally determined constraints on these values one finds that the phase δ is still undetermined.

For the absolute values of the KM matrix elements one finds:

$$|V| = \begin{pmatrix} 0.9751 \pm 0.0007 & 0.221 \pm 0.003 & V_{ub} \leq 0.012 \\ 0.221 \pm 0.002 & 0.9741 \pm 0.0008 & 0.049 \pm 0.007 \\ 0.006 \leq V_{td} \leq 0.018 & 0.048 \pm 0.007 & 0.9988 \pm 0.0004 \end{pmatrix}.$$

9.2. *Outlook*

Although progress in B physics has been substantial in the last few years, many measurements remain to be performed in order to complete our picture of B decays in the standard model. Specifically, the relevant KM matrix elements have to be determined more precisely. Then it becomes possible not only to obtain more precise values for the quark mixing angles β and γ and the phase δ, but also to study possible

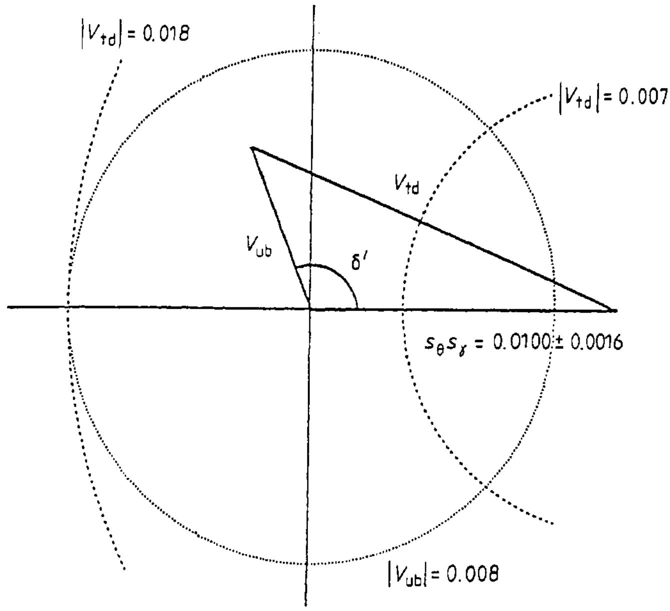

Figure 45. Correlation between the KM matrix elements V_{td}, V_{ub} and V_{cb} in the complex plane.

relations between the KM matrix elements and the fermion masses, which might provide further insight into the standard model. Such relations are expected between the phenomena of weak quark mixing and the breaking of the flavour symmetry. For example, for equal masses of the down-type quarks, no weak transitions would occur between the three families, as is the case in the lepton sector. The obvious measurements yet to be performed are as follows.

(i) Precise measurements of $B^0\bar{B}^0$ mixing and of $B_s\bar{B}_s$ mixing yielding the KM matrix elements V_{td} and V_{ts} if M_t and $B_B f_B^2$ are known.

(ii) Measurement of $(b \to u)$ transitions, which are expected to be calculable in a reliable way, such as $B^+ \to \rho^0 l^+ \nu$ or $B^+ \to \tau^+ \nu_\tau$, where the branching ratio for the latter is given by:

$$\text{BR}(B^+ \to \tau^+ \nu_\tau) \simeq 0.007 (V_{ub}/V_{cb})^2 (f_B/0.15)^2.$$

These measurements will yield V_{ub} and f_B.

(iii) Observation of rare penguin-type decays which are sensitive to V_{ts} and M_t.

(iv) Semileptonic branching ratios or lifetimes for all species of b hadrons allowing a check of quark decay models.

(v) Search for CP violation.

Some of these questions will be attacked as early as 1990, at which time the experiments ARGUS and CLEO will have each collected about five times as many $B\bar{B}$ pairs with improved detectors. A micro-vertex driftchamber, which will give vertex resolutions of 30 μm, will be added in 1989 to the present ARGUS detector (Albrecht *et al* 1986). This will allow the reconstruction of roughly a factor of five more B mesons, and will suppress the combinatorial background. The CLEO detector was being completely rebuilt in 1988 as CLEO II (CLEO 1985) in which much emphasis is put on an excellent calorimeter of CsI crystals in order to obtain an efficient reconstruction of π^0 mesons with less combinatorial background, and thus also to increase substantially the number of reconstructed B mesons.

The observation of CP violation in B decays requires, as a realistic lower limit, of the order of 10^8 B mesons. This will not be reached with the present machines. Moreover, there will be no CP violating effects for B^0 mesons from $\Upsilon(4S)$ decays, if one measures only time-integrated rates (Bigi and Sanda 1987b).

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References

Adeva B *et al* (MARKJ) 1983 *Phys. Rev. Lett.* **51** 443
Adler J *et al* (MARK III) 1988 *Phys. Rev. Lett.* **60** 89
Aguilar-Benitez M *et al* (Particle Data Group) 1986 *Phys. Lett.* **170B** 1
Aihara H *et al* (TPC) 1985a *Phys. Rev.* D **31** 2719
—— 1985b *Z. Phys.* C **27** 39
Alam M S *et al* (CLEO) 1986 *Phys. Rev.* D **34** 3279
—— 1987 *Phys. Rev. Lett* **59** 22
Albajar C *et al* (UA1) 1987 *Phys. Lett.* **186B** 247
Albrecht H *et al* (ARGUS) 1985 *Phys. Lett.* **162B** 395
—— 1986 *DESY internal report DESY F15-86-01*
—— 1987a *Phys. Lett.* **185B** 218
—— 1987b *Phys. Lett.* **199B** 451
—— 1987c *Phys. Lett.* **197B** 452
—— 1987d *Phys. Lett.* **192B** 245
—— 1987e *Phys. Lett.* **187B** 425
—— 1988a *DESY preprint DESY 88-080*
—— 1988b *Phys. Lett.* **215B** 424
—— 1988c *Phys. Lett.* **210B** 263
—— 1988d *DESY preprint DESY 88-145*
—— 1988*e Phys. Lett.* **209B** 119
—— 1988f *Phys. Lett.* **210B** 258
Ali A 1987 *DESY preprint DESY 87-083*
Ali A and Aydin Z Z 1978 *Nucl. Phys.* B **148** 165
Ali A and Pietarinnen E 1979 *Nucl. Phys.* B **154** 519
Ali A and Yang T C 1976 *Phys. Lett.* **65B** 275
Altarelli G 1987 *Proc. Int. Europhys. Conf. on High Energy Physics (Uppsala)* (Geneva: EPS) p 1002
Altarelli G and Franzini P 1988 *Z. Phys.* C **37** 271
Altarelli G *et al* 1981 *Nucl. Phys.* B **187** 461
—— 1982 *Nucl. Phys.* B **208** 365
Althoff M *et al* (TASSO) 1984a *Z. Phys.* C **22** 219
—— 1984b *Phys. Lett.* **146B** 443
Altomari T and Wolfenstein L 1987 *Phys. Rev. Lett.* **58** 1583, *Phys. Rev.* D **37** 681
Ammar R (ARGUS) 1987 *Proc. Int. Europhys. Conf. on High Energy Physics (Uppsala)* (Geneva: EPS) p 360
Andrews D *et al* (CLEO) 1983 *Nucl. Instrum. Methods* **211** 47
Angelini L *et al* 1986 *Phys. Lett.* **172B** 447
Anjos J C (E691) 1988 *Fermilab preprint FERMILAB-PUB-88-141*
Anselm A A *et al* 1985 *Phys. Lett.* **156B** 102
Appelquist T and Politzer H D 1975 *Phys. Rev. Lett.* **34** 34

Arturo M *et al* (CLEO) 1988 *Cornell preprint CLNS-89-889*
Ash W W *et al* (MAC) 1987 *Phys. Rev. Lett.* **58** 640
Avery P *et al* (CLEO) 1987 *Cornell preprint CLNS 86/737*
Bacino W *et al* (DELCO) 1979 *Phys. Rev. Lett.* **43** 1073
Baltrusaitis R M *et al* (MARK III) 1985 *Phys. Rev. Lett.* **54** 1976
Band H R *et al* (MAC) 1988 *Phys. Lett.* **200B** 221
Bander M *et al* 1979 *Phys. Rev. Lett.* **43** 242
Barbieri R *et al* 1975 *Phys. Lett.* **57B** 455
Barger V *et al* 1987 *Phys. Lett.* **194B** 312
Barshay S *et al* 1988 *Phys. Lett.* **202B** 402
Bartel W *et al* (JADE) 1983 *Z. Phys.* C **20** 187
—— 1986 *Z. Phys.* C **31** 347
—— 1987a *Z. Phys.* C **33** 339
—— 1987b *Int. Symp. on Lepton and Photon Interactions at High Energies (Hamburg)* contributed paper
Bauer M *et al* 1987 *Z. Phys.* C **34** 103
Bean A *et al* (CLEO) 1987a *Int. Symp. on Lepton and Photon Interactions at High Energies (Hamburg)* contributed paper
—— 1987b *Phys. Rev. Lett.* **58** 183
Bebek C *et al* (CLEO) 1987 *Phys. Rev.* D **36** 1289
—— 1988 *Cornell preprint CLNS-88-862*
Behrends H J *et al* (CELLO) 1983 *Z. Phys.* C **19** 291
Behrends S *et al* (CLEO) 1987a *Phys. Rev.* D **36** 1289
—— 1987b *Cornell preprint CLNS 87/78*
Berger C *et al* 1978 *Phys. Lett.* **76B** 243
Berkelmann K 1983 *Phys. Rep.* **98** 145
Bertolini S *et al* 1987a *Phys. Lett.* **194B** 54
—— 1987b *Phys. Rev. Lett.* **59** 180
Besson D *et al* (CLEO) 1985 *Phys. Rev. Lett.* **54** 381
Bienlein J K *et al* 1979 *Phys. Lett.* **78B** 361
Bigi I 1981 *Phys. Lett.* **106B** 510
Bigi I and Ewertz H 1982 *Nucl. Phys.* B **208** 359
Bigi I and Sanda A 1984 *Phys. Rev.* D **29** 1393
—— 1987a *Phys. Lett.* **194B** 307
—— 1987b *Nucl. Phys.* B **281** 41
Blockus D *et al* (HRS) 1987 *Indiana preprint IUHEE-87-01*
Bortoletto D *et al* (CLEO) 1987 *Phys. Rev.* D **35** 19
—— 1988 *Phys. Rev.* D **37** 1988
Bose S K and Paschos E A 1980 *Nucl. Phys.* B **169** 384
Braunschweig W *et al* (TASSO) 1987 *Int. Symp. on Lepton and Photon Interactions at High Energies (Hamburg)* contributed paper
Buchmüller W and Cooper S 1987 *MIT report MIT-LNS-159*
Cabibbo N and Maiani L 1978 *Phys. Lett.* **79B** 109
Cabibbo N *et al* 1979 *Nucl. Phys.* B **155** 93
Campbell B A and O'Donnell P J 1982 *Phys. Rev.* D **25** 1989
Chau L L and Cheng H Y 1986 *Phys. Lett.* **165B** 429
Chau L L and Keung W Y 1984 *Phys. Rev. Lett.* **53** 1802
—— 1987 *Davis preprint UCD-87-02*
CLEO 1985 preprint CLNS 85/634
Close F E *et al* 1984 *Phys. Lett.* **149B** 209
Costa G *et al* 1988 *Nucl. Phys.* B **297** 244
Cox P H *et al* 1985 *Phys. Rev.* D **32** 1157
Darden C W *et al* 1978 *Phys. Lett.* **76B** 246
—— 1979 *Phys. Lett.* **78B** 364
Datta A *et al* 1987 *Phys. Lett.* **196B** 376
Davier M 1986 *Proc. XXIII Int. Conf. on High Energy Physics (Berkeley)* (Singapore: World Scientific) p 25
DeGrand T A and Toussaint D 1980 *Phys. Lett.* **89B** 256
Deshpande N G *et al* 1987a *University of Oregon preprint OITS 370*
—— 1987b *Phys. Rev. Lett.* **59** 183
Donoghue J F *et al Phys. Lett.* **195B** 285
Du D and Zhao Z 1987 *Phys. Rev. Lett.* **59** 1072

Ecker G and Grimus W 1986 *Z. Phys.* C **30** 293
Eilam G 1982 *Phys. Rev. Lett.* **49** 1478
Ellis J *et al* 1977 *Nucl. Phys.* B **131** 285
—— 1987 *Phys. Lett.* **192B** 245
Fakirov D and Stech B 1978 *Nucl. Phys.* B **133** 315
Fernandez B *et al* (MAC) 1983 *Phys. Rev. Lett.* **50** 2054
Franzini P and Lee-Franzini J 1983 *J. Ann. Rev. Nucl. Part. Sci.* **33** 1
Frère J M *et al* 1983 *Phys. Lett.* **125B** 275
Fritzsch H 1979 *Phys. Lett.* **86B** 343
Gaillard M K and Lee B W 1974 *Phys. Rev.* D **10** 897
Gavela M B *et al* 1985a *Phys. Lett.* **154B** 147
—— 1985b *Phys. Lett.* **154B** 425
Gell-Mann M and Pais A 1955 *Phys. Rev.* **97** 1387
Giles R D *et al* (CLEO) 1984 *Phys. Rev.* D **29** 1285
Gingrich D (ARGUS) 1988 *PhD Thesis* University of Toronto
Gläser R (ARGUS) 1988 *PhD Thesis* Universität Hamburg *(DESY preprint DESY 88-178)*
Glashow S L *et al* 1970 *Phys. Rev.* D **2** 1285
Grinstein B *et al* 1986 *Phys. Rev. Lett.* **56** 298
Gronau M and Rosner J L 1987 *University of Chicago preprint EFI 87-35*
Gronau M and Schechter J 1985 *Phys. Rev.* D **31** 1668
Guberina B 1984 *Fizika (Yugoslavia)* **16** 49
Guberina B *et al* 1980 *Phys. Lett.* **90B** 169
Haas P *et al* (CLEO) 1985 *Phys. Rev. Lett.* **55** 1248
—— 1986 *Phys. Rev. Lett.* **56** 2781
Hall L J and Wise M B 1981 *Nucl. Phys.* B **187** 397
Han K *et al* (CUSB) 1985 *Phys. Rev. Lett.* **55** 36
Harari H and Nir Y 1987 *Phys. Lett.* **195B** 586
Harder G (ARGUS) 1988 *PhD Thesis* Universität Hamburg
Herb S W *et al* 1977 *Phys. Rev. Lett.* **39** 252
Hoogeveen F and Leung C N 1987 *MPI München preprint MPI-PAE/Pth 50/87*
Hou W S *et al* 1987 *Phys. Rev. Lett.* **59** 1521
Ito M (CLEO) 1986 *PhD Thesis* Cornell University
Jarlskog C 1986 *Z. Phys.* C **29** 491
Khoze V and Uraltsev N 1987 *Leningrad Nucl. Phys. Inst. preprint LINP-1290*
Kleinknecht K and Renk B 1987 *Z. Phys.* C **34** 209
Klem D E *et al* (DELCO) 1986 *SLAC preprint SLAC-PUB-4025*
Klopfenstein C *et al* (CUSB) 1983 *Phys. Lett.* **130B** 444
Kobayashi M and Maskawa T 1973 *Prog. Theor. Phys.* **49** 652
Körner J G and Schuler G A 1988 *Z. Phys.* C **38** 511
Kühn J *et al* 1980 *Z. Phys.* C **5** 117
Kühn J and Rückl R 1984 *Phys. Lett.* **135B** 477
Landé E E *et al* 1956 *Phys. Rev.* **103** 1901
Levman G *et al* (CUSB) 1984 *Phys. Lett.* **141B** 271
Lockyer N *et al* (MARK II) 1983 *Proc. 11th SLAC Summer Institute on Particle Physics (Stanford)* SLAC Report 267 p 689, SLAC 3245
Maalampi J and Roos M 1987 *Phys. Lett.* **195B** 489
Nelson M E *et al* (MARK II) 1983 *Phys. Rev. Lett.* **50** 1542
Novikov V A *et al* 1978 *Phys. Rep.* **41** 1
Okun L B *et al* 1975 *Lett. Nuovo Cim.* **13** 218
Ong R A *et al* (MARK II) 1987 contributed paper *Int. Symp. on Lepton and Photon Interactions at High Energies (Hamburg) 1987*, SLAC 320
Pal T *et al* (DELCO) 1986 *Phys. Rev.* D **33** 2708
Paschos E A 1986 *Proc. Int. Symp. on Production and Decay of Heavy Hadrons (Universität Heidelberg, DESY)* (Hamburg: DESY) pp 391-394 and references therein
Paschos E A *et al* 1987 *Universität Dortmund preprint DO-TH 87/8*
Paschos E A and Tuerke U 1984 *Nucl. Phys.* **B243** 29
Perl M L *et al* 1975 *Phys. Rev. Lett.* **35** 489
Piccolo M *et al* (MAC) 1983 *Proc. 11th SLAC Summer Institute on Particle Physics (Stanford)* SLAC Report 267 p 673
Rückl R 1984 *Habilitationsschrift* Universität München

Schaad T *et al* (MARK II) 1985 *Phys. Lett.* **160B** 188
Schamberger R D *et al* (CUSB) 1982 *Phys. Rev.* D **26** 720
Schröder H (ARGUS) 1988 *Proc. 23rd Rencontre de Moriond (Les Arcs)* (Paris: Editions Frontière) p 311
Schubert K R *et al* (ARGUS) 1986 *Proc. XXIII Int. Conf. on High Energy Physics (Berkeley)* (Singapore: World Scientific) p 781
Shifman M 1986 *Proc. Int. Symp. on Production and Decay of Heavy Hadrons (Universität Heidelberg, DESY)* (Hamburg: DESY) pp 199–278
Shifman M and Volshin M 1987 *ITEP Moscow preprint LTEP 87-64*
Suzuki M 1978 *Nucl. Phys.* B **145** 420
—— 1985 *Nucl. Phys.* B **155** 112
Swain J D (ARGUS) 1988 *PhD Thesis* University of Toronto
Takasaki F 1987 *Proc. Int. Symp. on Lepton and Photon Interactions at High Energies (Hamburg)* p 17
Tanimoto M 1987 *Z. Phys.* C **36** 193
Thorndike E H and Poling R A 1988 *Phys. Rep.* **157** 183
VanRoyen R and Weisskopf V F 1967 *Nuovo Cimento* **50** 617; **51** 583
Wachs K *et al* (Crystal Ball) 1987 *DESY preprint DESY 87-084*
Weseler S (ARGUS) 1986 *Proc. Int. Symp. on Production and Decay of Heavy Hadrons (Universität Heidelberg, DESY)* (Hamburg: DESY) pp 119–24
Willey R S and Yu H L 1982 *Phys. Rev.* D **26** 3086
Wirbel M *et al* 1986 *Z. Phys.* C **29** 637
Wise M B 1980 *Phys. Lett.* **89B** 229
Wu S L 1987 *DESY preprint DESY 87-164*