

OBSERVATION OF B^0 - \bar{B}^0 MIXING

ARGUS Collaboration

H. ALBRECHT, A.A. ANDAM ¹, U. BINDER, P. BÖCKMANN, R. GLÄSER, G. HARDER,
A. NIPPE, M. SCHÄFER, W. SCHMIDT-PARZEFALL, H. SCHRÖDER, H.D. SCHULZ,
R. WURTH, A. YAGIL ^{2,3}

DESY, D-2000 Hamburg, Fed. Rep. Germany

J.P. DONKER, A. DRESCHER, D. KAMP, H. KOLANOSKI, U. MATTHIESEN, H. SCHECK,
B. SPAAN, J. SPENGLER, D. WEGENER

Institut für Physik ⁴, Universität Dortmund, D-4600 Dortmund, Fed. Rep. Germany

C. EHMANN, J.C. GABRIEL, T. RUF, K.R. SCHUBERT, J. STIEWE, K. STRAHL, R. WALDI,
S. WESELER

Institut für Hochenergiephysik ⁵, Universität Heidelberg, D-6900 Heidelberg, Fed. Rep. Germany

K.W. EDWARDS ⁶, W.R. FRISKEN ⁷, D.J. GILKINSON ⁸, D.M. GINGRICH ⁸, H. KAPITZA ⁶,
P.C.H. KIM ⁸, R. KUTSCHKE ⁸, D.B. MACFARLANE ⁹, J.A. McKENNA ⁸, K.W. McLEAN ⁹,
A.W. NILSSON ⁹, R.S. ORR ⁸, P. PADLEY ⁸, J.A. PARSONS ⁸, P.M. PATEL ⁹, J.D. PRENTICE ⁸,
H.C.J. SEYWERD ⁸, J.D. SWAIN ⁸, G. TSIPOLITIS ⁹, T.-S. YOON ⁸, J.C. YUN ⁶

Institute of Particle Physics ¹⁰, Canada

R. AMMAR, D. COPPAGE, R. DAVIS, S. KANEKAL, N. KWAK

University of Kansas ¹¹, Lawrence, KS 66045, USA

B. BOŠTJANČIČ, G. KERNEL, M. PLEŠKO

Institut J. Stefan and Department of Physics ¹², Univerza v Ljubljani, 61111 Ljubljana, Yugoslavia

L. JÖNSSON

Institute of Physics ¹³, University of Lund, S-223 62 Lund, Sweden

A. BABAEV, M. DANILOV, B. FOMINYKH, A. GOLUTVIN, I. GORELOV, V. LUBIMOV,
V. MATVEEV, V. NAGOVITSIN, V. RYLTSOV, A. SEMENOV, V. SHEVCHENKO,
V. SOLOSHENKO, V. TCHISTILIN, I. TICHOMIROV, Yu. ZAITSEV

Institute of Theoretical and Experimental Physics, 117 259 Moscow, USSR

R. CHILDERS, C.W. DARDEN, Y. OKU

University of South Carolina ¹⁴, Columbia, SC 29208, USA

and

H. GENNOW

University of Stockholm, S-113 46 Stockholm, Sweden

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Using the ARGUS detector at the DORIS II storage ring we have searched in three different ways for $B^0-\bar{B}^0$ mixing in $\Upsilon(4S)$ decays. One explicitly mixed event, a decay $\Upsilon(4S) \rightarrow B^0 B^0$, has been completely reconstructed. Furthermore, we observe a 4.0 standard deviation signal of 24.8 events with like-sign lepton pairs and a 3.0 standard deviation signal of 4.1 events containing one reconstructed $B^0(\bar{B}^0)$ and an additional fast $\ell^+(\ell^-)$. This leads to the conclusion that $B^0-\bar{B}^0$ mixing is substantial. For the mixing parameter we obtain $r=0.21 \pm 0.08$.

We report the observation of $B^0-\bar{B}^0$ mixing. This conclusion is based on the study of B mesons produced in $\Upsilon(4S)$ decays, using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY. $B^0-\bar{B}^0$ mixing provides basic information on the parameters and validity of the standard model [1], and is potentially a sensitive probe for new physics [2]. A B^0 meson can either decay directly or, through mixing, transform into its anti-particle, the \bar{B}^0 , before decaying. The ratio of the decay widths [3,4]

$$r = \frac{\Gamma(B^0 \rightarrow \bar{B}^0 \rightarrow X')}{\Gamma(B^0 \rightarrow X)}$$

of these two competing reactions describes the strength of mixing. In decays of the $\Upsilon(4S)$, pairs of $B^0\bar{B}^0$ mesons are produced in a P-wave, so that r is given in this case [5] by the ratio

$$r = \frac{N(B^0 B^0) + N(\bar{B}^0 \bar{B}^0)}{N(B^0 \bar{B}^0)}.$$

¹ On leave from University of Science and Technology, Kumasi, Ghana.

² Weizmann Institute of Science, 76100 Rehovot, Israel.

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⁵ Supported by the German Bundesministerium für Forschung und Technologie under the contract number 054HD24P.

⁶ Carleton University, Ottawa, Ontario, Canada K1S 5B6.

⁷ York University, Downsview, Ontario, Canada M3J 1P3.

⁸ University of Toronto, Toronto, Ontario, Canada M5S 1A7.

⁹ McGill University, Montreal, Quebec, Canada H3A 2T8.

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Thus, the existence of mixing leads to events consisting of $B^0 B^0$ or $\bar{B}^0 \bar{B}^0$ pairs which can be detected experimentally.

An upper limit for $B^0-\bar{B}^0$ mixing of 24% at 90% CL has been published by the CLEO Collaboration [6]. An investigation by the MARK II Collaboration [7] of dilepton rates in continuum e^+e^- annihilations at 29 GeV, well above the B_s production threshold, resulted in combined upper limits for $B^0-\bar{B}^0$ and $B_s-\bar{B}_s$ mixing. The UA1 Collaboration [8] has reported evidence for an excess of like-sign lepton pairs produced in $p\bar{p}$ collisions, which they interpreted as signature for $B_s-\bar{B}_s$ mixing.

The mixing study reported here is made with B mesons produced in 88000 $\Upsilon(4S)$ decays. The event sample corresponds to an integrated luminosity of 103 pb^{-1} on the $\Upsilon(4S)$ and 42 pb^{-1} in the continuum just below the $\Upsilon(4S)$. A short description of the ARGUS detector and its trigger can be found in ref. [9] and its particle identification capabilities in ref. [10].

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 $B^0 B^0$ or $\bar{B}^0 \bar{B}^0$ pairs. Efficient and clean reconstruction of B mesons is accomplished by using B decays involving D^{*-} mesons ^{#1} which are reconstructed through their decays $D^{*-} \rightarrow \bar{D}^0 \pi^-$, followed by

$$\begin{aligned} \bar{D}^0 &\rightarrow K^+ \pi^- \\ &\rightarrow K^+ \pi^- \pi^0 \\ &\rightarrow K^+ \pi^- \pi^+ \pi^- \\ &\rightarrow K_S^0 \pi^+ \pi^- . \end{aligned}$$

^{#1} References in this paper to a specific charged state are to be interpreted as implying the charge-conjugate state also.

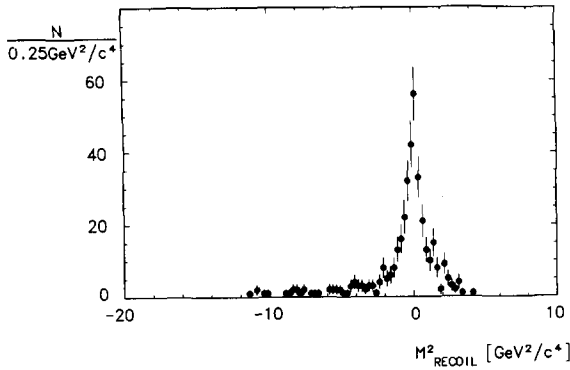
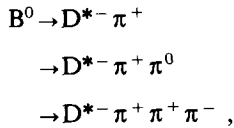
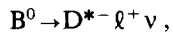


Fig. 1. Recoil mass $M_{\text{Recoil}}^2 = [E_{\text{beam}} - (E_{D^{*-}} + E_{\ell^+})]^2 - (\mathbf{p}_{D^{*-}} + \mathbf{p}_{\ell^+})^2$ with $D^{*-} \rightarrow \bar{D}^0 \pi^-$, $\bar{D}^0 \rightarrow K^+ \pi^-$, $K^0 \pi^+ \pi^-$, $K^+ \pi^- \pi^0$, $K^+ \pi^- \pi^+ \pi^-$ and one lepton (π^+ , e^+) with momentum $p > 1.0 \text{ GeV}/c$.

B^0 mesons are either reconstructed in the hadronic decay modes [11].



or in the channel



with ℓ^+ being an e^+ or μ^+ . The partial reconstruction of the decay $B^0 \rightarrow D^{*-} \ell^+ \nu$ is possible because B^0 mesons produced in $\Upsilon(4S)$ decays are nearly at rest. The neutrino is unobserved, but can be inferred if the recoil mass against the $D^{*-} \ell^+$ system, M_{Recoil}^2 , is consistent with zero. M_{Recoil}^2 is defined by

$$M_{\text{Recoil}}^2 = [E_{\text{beam}} - (E_{D^{*-}} + E_{\ell^+})]^2 - (\mathbf{p}_{D^{*-}} + \mathbf{p}_{\ell^+})^2.$$

By requiring the D^{*-} to have momentum less than $2.45 \text{ GeV}/c$ and the lepton to have momentum above $1.0 \text{ GeV}/c$, we obtain the recoil mass spectrum shown in fig. 1. The prominent peak at $M_{\text{Recoil}}^2 = 0$ corresponds to a B^0 signal on a low background. The position and shape of the signal is well described by the Monte Carlo prediction for $\Upsilon(4S) \rightarrow B^0 \bar{B}^0$ followed by the semi-leptonic decay $B^0 \rightarrow D^{*-} \ell^+ \nu$.

In the sample of events with a single reconstructed B^0 , we can attempt to reconstruct the second B^0 , now with a less restrictive choice of possible decay channels. By this means, we have succeeded in completely reconstructing a decay $\Upsilon(4S) \rightarrow B^0 \bar{B}^0$, the first

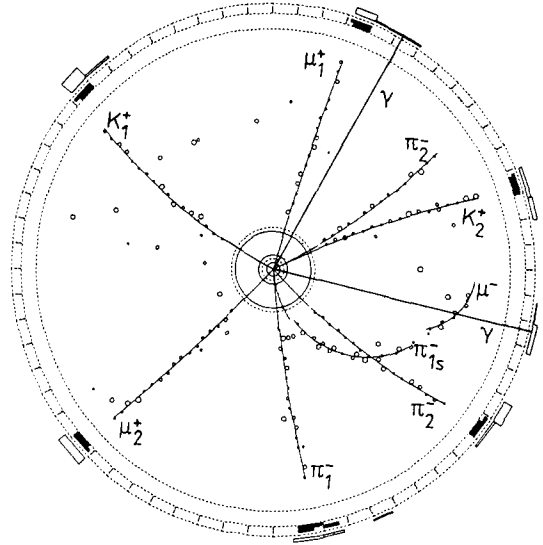
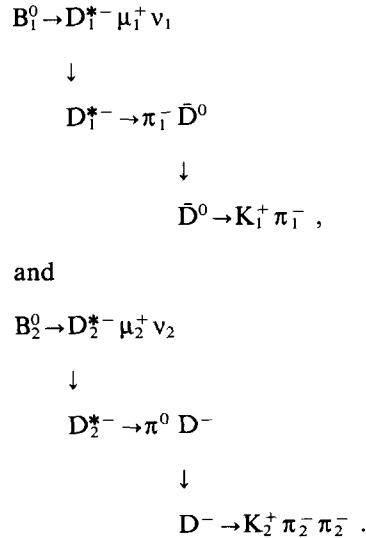


Fig. 2. Completely reconstructed event consisting of the decay $\Upsilon(4S) \rightarrow B^0 \bar{B}^0$.

observation of $B^0 - \bar{B}^0$ mixing. The two B^0 mesons (B_1^0 and B_2^0) decay in the following way:



The event is shown in fig. 2 and its kinematical quantities are listed in table 1. The masses of the intermediate states agree well with the table values [12]. Both D^{*-} mesons contain positive kaons of momenta $p(K_1) = 0.548 \text{ GeV}/c$ and $p(K_2) = 0.807 \text{ GeV}/c$ which are uniquely identified by the measurements of specific ionisation loss (dE/dx) and of time-of-flight. The two positive muons are the fastest

Table 1
Kinematical quantities of the observed $\Upsilon(4S) \rightarrow B_1^0 B_2^0$ event.

Decay	Mass (GeV/c ²)	P (GeV/c)	M_{Recoil}^2 (GeV ² /c ⁴)
$B_1^0 \rightarrow D_1^{*-} \mu_1^+ (\nu_1)$	4.393 ± 0.088 ^{a)}	1.090 ± 0.108 ^{a)}	-0.609
$D_1^{*-} \rightarrow \pi_1^- \bar{D}^0$	2.008 ± 0.001	1.196 ± 0.013	
$\bar{D}^0 \rightarrow K_1^+ \pi_1^-$	1.873 ± 0.021	1.091 ± 0.012	
$B_2^0 \rightarrow D_2^{*-} \mu_2^+ (\nu_2)$	3.969 ± 0.032 ^{a)}	1.244 ± 0.015 ^{a)}	-0.275
$D_2^{*-} \rightarrow \pi^0 D^-$	2.008 ± 0.005	1.611 ± 0.017	
$\pi^0 \rightarrow 2\gamma$	0.180 ± 0.028	0.136 ± 0.019	
$D^- \rightarrow K_2^+ \pi_2^- \pi_2^-$	1.886 ± 0.015	1.478 ± 0.007	

^{a)} Mass and momentum without neutrino.

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 semi-leptonically, 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^+ 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 is fully reconstructed in spite of the fact that two neutrinos are present. Specifically, the missing mass in the decay of B_2^0 is only compatible 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 $r=0.2$, we expect to reconstruct 0.3 events of this type where both B mesons decay as $B^0 \rightarrow D^{*-} \ell^+ \nu$. 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 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, we find no fake candidate for mixing.

In the second analysis method we investigate events containing lepton pairs originating from $\Upsilon(4S)$ decays. The charge of the primary lepton from the decay of the b quark identifies whether the decaying

meson is a B or a \bar{B} . Thus, $B^0 - \bar{B}^0$ mixing manifests itself in the production of like-sign lepton pairs.

An event selection is made by applying cuts to suppress continuum dilepton sources: (1) the second Fox-Wolfram moment [13] less than 0.6, (2) charged multiplicity $n_{\text{ch}} \geq 5$ and (3) total multiplicity $n_{\text{ch}} + \frac{1}{2} n_{\gamma} \geq 7$. The angle between all particles and the beam axis is required to satisfy $\cos \theta_{\text{lab}} < 0.9$. 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 originating from charmed mesons in B decays. For lepton identification, information from all detector components is used coherently by combining the measurements into an overall likelihood [14]. The available information consists of dE/dx and time-of-flight measurements, and the magnitude and topology of energy depositions in the shower counters. In addition, for muons, a hit in an outer muon chamber is required and information on the hit-impact point distance is included in the likelihood.

Further requirements are made in order to reduce background sources of lepton pairs. B decays to $J/\psi(\psi')$ produce e^+e^- or $\mu^+\mu^-$ pairs. To suppress this background, events containing those pairs are rejected if the mass of the pair coincides with the mass of the J/ψ or ψ' within ± 150 MeV/c². Electrons originating from photon conversion are suppressed by requiring that no other positron candidate of any momentum lie within a cone of 32° around the high momentum electron track.

The distribution of the opening angle $\theta_{\ell\ell}$ between the leptons is shown in fig. 3 for events passing these cuts. For leptons originating from two different B

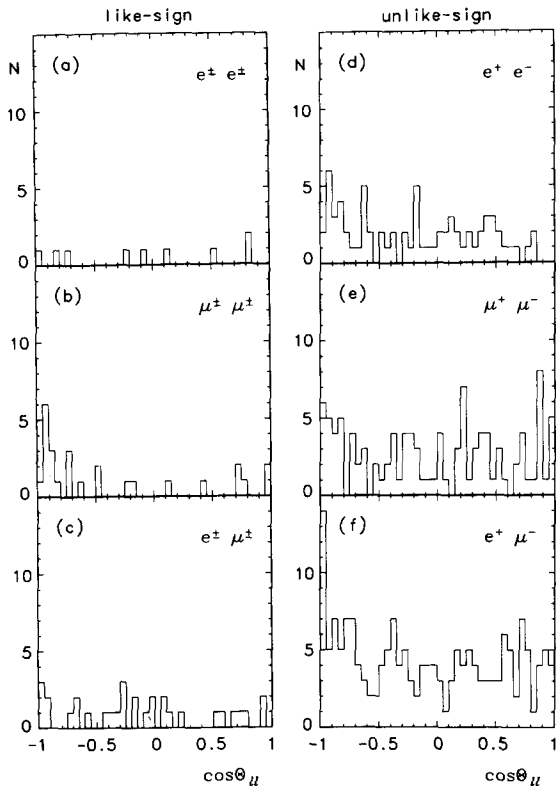


Fig. 3. Distribution of the opening angle between the leptons for like-sign (a)–(c) and unlike-sign (d)–(f) pairs.

mesons, this distribution should be isotropic. Lepton pairs from continuum or originating from the same B meson tend to be back-to-back. These contributions are reduced by requiring $\cos\theta_{ll} > -0.85$. Table 2 gives the number of dilepton events surviving these cuts both on the $\Upsilon(4S)$ resonance and in the continuum below. The number of dilepton events from $\Upsilon(4S)$ decays is determined by subtracting the continuum contribution scaled by a factor 2.5 according to the ratio of luminosities. Further, the e^+e^- and $\mu^+\mu^-$ pair events are corrected for losses due to the invariant mass cut to remove recognized J/ψ (ψ') decays.

The remaining dilepton events still include contributions from background 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. To determine the fake rate per track we use our data samples of

$\tau^- \rightarrow \nu\pi^-\pi^-\pi^+ + n\pi^0$ ($n=0, 1$) and $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$ decays which provide clean sources of high energy pions and kaons, respectively. Decay-in-flight and punch-through result in a π/μ misidentification probability of $(2.2 \pm 0.2)\%$ per pion. For K/μ misidentification the fake rate is $(1.9 \pm 0.5)\%$ per kaon, including a correction for kaon decays between the interaction point and the drift chamber. The fake rates due to π/e and K/e misidentification are both $(0.5 \pm 0.1)\%$. The lepton–hadron misidentification rates have also been determined using hadronic decays of the $\Upsilon(1S)$ where the fraction of leptons is negligible. The results obtained agree with the quoted values.

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. These momentum spectra, folded with lepton–hadron misidentification probabilities, are shown in fig. 4 for both like-sign and unlike-sign lepton–hadron samples. Since the fake rate per track is within errors the same for pions and kaons, it is not necessary to account for their relative fractions. One unlike-sign dimuon event is expected to occur where both muons are misidentified hadrons.

The background due to secondary leptons is determined by a Monte Carlo simulation of B decays. A spectator model [15] is used to describe the decay of the b quark, with the final state hadrons produced using the Lund string fragmentation model [16]. The simulation is 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 [17]. All these data are well reproduced. The uncertainty in the calculation is expected to be $\pm 25\%$. 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 are given in table 2. Out of the 50 like-sign dilepton events, $25.2 \pm 5.0 \pm 3.8$ events are attributed to the background sources as described above. The first error is the statistical and the second one the systematical uncertainty in the background determination. The probability for the measured 50 events to be a fluctuation of the background corresponds to 4.0 standard deviations. Thus,

Table 2
Dilepton rates.

		e^+e^+	$\mu^+\mu^+$	$e^+\mu^+$
dilepton candidates	$\Upsilon(4S)$ + continuum	8	16	26
	continuum	0	0	0
	$\Upsilon(4S)$ direct	8.0 ± 3.9	16.0 ± 4.8	26.0 ± 5.8
background	fakes	0.7	5.7	4.9
	conversion	0.5	–	0.5
	secondary decays	2.3	2.9	4.6
	J/ψ decays	0.7	0.9	1.5
signal		$3.8 \pm 3.9 \pm 0.9$	$6.5 \pm 4.8 \pm 1.3$	$14.5 \pm 5.8 \pm 1.8$
sum: 50 dilepton candidates				
background: $25.2 \pm 5.0 \pm 3.8$ events				
signal: $24.8 \pm 7.6 \pm 3.8$ like-sign lepton pairs				
		e^+e^-	$\mu^+\mu^-$	$e^+\mu^-$
dilepton candidates	$\Upsilon(4S)$ + continuum	60	92	149
	continuum	3	1	2
	$\Upsilon(4S)$ direct	52.6	89.5	144.1
	corrected for J/ψ cut	$58.5 \pm 9.8 \pm 1.6$	$99.6 \pm 11.3 \pm 2.5$	144.1 ± 12.4
background	fakes	1.4	12.1	10.2
	conversion	0.5	–	0.5
	secondary decays	0.7	1.5	1.6
	J/ψ decays	1.0	0.9	1.5
signal		$54.9 \pm 9.8 \pm 1.6$	$85.1 \pm 11.3 \pm 3.1$	$130.3 \pm 12.4 \pm 1.8$
signal: $270 \pm 19.4 \pm 5.0$ unlike-sign lepton pairs				
mixing parameter r		$0.17 \pm 0.19 \pm 0.04$	$0.19 \pm 0.16 \pm 0.04$	$0.28 \pm 0.14 \pm 0.04$
combined mixing parameter $r = 0.22 \pm 0.09 \pm 0.04$				

we attribute the signal of $24.8 \pm 7.6 \pm 3.8$ events to $B^0-\bar{B}^0$ mixing. The signal for unlike-sign pairs is $270.3 \pm 19.4 \pm 5.0$ events.

The mixing parameter r for dilepton events has the form

$$r = \frac{[N(\ell^+\ell^+) + N(\ell^-\ell^-)](1+\lambda)}{N(\ell^+\ell^-) - [N(\ell^+\ell^+) + N(\ell^-\ell^-)]\lambda}$$

In order to account for $\Upsilon(4S)$ decays into B^+B^- pairs, a factor

$$\lambda = \frac{f^+}{f^0} \left(\frac{Br_{sl}^+}{Br_{sl}^0} \right)^2$$

has to be introduced where f^+ (f^0) is the branching

ratio of the decay $\Upsilon(4S)$ into charged (neutral) B mesons and Br_{sl}^+ (Br_{sl}^0) the semi-leptonic branching ratio of charged (neutral) B mesons. All these numbers are unknown, and we assume λ to be equal to 1.2. The acceptance for ee , $\mu\mu$ and $e\mu$ events is different, thus the mixing parameter r is calculated for each sample separately. Combining these results, we obtain

$$r = 0.22 \pm 0.09 \pm 0.04$$

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.

The third analysis method involves the reconstruction of one of the B^0 mesons originating from the $\Upsilon(4S)$ decay, using the same channels as for the

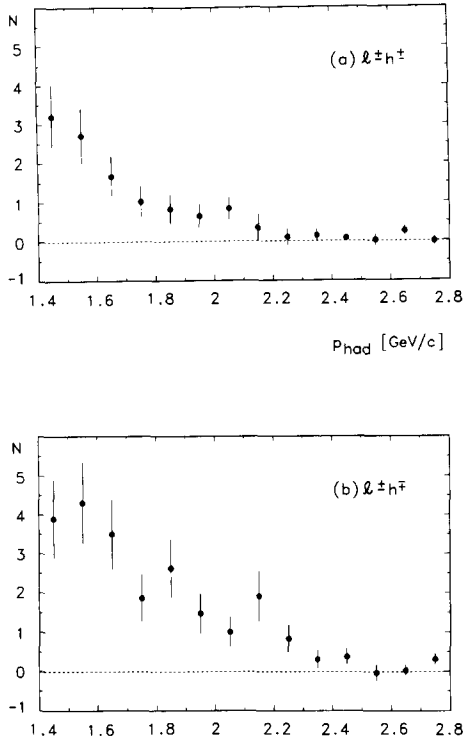


Fig. 4. Momentum spectrum of misidentified hadrons for faked dilepton events: (a) like-sign, (b) unlike-sign.

first method described above, and tagging the second B^0 with a fast lepton. This method is considerably less sensitive to background from lepton misidentification.

Fig. 5 shows the spectrum for the recoil mass against a $D^{*-} \ell^+$ system if the event contains one additional lepton with momentum larger than 1.4

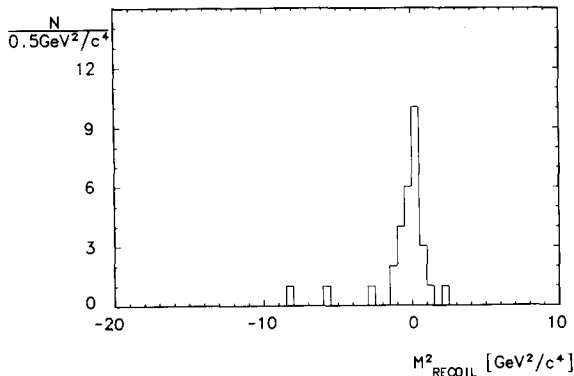


Fig. 5. Same as fig. 1 with requiring an additional lepton (μ, e) with momentum $p > 1.4$ GeV/c in the event.

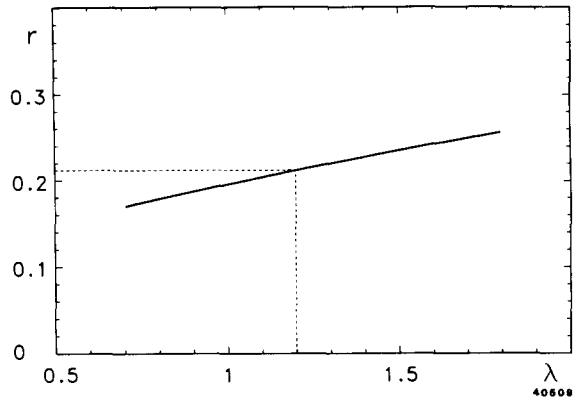


Fig. 6. The mixing parameter r as a function of the factor λ . The dotted line indicates our chosen value $\lambda = 1.2$.

GeV/c. Adding two events where the B^0 mesons are reconstructed in the hadronic channels, we obtain a total of 23 candidates for unmixed events and five candidates for mixed events. These five events are composed of two $B^0 e^+$, two $\bar{B}^0 e^-$ and one $\bar{B}^0 \mu^-$ events. The background for the mixed sample, determined in the same way as for the second method, is expected to be 0.4 events due to misidentification and 0.5 events due to secondary leptons. After subtracting 0.9 ± 0.3 events we are left with 4.1 events from $B^0 - \bar{B}^0$ mixing. The probability for the observed events to be a fluctuation of the background corresponds to 3.0 standard deviations. The background to the unmixed events is 2.2 ± 1.1 events. Thus, we find a value for the mixing parameter r of

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

Two like-sign and eleven unlike-sign events from this sample are also present in the dilepton sample. Taking this correlation into account, we get a combined result of

$$r = 0.21 \pm 0.08$$

for $\lambda = 1.2$. The λ dependence of this result is shown in fig. 6. The parameter $\chi = r/(1+r)$ turns out to be $\chi = 0.17 \pm 0.05$ for $r = 0.21 \pm 0.08$.

We discuss our result in the framework of the standard model with three generations. Assuming dominance of the box diagram, mixing is described by the parameter x [1]:

Table 3

Limits on parameters consistent with the observed mixing rate.

Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson (\approx pion) decay constant
$m_b < 5$ GeV/c ²	b-quark mass
$\tau < 1.4 \times 10^{-12}$ s	B meson lifetime
$ V_{id} < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{\text{QCD}} < 0.86$	QCD correction factor ^{a)}
$m_t > 50$ GeV/c ²	t quark mass

^{a)} Ref. [18].

$$x = \frac{\Delta M}{\Gamma} = 32\pi \frac{B f_B^2 m_t^2 m_b}{m_\mu^5} \frac{\tau_b}{\tau_\mu} |V_{id}|^2 \eta_{\text{QCD}},$$

and related to experiment by

$$r = \frac{x^2}{x^2 + 2}.$$

The rate of $B^0-\bar{B}^0$ mixing provides a strong constraint on parameters of the standard model. Specifically, our result shows that the Kobayashi–Maskawa element V_{id} is non-zero. The observed value of r can still be accommodated by the standard model within the present knowledge of its parameters. As an illustration, one example of a set of limits is given in table 3.

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson–lepton events on the $\Upsilon(4S)$ leads to the conclusion that $B^0-\bar{B}^0$ mixing has been observed and is substantial.

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