B MESON DECAYS INTO CHARMONIUM STATES

ARGUS Collaboration

H. ALBRECHT, A.A. ANDAM [1], U. BINDER, P. BÖCKMANN, R. GLÄSER, G. HARDER, A. KRÜGER, 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, Universität Dortmund [4], Universität Dortmund, D-6400 Dortmund, Fed. Rep. Germany

J.C. GABRIEL, T. RUF, K.R. SCHUBERT, J. STIEWE, K. STRAHL, R. WALDI
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, S. BALL, 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 Oddelek za fiziko [12], Univerza v Ljubljani, 61111 Ljubljana, Yugoslavia

L. JÖNSSON
Institute of Physics [13], University of Lund, S-22362 Lund, Sweden

A. BABAEV, M. DANILOV, B. FOMINYKH, A. GOLUTVIN, I. GORELOV, V. LUBIMOV, V. MATVEEV, V. RYLTSOV, A. SEMENOV, V. SHEVCHENKO, V. SOLOSHENKO, V. TCHISTILIN, I. TICHOMIROV, Yu. ZAITSEV
Institute of Theoretical and Experimental Physics, 117259 Moscow, USSR

R. CHILDERS, C.W. DARDEN, R.C. FERNHOLZ and Y. OKU
University of South Carolina [14], Columbia, SC 29208, USA

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Using the ARGUS detector at the e^+e^- storage ring DORIS II, we have studied the colour-suppressed decays $B \to J/\psi$ X and $B \to \psi'$ X. We find the inclusive branching ratios for these two channels to be $(1.07 \pm 0.16 \pm 0.19)\%$ and $(0.46 \pm 0.17 \pm 0.11)\%$, respectively. From a sample of reconstructed exclusive events the masses of the B^0 and B^+ mesons are determined to be $(5279.5 \pm 1.6 \pm 3.0)$ MeV/c^2 and $(5278.5 \pm 1.8 \pm 3.0)$ MeV/c^2, respectively. Branching ratios are determined from five events of the type $B^0 \to J/\psi\ K^{*0}$ and three of $B^+ \to J/\psi\ K^+$. In the same data sample a search for $B^0 \to e^+e^-$, $\mu^+\mu^-$ and $\mu^\pm e^\mp$ leads to upper limits for such decays.

Decays of B mesons into J/ψ mesons are expected to proceed dominantly through the diagram shown in fig. 1. This process is called *colour-suppressed*, because colour matching between c and $\bar{c}$ is required. How this matching is accomplished by hard and soft gluon echange is a question which has attracted considerable theoretical attention. The predictions [1] of the inclusive branching ratio range from 1.6% to 2.4% neglecting QCD corrections and from 0.3% to 0.7% including short-distance QCD effects. Higher values which are predicted if one disregards colour altogether are excluded by previous measurements [2,3]. The formfactor model of Bauer et al. [4] predicts the exclusive branching ratio for $B^+ \to J/\psi\ K^+$ of about 0.1% and for $B^0 \to J/\psi\ K^{*0}$ of about 0.3%.

The results reported here are an update of earlier ARGUS measurements [3]. The full sample now corresponds to an integrated luminosity of 103/pb on the $\Upsilon(4S)$ resonance and 35/pb in the continuum below the resonance. Thus, the present sample is about eight times larger than used in ref. [3]. The number of B mesons in this sample is estimated to

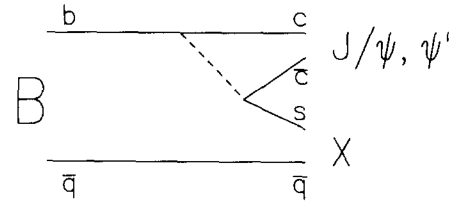

Fig. 1. Quark diagram for the weak decay $B \to J/\psi$ X.

be 176 000, assuming that the $\Upsilon(4S)$ decays predominantly into $B\bar{B}$.

A short description of the ARGUS detector and trigger conditions can be found in ref. [5]. Hadronic events were selected by requiring at least three reconstructed charged particles coming from the interaction region with transverse momentum larger than 80 MeV/c and $|\cos\theta| < 0.9$. In order to suppress the background contribution from continuum, low multiplicity events were rejected by the requirement $n_\gamma/2 + n_{ch} \geq 5$, where n_γ is the number of photons with energy larger 100 MeV detected in the shower counters or reconstructed conversion pairs, and n_{ch} is the number of remaining charged tracks. In addition, if the maximum momentum of any charged track in an event exceeded 3 GeV/c, the event was rejected. This is the kinematic limit for $\Upsilon(4S)$ decays at rest into two B mesons.

All selected events were searched for e^+e^- and $\mu^+\mu^-$ pairs. The lepton identification procedure was the same as in ref. [6] and is described for electrons in detail in ref. [7]. It is based on calculating the likelihood function for the lepton hypothesis using four detector measurements: specific ionization in the drift chamber, time of flight, the energy deposition and shower shape in the electromagnetic calorimeter and hits in the muon chambers.

The invariant mass distributions of e^+e^- and $\mu^+\mu^-$ combinations in the selected events, with $p(\ell^+\ell^-) < 2.0$ GeV/c, $p(\ell) > 0.9$ GeV/c and $|\cos\theta(\ell)| < 0.9$, are shown in figs. 2a, 2b. With these cuts, the efficiency for observing the decays

[1] On leave from University of Science and Technology, Kumasi, Ghana.
[2] Weizmann Insitute of Science 76100, Rehovot, Israel.
[3] Supported by the Minerva Stiftung.
[4] Supported by the German Bundesministerium für Forschung und Technologie, under contract number 054D051P.
[5] Supported by the German Bundesministerium für Forschung und Technologie, under 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 2T
[10] Supported by the Natural Sciences and Engineering Research Council, Canada.
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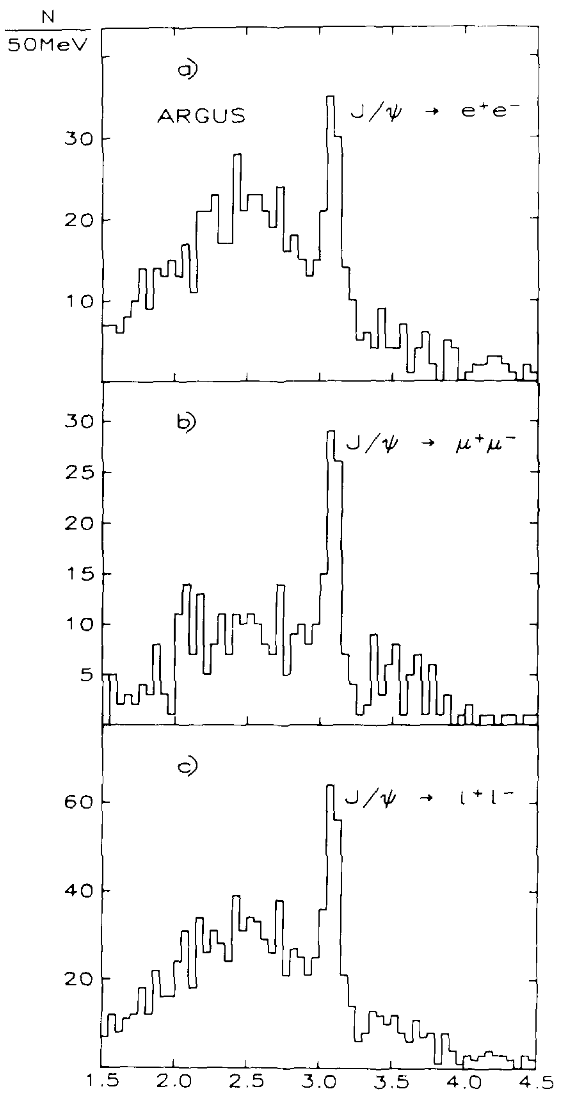

Fig. 2. Distribution of the invariant mass of the lepton pair candidates with $p_\ell > 0.9$ GeV/c and $p_{\ell\ell} < 2.0$ GeV/c. (a) e^+e^-; (b) $\mu^+\mu^-$; (c) sum of both.

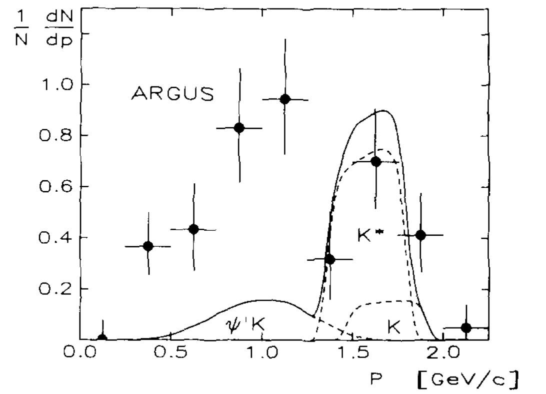

Fig. 3. Momentum distribution of J/ψ mesons in B decays. The dashed curves are the expectations of B→J/ψ K, B→J/ψ K* and (B→ψ′ K, ψ′→J/ψ X) with the branching ratios obtained in this paper. The full line is the sum of these expectations.

J/ψ→e^+e^- and $\mu^+\mu^-$ was determined by detector simulation and found to be about 47% for both decay modes. A fit to the J/ψ signal with a gaussian and a polynomial background of third order leads to 63 ± 15 events J/ψ→e^+e^- and 57 ± 11 events J/ψ→$\mu^+\mu^-$. The same analysis applied to continuum events shows no signal, corresponding to less than 12 events in the ϒ(4S) sample with 90% confidence. Using [8] BR(J/ψ→e^+e^-) = BR(J/ψ→$\mu^+\mu^-$) = (6.9 ± 0.9)%, the estimated number of B mesons, and the acceptance given above, we find BR(B→J/ψ X) = $(1.12 \pm 0.26 \pm 0.21)$% and $(1.04 \pm 0.20 \pm 0.24)$% for the e^+e^- and $\mu^+\mu^-$ samples respectively. The first errors are statistical and the second systematic, mainly due to uncertainty in the J/ψ branching ratio into lepton pairs. The weighted average of the two results is

$$\mathrm{BR}(B \to J/\psi\, X) = (1.07 \pm 0.16 \pm 0.22)\% . \qquad (1)$$

To obtain the J/ψ momentum distribution in B decays, the invariant mass spectrum of the lepton pair candidates was divided into nine momentum bins between zero and 2.25 GeV/c. Fig. 3 shows the acceptance corrected number of J/ψ mesons in each of these momentum bins as obtained by the fits and normalized to unity. The surprisingly soft behaviour could be the result of radiative gluon and non-spectator effects, or to a sizeable contribution of cascade decays, such as B→ψ′ X, ψ′→J/ψ ππ.

To clarify this last statement, we searched for reconstructed ψ′ mesons in the decays ψ′→J/ψ $\pi^+\pi^-$ and ψ′→$\ell^+\ell^-$. For the first decay channel, ψ′→J/ψ $\pi^+\pi^-$, all J/ψ candidates in fig. 2c with $m(\ell\ell) = m(J/\psi) + 70$ MeV/c^2 were considered. The pions were required to have $p_t > 80$ MeV/c, $|\cos\theta| < 0.9$ and a ππ invariant mass larger than 400 MeV/c^2. The last cut takes into account the shape of the invariant ππ mass distribution [9] in the decay

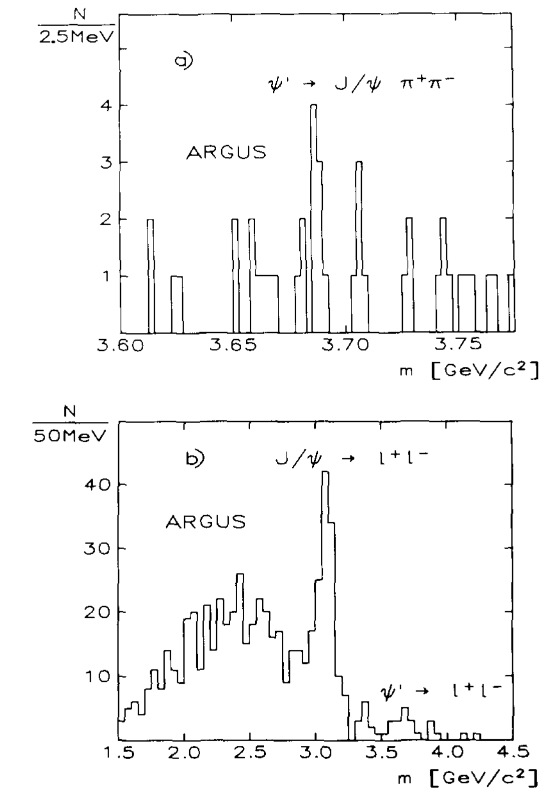

Fig. 4. Distribution of the invariant mass of ψ' candidates. (a) $\psi' \to J/\psi\ \pi^+\pi^-$; (b) $\psi' \to \ell^+\ell^-$.

$\psi' \to J/\psi\ \pi^+\pi^-$. To improve the resolution on the ψ' mass we applied a mass constraint fit to the J/ψ candidates. A signal at the mass of the ψ' meson is visible (fig. 4a). The expected number of events in the ψ' region is 3.7 ± 2.0 events, if no signal is present. We observe 11 events, which corresponds to a deviation of more than 3.5 standard deviations from the background level. The width of the signal agrees with the expected value of about 4 MeV/c^2. From a fit with a gaussian we obtain 7.7 ± 3.6 ψ' candidates leading to a branching ratio $BR(B \to \psi' X) = (0.39 \pm 0.19 \pm 0.10)\%$.

An independent search for decays $B \to \psi' X$ has been made directly in the lepton pair sample. Given the high background level in fig. 2c around $m(\ell\ell) = 3686$ MeV/c^2, no signal for $\psi' \to \ell^+\ell^-$ can be seen. We therefore apply further cuts. Entries from continuum events are effectively rejected if one uses an event shape cut against two-jet events [10]. Fig. 4b shows the $m(\ell\ell)$ distribution in events with $H_2 < 0.35$, where H_2 is the second Fox–Wolfram moment. In addition, the momentum of the $\ell^+\ell^-$ system is required to be lower than 1.6 GeV/c, which is the kinematical limit for ψ' mesons in B decays produced on the $\Upsilon(4S)$ resonance. The background is thereby considerably reduced, and a $\psi' \to \ell^+\ell^-$ signal of 8.0 ± 3.9 candidates becomes visible. Using $BR(\psi' \to e^+e^-$ and $\mu^+\mu^-) = (1.65 \pm 0.21)\%$ and assuming that the acceptance of the H_2 cut is the same for ψ' mesons as for J/ψ mesons, this signal leads to $BR(B \to \psi' X) = (0.72 \pm 0.36 \pm 0.17)\%$.

Being compatible with the $\psi' \to J/\psi\ \pi^+\pi^-$ result above, we combine the two observations and obtain

$$BR(B \to \psi' X) = (0.46 \pm 0.17 \pm 0.11)\% . \quad (2)$$

This result agrees with theoretical expectations [1] about the ratio of $B \to \psi' X / B \to J/\psi X$ and it can be used to estimate how many J/ψ mesons in B decays

Table 1
Branching ratios for exclusive B decays.

Decay channel	Signal (events)	Background (events)	Branching ratio
$B^0 \to J/\psi\ K^0_s$	1	<0.1	
$B^+ \to J/\psi\ K^+$	3	<0.1	(0.07±0.04)%
$B^0 \to J/\psi\ (K^+\pi^-)_{nonres.}$	0		<0.13%
$B^0 \to J/\psi\ K^{*0}$	5	<0.1	(0.33±0.18)%
$B^+ \to J/\psi\ K^+\pi^-\pi^+$ [a]	6	$1.2^{+2.5}_{-1.1}$	(0.11±0.07)%
$B^+ \to \psi'\ K^+$	3	<0.1	(0.22±0.17)%
$B^0 \to \psi'\ K^{*0}$	1	<0.1	

[a] Without $B^+ \to \psi'\ K^+$

originate from $B \to \psi' X$ decays. Using [11] $BR(\psi' \to J/\psi\ X) = (55.2 \pm 6.9)\%$, we find this fraction to be $(24 \pm 10)\%$. Therefore:

$$BR(B \to J/\psi\ X, \text{ where } J/\psi \text{ not from } \psi') = (0.81 \pm 0.23)\% . \quad (3)$$

The search for exclusive B decays was restricted to $B \to \psi + K + n\pi$, where ψ stands for J/ψ or ψ', $K = K^{\pm}$ or K^0_s and $n \leqslant 2$. All lepton pair candidates with $m(\ell\ell) = m(\psi) \pm 100$ MeV/c^2 and all $\ell^+\ell^-\pi^+\pi^-$ candidates with $m(\ell\ell) = m(J/\psi) \pm 70$ MeV/c^2, $m(J/\psi\pi\pi) = m(\psi') \pm 10$ MeV/c^2, are kinematically fitted with the relevant mass constraint and then combined with further particles fulfilling the appropriate kaon or pion idendification [12] criteria. A $K\pi$ combination is called a K^* meson if its invariant mass lies within an interval of ± 100 MeV/c^2 around the $K^*(892)$ mass. All combinations $\psi K n\pi$ with $|E - \frac{1}{2}m(\Upsilon(4S))| < 3\sigma_E$ are then kinematically fitted with the energy constraint $E = \frac{1}{2}m(\Upsilon(4S))$ resulting in a mass of the $\psi K n\pi$ candidate.

The mass spectrum for candidates in all decay channels [#1] listed in table 1 satisfying the cuts described above is shown in fig. 5. The very small number of entries below the expected B mass in the low multiplicity decay channels ($B \to \psi K$, K^*) shows that the background under these signals is negligible. A Monte Carlo simulation leads to an upper limit of 8×10^{-2} background events with 90% CL in each of these channels. The number of background events in the case of decays $B^+ \to J/\psi K^+\pi^+\pi^-$, where $J/\psi\pi^+\pi^-$ is not ψ', is determined by wrong-flavour combinations $K^-\pi^+\pi^-$. Fig. 5d shows that the background decreases with higher invariant masses. A fit with a gaussian to the invariant mass distributions of the neutral and charged B mesons in the low multiplicity decay channels leads to the mass values

$$m(B^0) = (5279.5 \pm 1.6 \pm 3.0)\ \text{MeV}/c^2 , \quad (4)$$

$$m(B^+) = (5278.2 \pm 1.8 \pm 3.0)\ \text{MeV}/c^2 . \quad (5)$$

For this determination, we have used [11] $m(\Upsilon(4S)) = 10\,577$ MeV/c^2. The first error is statistical, including the effect of the DORIS energy spread, and the second error reflects the present error on the $\Upsilon(4S)$ mass and with an additional uncertainty from the DORIS energy setting. The measured masses of the B^0 and B^+ mesons are in good agreement with a previous ARGUS result [13] obtained from reconstructed $B \to D^* n\pi$ events.

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

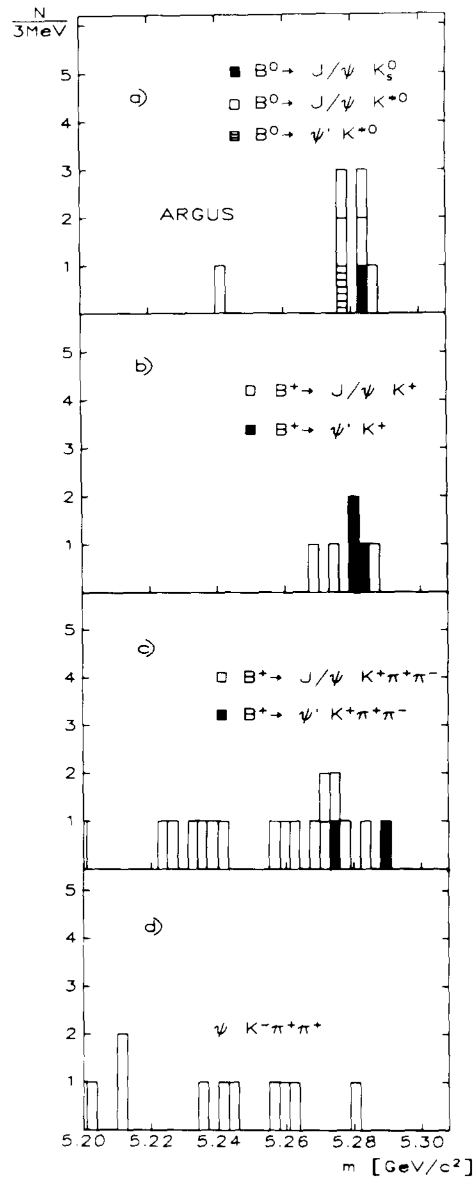

Fig. 5. Distribution of the invariant mass of B candidates. (a) two body decays of neutral B mesons; (b) two body decays of charged B mesons; (c) many body decays of charged B mesons; (d) wrong flavour combinations.

In order to determine branching ratios, we assume that 55% of all $\Upsilon(4S)$ mesons decay into B^+B^- and 45% into $B^0\bar{B}^0$ pairs. The number of observed events and the estimated branching ratios are given in table 1. Neglecting differences between B^0 and $B^{\pm}$, the branching ratio for $B \to J/\psi$ K, K* is roughly one half of that given in eq. (3). Fig. 3 illustrates that this conclusion is consistent with the observed J/ψ momentum spectrum in inclusive $B \to J/\psi$ X decays. The curves are the expectation from $B \to J/\psi$ K with a 0.07%, $B \to J/\psi$ K* with a 0.33%, and $B \to \psi'$ K, $\psi' \to J/\psi$ X with a 0.22×0.55% branching ratio. There is a clear indication for an additional contribution at low J/ψ momentum, i.e., at high recoil mass. From the number of events with $p(J/\psi)$ greater than 1.25 GeV/c, an upper limit with 90% confidence of $BR(B \to J/\psi\ X) < 0.5\%$, where $m_X < 1$ GeV/c^2, is found.

We have also used our event sample to determine upper limits on the decays $B^0 \to e^+e^-$, $\mu^+\mu^-$, which are sensitive to *flavour-changing neutral currents* and on decays $B^0 \to e^{\pm}\mu^{\mp}$, which test the occurence of *lepton-flavour violation.*

The lepton identification procedure was the same as described above. For lepton pair candidates with $|E - \frac{1}{2}m(\Upsilon(4S))| < 3\sigma_E$ an energy constraint fit was performed. The result of this search is shown in table 2. No candidates for the decay $B^0 \to \mu^+\mu^-$, $\mu^{\pm}e^{\mp}$ were found within $\pm 5\sigma$ around the B mass. In the case of e^+e^- combinations we have contamination from radiative Bhabha events in the region of the B^0 mass. After scanning these events we remain with one unidentified event, leading to the upper limit shown in table 2.

In conclusion, we have observed eight times more decays of B mesons into J/ψ mesons than in our previous analysis of this decay channel. The inclusive branching ratio is $(1.07 \pm 0.16 \pm 0.22)$%, which confirms the important role of colour surpression in these decays. The predictions of the formfactor model of Bauer et al. [4] are in good agreement with the rate derived from our five fully reconstructed $B^0 \to J/\psi\ K^{*0}$ decays and three $B^+ \to J/\psi\ K^+$ decays, and from the high momentum region of the inclusive J/ψ momentum spectrum. We also present new upper limits on the occurrence of *flavour-changing neutral currents* and *lepton-flavour violation* in B decays.

Table 2
Upper limits for exclusive dilepton decays.

Decay channel	Upper limit with 90% CL [$\times 10^{-5}$]
$B^0 \to e^+e^-$	8.5
$B^0 \to \mu^+\mu^-$	5.0
$B^0 \to e^{\pm}\mu^{\mp}$	5.0

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