Search for $b \to sX^+X^-$ in exclusive decays of B mesons

ARGUS Collaboration

H. Albrecht, R. Gläser, G. Harder, A. Krüger, A. Nippe, T. Oest, M. Reidenbach, M. Schäfer, W. Schmidt-Parzefall, H. Schröder, H.D. Schulz, F. Sefkow, R. Wurth
DESY, W-2000 Hamburg, FRG

R.D. Appuhn, A. Drescher, C. Hast, G. Herrera, H. Kolanoski, A. Lange, A. Lindner, R. Mankel, H. Scheck, G. Schweda, B. Spaan, A. Walther, D. Wegener
Institut für Physik [1], Universität Dortmund, W-4600 Dortmund, FRG

M. Paulini, K. Reim, U. Volland, H. Wegener
Physikalisches Institut[2], Universität Erlangen-Nürnberg, W-8520 Erlangen, FRG

W. Funk, J. Stiewe, S. Werner
Institut für Hochenergiephysik [3], Universität Heidelberg, W-6900 Heidelberg, FRG

S. Ball, J.C. Gabriel, C. Geyer, A. Hölscher, W. Hofmann, B. Holzer, S. Khan, J. Spengler
Max-Planck-Institut für Kernphysik, W-6900 Heidelberg, FRG

C.E.K. Charlesworth [4], K.W. Edwards [5], W.R. Frisken [6], H. Kapitza [5], P. Krieger [4], R. Kutschke [4], D.B. MacFarlane [7], K.W. McLean [7], R.S. Orr [4], J.A. Parsons [4], P.M. Patel [7], J.D. Prentice [4], S.C. Seidel [4], J.D. Swain [4], G. Tsipolitis [7], T.-S. Yoon [4]
Institute of Particle Physics [8], Canada

R. Davis
University of Kansas [9], Lawrence, KS 66045-2151, USA

T. Ruf, S. Schael, K.R. Schubert, K. Strahl, R. Waldi, S. Weseler
Institut für Experimentelle Kernphysik [10], Universität Karlsruhe, W-7500 Karlsruhe, FRG

B. Boštjančič, G. Kernel, P. Križan [11], E. Križnič, M. Pleško
Institut J. Stefan and Oddelek za fiziko [12], Univerza v Ljubljani, YU-61111 Ljubljana, Yugoslavia

H.I. Cronström, L. Jönsson, A.W. Nilsson
Institute of Physics [13], University of Lund, S-223 62 Lund, Sweden

A. Babaev, M. Danilov, B. Fominykh, A. Golutvin, I. Gorelov, V. Lubimov, A. Rostovtsev, A. Semenov, S. Semenov, V. Shevchenko, V. Soloshenko, V. Tchistilin, I. Tichomirov, Yu. Zaitsev
Institute of Theoretical and Experimental Physics, SU-117 259 Moscow, USSR

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R. Childers and C.W. Darden
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 at DESY, penguin decays of B mesons involving $b \to sX^+X^-$ have been searched for, where X is one of e, μ, π, or K. No evidence for these decays was found and upper limits are quoted. These numbers represent important constraints of flavour-changing neutral currents in B meson decays and probe the heavy-quark and Higgs sectors of the standard model.

In recent years there has been considerable interest in penguin decays of B mesons and the general loop-induced $b \to s$ transition. Such transitions are an interesting probe of the electroweak interactions and provide a possible window on physics well beyond the directly accessible mass-scale [1–17]. Other ARGUS papers have dealt with $b \to s$ gluon [18] and $b \to s\gamma$ [19,20]. Here we consider decays of $b \to sX^+X^-$ where X may be μ, e, π, or K. These decays all involve flavour-changing neutral currents (FCNC). These can occur within the standard model (SM) at the one-loop level, or at tree level due to processes not described by the SM.

The decay modes searched for were $B \to K^{(*)}X^+X^-$ where X is one of e, μ, π or K, and $K^{(*)}$ denotes one of K or K*(892). Charged and neutral B mesons were studied separately. No evidence was found for any of these decays. The results of this search are a set of upper limits which form a significant addition to the published limits on standard and electromagnetic penguin decays [18–23].

The processes under consideration are expected to arise in the SM from processes such as $b \to s\gamma^*$ or $b \to sH$ where γ^* is a virtual photon and H is a real or virtual Higgs boson, with the H or γ^* coupling to the X^+X^- pair. (See figs. 1 and 2). The HX^+X^- vertex will be discussed in some detail later in this paper. Branching ratios expected within the framework of the three-generation SM for $B \to K\ell^+\ell^-$ are of the order of 10^{-6} if one calculates only the processes involving virtual photons [2]. If there is a fourth generation, these branching ratios may go up to a few times 10^{-4} [2].

The case of the Higgs boson merits some special considerations. Grinstein, Hall and Randall have recently pointed out [24] that in the three-generation SM a light Higgs boson should be produced in a quarter of all B meson decays. The rate for Higgs bo-

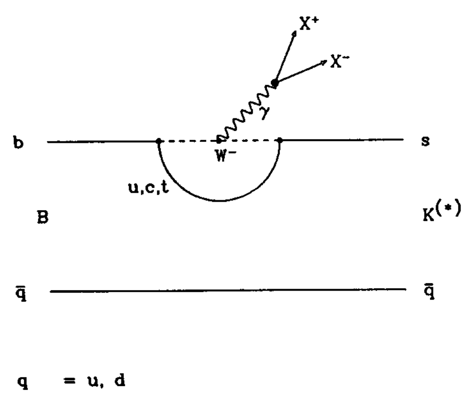

Fig. 1. Quark level diagram depicting an amplitude contributing to $B \to K^{(*)}X^+X^-$ via a virtual photon.

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[3] Supported by the German Bundesministerium für Forschung und Technologie, under contract number 054HD24P.
[4] University of Toronto, Toronto, Ontario, Canada M5S 1A7.
[5] Carleton University, Ottawa, Ontario, Canada K1S 5B6.
[6] York University, Downsview, Ontario, Canada M3J 1P3.
[7] McGill University, Montreal, Quebec, Canada H3A 2T8.
[8] Supported by the Natural Sciences and Engineering Research Council, Canada.
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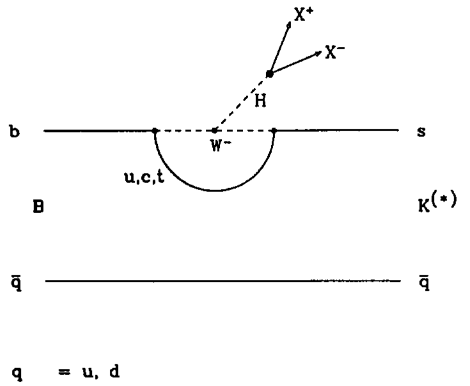

Fig. 2. Quark level diagram depicting an amplitude contributing to $B \to K^{(*)}X^+X^-$ via a Higgs boson.

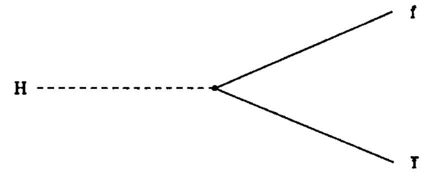

Fig. 3. Higgs coupling to a fermion f.

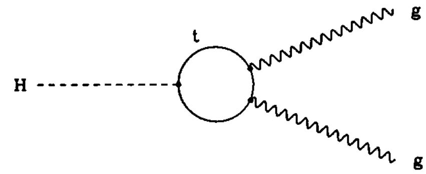

Fig. 4. Higgs coupling to two gluons via a heavy quark loop.

son production is very sensitive to the mass m_t of the top quark, growing as m_t^4. In fact these authors give the result, based on work first done by Willey and Yu [25], that for a light Higgs boson and a top quark mass greater than 80 GeV$/c^2$,

$$\frac{\Gamma(B\to sH)}{\Gamma(B\to all)} \geqslant 0.26\left(1-\frac{m_H^2}{m_B^2}\right)^2 ,$$

where m_H and m_B are the masses of the Higgs boson and B meson respectively. For a sufficiently light Higgs boson this can clearly be very large. If one considers extensions of the SM, a variety of effects can change this estimate. Supersymmetric particles can contribute significantly to these processes (see, for example, refs. [1,2]). If there is more than one Higgs doublet, this can enhance the branching ratios in question by an order of magnitude (see ref. [6]). In any case, it is certainly of great interest to search for possible evidence of these decays.

Even if Higgs bosons were copiously produced in B meson decays, the question remains of how the Higgs decays. The effective coupling of the Higgs boson to various particles is currently of great theoretical interest (see, for example, refs. [24–31]). The Higgs boson couples most strongly to the heaviest fermion in the theory. If the Higgs is real, then depending on its mass, it may decay predominantly into $f\bar{f}$ where f is the heaviest fermion species allowed by energy conservation (see fig. 3). For a light Higgs boson (mass less than $2m_\tau$) one expects decays into electrons or muon pairs, or light $q\bar{q}$ pairs (q=u, d, s), which should fragment to give final states such as $\pi^+\pi^-$ or K^+K^-. A heavier Higgs might decay into higher mass fermions (τ, c, etc.), but these will in general then decay into states which are much more difficult to reconstruct experimentally.

The situation is complicated by the fact that the Higgs, heavy or light, may couple most strongly to gluons (and thus to light quarks in the form of pions and kaons) via a triangle graph involving the top quark, which is the most massive fermion in the three-generation SM [29,30] (see fig. 4). Recent work [28] suggests that the Higgs–$\pi^+\pi^-$ coupling will be enhanced by final state interactions. Fig. 3 depicts the Higgs–fermion coupling, with an amplitude proportional to the mass of the fermion and fig. 4 shows the one-loop coupling to gluons. In view of the uncertainties in all physics involving the Higgs sector of the SM, it is clearly of importance to perform as comprehensive a study of possible decays as feasible.

Due to the theoretical considerations discussed above, we consider this an investigation of the decays $B \to K^{(*)}X^+X^-$ rather than a search for a light Higgs or for a set of electromagnetic penguin decays per se. In particular we do not exclude the possibility of a tree-level flavour-changing neutral process mediated by a particle of unknown mass.

There have been searches for a very light Higgs boson at LEP by all four of the experimental groups. These searches, together with those for a heavy Higgs have resulted in the exclusion of large ranges of possible Higgs boson masses. L3 [32] excludes a Higgs boson of mass between 0 and 41.8 GeV$/c^2$ at the 95% confidence level. ALEPH [33] excludes a mass from

0 to 41.6 GeV/c^2 at the 95% confidence level, and a minimal supersymmetric standard model Higgs of mass less than 3 GeV/c^2. OPAL [34] excludes Higgs bosons of mass less than $2m_\mu$ or between 3 and 44 GeV/c^2 at the 95% confidence level. DELPHI [35] finds that the Higgs boson mass must be greater than 34 GeV/c^2 at the 95% confidence level. Any interpretation of the X^+X^- combination coming from the decay of a Higgs boson should be compared with these results. The limits in this paper, however, still provide independent corroboration of part of the LEP results, and may still be of interest in the event that there are flavour-changing neutral currents mediated by light neutral particles which are not Higgs bosons, as mentioned earlier in this paper.

The results reported here are based on a data sample of 162 pb^{-1} taken on the $\Upsilon(4S)$ resonance with the ARGUS detector at the DORIS II e^+e^- storage ring at DESY. Assuming that the $\Upsilon(4S)$ always decays into $B\bar{B}$ pairs, this corresponds to about 274 000 B mesons. The ARGUS detector is a 4π spectrometer described in more detail elsewhere [36].

Charged pions and kaons were identified on the basis of measurements of both the specific ionization and time of flight. For a given track all mass hypotheses were accepted for which the likelihood ratio [36] exceeded 1%. Each $\pi^+\pi^-$ pair forming a secondary vertex with invariant mass within ± 0.03 GeV of the nominal K^0_S mass [37], was accepted as a K^0_S candidate. For each K^0_S candidate it was then required that the angle between its momentum vector and the vector joining the main vertex to the secondary vertex have a cosine greater than 0.85. This provided a cleaner sample of K^0_S with almost no loss in acceptance. For electrons a likelihood function involving specific ionization in the drift chamber, time of flight, the energy deposition and shower shape in the electromagnetic calorimeter is calculated. Similarity, a likelihood function was calculated for muon candidates, requiring a hit in the outer muon chambers and taking into account information on the distance between the hit and the expected impact point from drift chamber information. Leptons were required to have a likelihood greater than 0.8 for the appropriate hypothesis to be accepted for the analysis.

The $K^*(892)$ was reconstructed from the decay modes $K^{*0}(892)\to K^+\pi^-$ and $K^{*+}(892)\to K^0_S\pi^+$ [#1]. Candidate particle combinations were accepted as K^* mesons if their invariant masses were within $\pm\Gamma$ (one width) of the nominal K^* mass [37].

Since B mesons must have the beam energy, we required that the measured energy of the B meson candidate be within 2σ of the beam energy. For these combinations a fit is performed which constrains the energy of the candidate B meson to the beam energy. This improves the mass resolution by about one order of magnitude.

Background was expected from two sources: continuum and $\Upsilon(4S)$ decays. Some suppression of continuum events was obtained by requiring that candidate events have no measured tracks of momenta greater than 3.0 GeV/c (beyond the kinematical limit for particles from B meson decays). The background from continuum events is greatly reduced for the decays where $X=\pi$ or K by an additional cut, which is based on the observation that B mesons from $\Upsilon(4S)$ decays are produced almost at rest and decay isotropically. To make use of this fact, one thrust axis is calculated for the B meson candidate and one for the remaining particles in the event. For $\Upsilon(4S)$ decays, there is no correlation between the two axes, whereas in continuum events there is a strong probability for the axes to be nearly parallel. Defining α_{thrust} to be the angle between the two axes, we required $|\cos\alpha_{\text{thrust}}|\leqslant 0.5$, chosen as a good compromise between background rejection and good signal acceptance. This cut loses 50% of signal candidates, but in these channels the noise due to continuum is considerable and must be reduced sufficiently that a potential signal has a chance to be observed.

Further suppression of continuum events is made possible since B mesons have spin 0. In this case, their production angular distribution should be proportional to $\sin^2\theta_B$ where θ_B is the angle between the momentum of the B and the beam axis. We therefore required that $|\cos\theta_B|\leqslant 0.8$ in order to improve the signal-to-background ratio.

Neither this last cut, nor the cut on the angle between thrust axes, was necessary in the cases where $X=\mu$ or e, where the most significant backgrounds were expected from known decays of B mesons.

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

In particular, background arises from decays $B \to K^{(*)}J/\psi$ and $B \to K^{(*)}\psi'$ with the subsequent decay of the J/ψ or ψ' into a lepton–antilepton pair. Such events were suppressed by requiring that the invariant mass of the lepton pair lies outside 2σ of the nominal J/ψ and ψ' masses, where σ is the error in the measured invariant mass of the pair. The efficiency of this cut in keeping potential signal events which are uniformly distributed in phase space was determined from a Monte Carlo simulation of the detector to be over 92% (95%) for muon (resp. electron) pairs.

More difficult to suppress are the long-distance contributions to $b \to s\ell^+\ell^-$ due essentially to the process $b \to sV$ where V is a vector meson (such as one of the charmonium states discussed above) which may not necessarily be on shell, followed by its decay to a lepton pair. These processes have been discussed rather extensively in refs. [10,17]. Due to theoretical uncertainties, we neglect these possible effects. Another known background source is the decay $B \to D + n$ pions. In the decays $B \to K^{(*)}\pi^+\pi^-$, no pions were used in the $\pi^+\pi^-$ pair if they combined with any kaon in the event to form a system with invariant mass within 2σ of the nominal mass of the D meson. This cut kept over 98% of the signal events assuming their uniform distribution in phase space.

If more than one B candidate were present in an event, each was weighted by its probability of being a B meson as derived from the identification probabilities of each of its daughter particles and the χ^2 probability from the beam energy fit, with the sum of the weights being equal to unity.

To determine the reconstruction efficiency, $\Upsilon(4S)$ decays were simulated using the LUND 6.2 Monte Carlo program [38], adjusted to describe the general

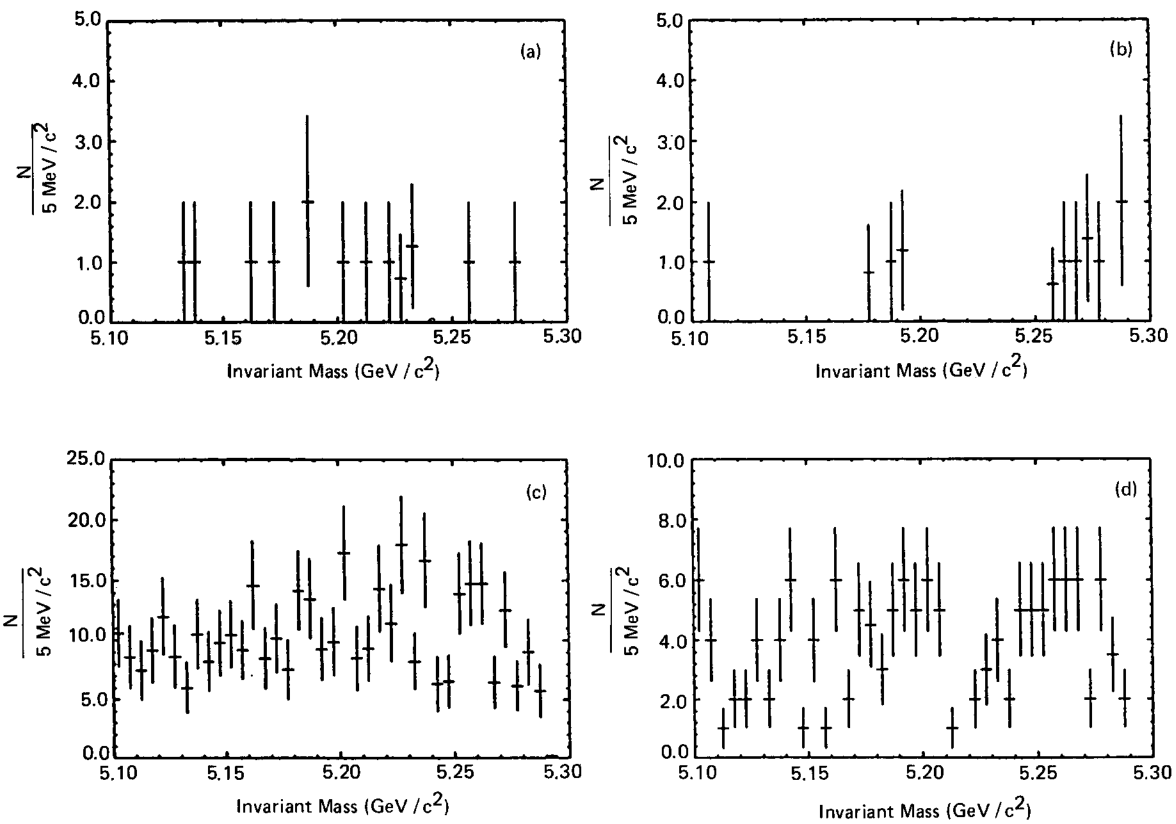

Fig. 5. Invariant mass distributions for $B^+ \to K^+X^+X^-$ for: (a) X=e, (b) X=μ, (c) X=π, and (d) X=K, with cuts as described in the text.

properties of B meson decays. The ratio of neutral and charged B mesons produced in $\Upsilon(4S)$ decays has been assumed to be 0.45/0.55. In each simulated decay of the $\Upsilon(4S)$, one of the B mesons was required to decay into $K^{(*)}X^+X^-$. These decays were generated with a distribution corresponding to three-body phase space. This assumes that if the Higgs-mediated processes occur, they involve virtual Higgs bosons only. The generated events were then passed through a full detector simulation [39] and reconstructed in the same manner as the real data.

In none of the decay channels there is any evidence of a signal. A set of representative mass plots is shown in fig. 5. In order to derive upper limits for the channels investigated, the mass distributions were fitted with a gaussian distribution centred at the B mass and having a width derived from Monte Carlo data (taking into account the width of the $\Upsilon(4S)$ resonance and the spread in the beam energy at DORIS this was typically 5 MeV/c^2), plus a function to model the background:

$$\frac{dN}{dM}=A\left(M\sqrt{1-\frac{M^2}{E^2_{\text{beam}}}}\right)\left\{\exp\left[-a\left(1-\frac{M}{E_{\text{beam}}}\right)\right]\right\},$$

where A and a are free parameters. The first term in braces represents the expected distribution of background uniformly distributed in phase space, while the second braced factor is an empirical term to model the drop in background at lower masses.

In general, the mass plots obtained after cuts were quite sparse and attempts at fitting directly with the function described above could easily lead to difficulties such as negative numbers of events. To avoid such problems, the fit was repeated for different fixed numbers of signal events in order to construct the likelihood function for various amounts of signal. Having this distribution it was then possible to numerically generate a likelihood function for the branching ratio taking into account errors in efficiency, in the Monte Carlo - calculated signal width, and in the branching ratios. This likelihood function was then integrated to 90% of its total integrated value in order to arrive at a limit on the branching ratio at the 90% confidence level. The results are summarized in table 1 where the numbers of events and branching ratios correspond to upper limits at the 90% confidence level.

For the reader who wishes to derive more stringent limits on potential Higgs bosons of specified masses, more details may be found in ref. [40].

In summary, no evidence for any of the decays studied has been found. The results are consistent with expectations based on the SM, but may serve to constrain some models involving more exotic phenomena. There is no doubt that the experimental and theoretical study of these decays will continue to provide valuable tests of the standard model and give one of the most important windows into physics beyond.

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Table 1
Summary of the limits at the 90% confidence limit on $B\to K^{(*)}X^+X^-$.

Decay mode	N_{events}	BR	Decay mode	N_{events}	BR
$B^0\to K^0_S e^+e^-$	<2.3	$<1.5\times10^{-4}$	$B^0\to K^{*0}e^+e^-$	<3.9	$<2.9\times10^{-4}$
$B^+\to K^+e^+e^-$	<3.5	$<9.0\times10^{-5}$	$B^+\to K^{*+}e^+e^-$	<2.3	$<6.3\times10^{-4}$
$B^0\to K^0_S\mu^+\mu^-$	<2.3	$<2.6\times10^{-4}$	$B^0\to K^{*0}\mu^+\mu^-$	<2.3	$<3.4\times10^{-4}$
$B^+\to K^+\mu^+\mu^-$	<5.0	$<2.2\times10^{-4}$	$B^+\to K^{*+}\mu^+\mu^-$	<2.3	$<1.1\times10^{-3}$
$B^0\to K^0_S\pi^+\pi^-$	<3.0	$<2.2\times10^{-4}$	$B^0\to K^{*0}\pi^+\pi^-$	<15.5	$<1.4\times10^{-3}$
$B^+\to K^+\pi^+\pi^-$	<11.5	$<3.3\times10^{-4}$	$B^+\to K^{*+}\pi^+\pi^-$	<3.1	$<1.1\times10^{-3}$
$B^0\to K^0_S K^+K^-$	<7.9	$<6.6\times10^{-4}$	$B^0\to K^{*0}K^+K^-$	<6.7	$<6.1\times10^{-4}$
$B^+\to K^+K^+K^-$	<10.5	$<3.5\times10^{-4}$	$B^+\to K^{*+}K^+K^-$	<4.4	$<1.6\times10^{-3}$

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