SEARCH FOR $b \to s\gamma$ IN EXCLUSIVE DECAYS OF B MESONS

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Using the ARGUS detector at the e^+e^- storage ring DORIS II at DESY, a search for decays $B \to K^* \gamma$ has been performed where K^* represents seven different K mesons. No evidence for such decays has been found, and upper limits are quoted. These provide valuable constraints on the top quark mass, the Higgs sector of the standard model, and a variety of extensions thereto.

In recent years there has been considerable interest in radiative penguin decays of B mesons and the general $b \to s\gamma$ 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. They proceed through loop diagrams which can involve virtual particles well-beyond our present ability to produce on-shell. Fig. 1 shows a diagram in the standard model contributing to this process. Another diagram is as in fig. 1, but with the photon attached to the quark line in the loop. Such processes are sensitive to the mass of the top quark, the structure of the Higgs sector (masses and number of Higgs bosons), a possible fourth family, and supersymmetric particles. Unfortunately, they are nontrivial to calculate theoretically due, among other factors, to expectedly large QCD corrections. For theoretical discussions the reader is referred to refs. [1–19].

The decay modes searched for were $B \to \gamma$ and one of $K^*(892)$, $K_1(1270)$, $K_1(1400)$, $K_2^*(1430)$, $K^*(1715)$, $K_3^*(1780)$, or $K_4^*(2075)$; we will henceforth refer to these K mesons collectively as K^*. These represent essentially all states of the K system for which it is feasible to search, and which are also allowed by conservation of angular momentum. Note in particular that $B \to K\gamma$ is forbidden as the K meson has spin 0. In order to minimize the number of untestable assumptions in this analysis, charged and neutral B mesons were handled separately. No evidence of a signal was seen in any of these channels, so the results of this search are 14 upper limits. These form a significant addition to the exisiting limits on standard and electromagnetic penguin decays [20,21].

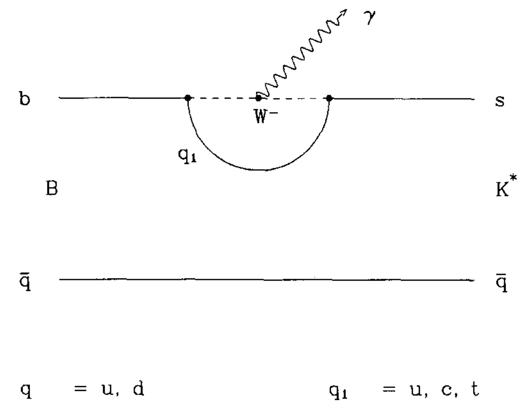

Fig. 1. Quark level diagram depicting an amplitude contributing to $B \to K^* \gamma$.

The results reported here are based on a data sample of 162 pb^{-1} taken with the ARGUS detector at the DORIS II storage ring on the $\Upsilon(4S)$ resonance. 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 detail elsewhere [22].

Charged particles 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 [22] ex-

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ceeded 1%. Each $\pi^+\pi^-$ pair forming a secondary vertex with invariant mass within ± 0.03 GeV/c^2 of the nominal K^0_S mass [23], 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 of greater than 0.85. This provided a cleaner sample of K^0_S mesons with almost no loss in acceptance.

The specific decay chains of the excited K systems studied are shown in table 1 [#1]. Candidate particle combinations were accepted as K* mesons if their invariant masses were within $\pm\Gamma$ (one width) of their nominal masses [23]. The ρ mesons were all neutral and taken from $\pi^+\pi^-$ combinations with a mass lying between -1.0Γ and $+1.2\Gamma$ of the nominal ρ^0 mass [23]. An asymmetric mass cut was used for the ρ mesons to allow for the fact that the ρ mass distribution should properly be described by a relativistic Breit–Wigner function. A symmetric mass cut of -1.0Γ to $+1.0\Gamma$ gives essentially the same results. Note that, in order to suppress background, no decay channels involving neutral pions were used. Photons were detected in a fine-grained electromagnetic calorimeter [24], made of lead-scintillator sandwich modules with wavelength shifter readout. The energy resolution σ_E as a function of deposited energy E is approximately given by

$$\sigma_E/E = \sqrt{0.07^2/E[\mathrm{GeV}] + 0.07^2}\ .$$

Photons were required to be well-measured, having an error in energy of less than 0.3 GeV.

This cut rejected some background while retaining essentially 100% of possible signal events.

Since B mesons produced on the $\Upsilon(4S)$ have the beam energy, we required that the measured energy of the B meson candidate be within 2σ of the beam energy. For accepted combinations a fit was 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. Assuming B mesons have spin 0, 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.

The background from continuum events is greatly reduced by a cut which is based on the observation that B mesons from $\Upsilon(4S)$ decays are produced almost at rest and decay isotropically. 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 tendency for the axes to be nearly parallel. Defining α_{thrust} to be the angle between the two axes, we required $|\cos\alpha_{\mathrm{thrust}}| \leqslant 0.8$, chosen as a good compromise between strong background rejection and good signal acceptance. Further suppression of continuum events is 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).

If more than one B candidate was selected in an event, each was weighted by its probability of being a B meson as derived from the identification probabil-

[#1] References in this paper to a specific charged state are to be interpreted as also implying the charge conjugate state. Branching ratios are always taken to be the summed over both charge states unless otherwise explicitly stated.

Table 1
Summary of decay chains used to reconstruct K*'s.

K*	Decay mode	K*	Decay mode
$K^{*0}(892)$	$K^+\pi^-$	$K^{*+}(892)$	$K^0_S\pi^+$
$K^0_1(1270)$	$K^0_S\rho^0$	$K^+_1(1270)$	$K^+\rho^0$
$K^0_1(1400)$	$K^{*+}(892)\pi^-$	$K^+_1(1400)$	$K^{*0}(892)\pi^+$
$K^{*0}_2(1430)$	$K^+\pi^-$	$K^{*+}_2(1430)$	$K^0_S\pi^+$
$K^{*0}(1715)$	$K^+\pi^-$	$K^{*+}(1715)$	$K^0_S\pi^+$
$K^{*0}_3(1780)$	$K^0_S\rho^0$	$K^{*+}_3(1780)$	$K^+\rho^0$
$K^{*0}_4(2070)$	$K^+\pi^-$	$K^{*+}_4(2070)$	$K^0_S\pi^+$

ities of each of its daughter particles and the χ^2 from the beam energy fit, with the sum of the weights being equal to unity.

To determine the reconstruction efficiency, $\Upsilon(4S)$ decays have been simulated using the LUND 6.2 Monte Carlo program [25], adjusted to describe the general 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 via a penguin diagram. The generated events were then passed through a full detector simulation [26] and reconstructed in the same manner as the real data.

In none of the decay channels is there any evidence of a signal. Figs. 2 and 3 show the results of searches for charged and neutral B mesons into a photon and the lowest mass K*. These are representative of the mass distributions obtained in the various decay modes investigated. 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 ~5 MeV) plus a function to model the background event density per unit mass:

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

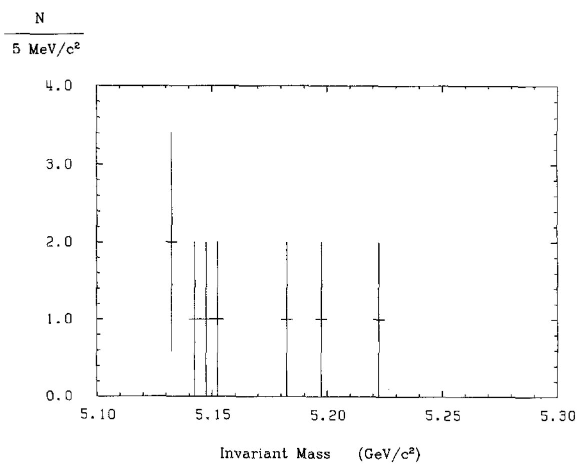

Fig. 2. $K^{*+}(892)\gamma$ invariant mass distribution.

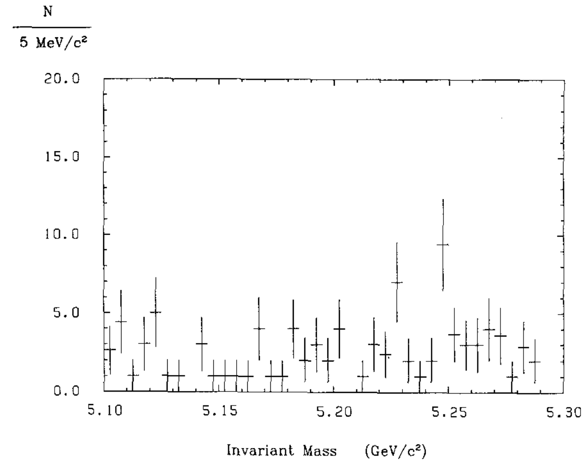

Fig. 3. $K^{*0}(892)\gamma$ invariant mass distribution.

where A and a are free parameters. The first term in parentheses 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 negative numbers of events. To circumvent this problem 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 the K* branching ratios. This likelihood function was then integrated to 90% of its total integrated value in order to arrive at a true limit at the 90% confidence level. Further details may be found in ref. [27]. The results are summarized in table 2.

In summary, no evidence for radiative penguin decays of B mesons has been found. The data presented here constitute the most comprehensive limits on the $b\to s\gamma$ transition. It is difficult to translate these directly into limits on the quark level process $b\to s\gamma$, as it is not well-understood to what degree this will be manifest in various final states. In the constituent quark model, predictions for $\Gamma(B\to K^*(892)\gamma)/\Gamma(b\to s\gamma)$ range from 5% to 40% [7,9,10]. Altomari [9] has provided the most complete set of estimates for other $K^*\gamma$ final states, suggesting that their

Table 2
Summary of the results on $B \to K^*\gamma$.

Decay mode	N_{events} (90% CL)	BR (90% CL)
$B_d^0 \to K^{*0}(892)\gamma$	$<$ 7.9	$<4.2\times10^{-4}$
$B_u^+ \to K^{*+}(892)\gamma$	$<$ 2.3	$<5.2\times10^{-4}$
$B_d^0 \to K_1^0(1270)\gamma$	$<$ 3.5	$<7.8\times10^{-3}$
$B_u^+ \to K_1^+(1270)\gamma$	$<$18.6	$<6.6\times10^{-3}$
$B_d^0 \to K_1^0(1400)\gamma$	$<$ 4.8	$<4.8\times10^{-3}$
$B_u^+ \to K_1^+(1400)\gamma$	$<$17.6	$<2.0\times10^{-3}$
$B_d^0 \to K_2^{*0}(1430)\gamma$	$<$ 4.6	$<4.4\times10^{-4}$
$B_u^+ \to K_2^{*+}(1430)\gamma$	$<$ 2.3	$<1.3\times10^{-3}$
$B_d^0 \to K^{*0}(1715)\gamma$	$<$16.7	$<2.2\times10^{-3}$
$B_u^+ \to K^{*+}(1715)\gamma$	$<$ 3.2	$<1.7\times10^{-3}$
$B_d^0 \to K_3^{*0}(1780)\gamma$	$<$ 4.8	$<1.1\times10^{-2}$
$B_u^+ \to K_3^{*+}(1780)\gamma$	$<$17.0	$<5.0\times10^{-3}$
$B_d^0 \to K_4^{*0}(2075)\gamma$	$<$ 7.7	$<4.8\times10^{-3}$
$B_u^+ \to K_4^{*+}(2075)\gamma$	$<$ 3.8	$<9.0\times10^{-3}$

branching ratios might be quite similar. His work motivated this rather extensive study.

The limit obtained on BR ($B_d^0 \to K^{*0}(892)\gamma$) implies an upper limit on BR($b \to s\gamma$) of 8.4×10^{-3} (1.1×10^{-3}) for $\Gamma(B \to K^*(892)\gamma)/\Gamma(b \to s\gamma)$ of 5% (40%). This is now difficult to translate into constraints on the standard model, or on new physics, and the interested reader is again referred to the theoretical literature [1–19]. Golowich and Pakvasa [11] have parametrized results of several authors to obtain an expression for the branching ratio BR($b \to s\gamma$) in terms of mass m_t of the top quark. (Here we assume the three-generation, one-Higgs doublet minimal standard model.) They give

$$\mathrm{BR}(b \to s\gamma) \cong 2.2\times10^{-4}(m_t/60\ \mathrm{GeV})^{1.16}$$

Our limit then implies that $m_t < 1400$ (240) GeV for $\Gamma(B \to K^*(892)\gamma)/\Gamma(b \to s\gamma)$ of 5% (40%). This, however, as Golowich and Pakvasa discuss, is subject to large uncertainties due to long-range effects. It is to be hoped that further theoretical developments will allow a more precise statement about the top quark mass to be made from the data in this paper. There can be no doubt that the experimental and theoretical study of these decays will continue to test the standard model and provide a window into physics beyond.

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