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R. AMMAR

M. THULASIDAS
Singapore Management University, manojt@smu.edu.sg

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Evidence for Penguin-Diagram Decays: First Observation of $B \to K^*(892)\gamma$

R. Ammar,[1] S. Ball,[1] P. Baringer,[1] D. Coppage,[1] N. Copty,[1] R. Davis,[1] N. Hancock,[1] M. Kelly,[1] N. Kwak,[1] H. Lam,[1] Y. Kubota,[2] M. Lattery,[2] J. K. Nelson,[2] S. Patton,[2] D. Perticone,[2] R. Poling,[2] V. Savinov,[2] S. Schrenk,[2] R. Wang,[2] M. S. Alam,[3] I. J. Kim,[3] B. Nemati,[3] J. J. O'Neill,[3] H. Severini,[3] C. R. Sun,[3] M. M. Zoeller,[3] G. Crawford,[4] M. Daubenmeir,[4] R. Fulton,[4] D. Fujino,[4] K. K. Gan,[4] K. Honscheid,[4] H. Kagan,[4] R. Kass,[4] J. Lee,[4] R. Malchow,[4] F. Morrow,[4] Y. Skovpen,[4,*] M. Sung,[4] C. White,[4] J. Whitmore,[4] P. Wilson,[4] F. Butler,[5] X. Fu,[5] G. Kalbfleisch,[5] M. Lambrecht,[5] W. R. Ross,[5] P. Skubic,[5] J. Snow,[5] P. L. Wang,[5] M. Wood,[5] D. Bortoletto,[6] D. N. Brown,[6] J. Fast,[6] R. L. McIlwain,[6] T. Miao,[6] D. H. Miller,[6] M. Modesitt,[6] S. F. Schaffner,[6] E. I. Shibata,[6] I. P. J. Shipsey,[6] P. N. Wang,[6] M. Battle,[7] J. Ernst,[7] H. Kroha,[7] S. Roberts,[7] K. Sparks,[7] E. H. Thorndike,[7] C. H. Wang,[7] J. Dominick,[8] S. Sanghera,[8] T. Skwarnicki,[8] R. Stroynowski,[8] M. Artuso,[9] D. He,[9] M. Goldberg,[9] N. Horwitz,[9] R. Kennett,[9] G. C. Moneti,[9] F. Muheim,[9] Y. Mukhin,[9] S. Playfer,[9] Y. Rozen,[9] S. Stone,[9] M. Thulasidas,[9] G. Vasseur,[9] G. Zhu,[9] J. Bartelt,[10] S. E. Csorna,[10] Z. Egyed,[10] V. Jain,[10] P. Sheldon,[10] D. S. Akerib,[11] B. Barish,[11] M. Chadha,[11] S. Chan,[11] D. F. Cowen,[11] G. Eigen,[11] J. S. Miller,[11] C. O'Grady,[11] J. Urheim,[11] A. J. Weinstein,[11] D. Acosta,[12] M. Athanas,[12] G. Masek,[12] B. Ong,[12] H. Paar,[12] M. Sivertz,[12] A. Bean,[13] J. Gronberg,[13] R. Kutschke,[13] S. Menary,[13] R. J. Morrison,[13] S. Nakanishi,[13] H. N. Nelson,[13] T. K. Nelson,[13] J. D. Richman,[13] A. Ryd,[13] H. Tajima,[13] D. Schmidt,[13] D. Sperka,[13] M. S. Witherell,[13] M. Procario,[14] S. Yang,[14] R. Balest,[15] K. Cho,[15] M. Daoudi,[15] W. T. Ford,[15] D. R. Johnson,[15] K. Lingel,[15] M. Lohner,[15] P. Rankin,[15] J. G. Smith,[15] J. P. Alexander,[16] C. Bebek,[16] K. Berkelman,[16] D. Besson,[16] T. E. Browder,[16] D. G. Cassel,[16] H. A. Cho,[16] D. M. Coffman,[16] P. S. Drell,[16] R. Ehrlich,[16] M. Garcia-Sciveres,[16] B. Geiser,[16] B. Gittelman,[16] S. W. Gray,[16] D. L. Hartill,[16] B. K. Heltsley,[16] C. D. Jones,[16] S. L. Jones,[16] J. Kandaswamy,[16] N. Katayama,[16] P. C. Kim,[16] D. L. Kreinick,[16] G. S. Ludwig,[16] J. Masui,[16] J. Mevissen,[16] N. B. Mistry,[16] C. R. Ng,[16] E. Nordberg,[16] M. Ogg,[16,†] J. R. Patterson,[16] D. Peterson,[16] D. Riley,[16] S. Salman,[16] M. Sapper,[16] H. Worden,[16] F.Würthwein,[16] P. Avery,[17] A. Freyberger,[17] J. Rodriguez,[17] R. Stephens,[17] J. Yelton,[17] D. Cinabro,[18] S. Henderson,[18] K. Kinoshita,[18] T. Liu,[18] M. Saulnier,[18] F. Shen,[18] R. Wilson,[18] H. Yamamoto,[18] M. Selen,[19] and A. J. Sadoff[20]

(CLEO Collaboration)

[1] *University of Kansas, Lawrence, Kansas 66045*
[2] *University of Minnesota, Minneapolis, Minnesota 55455*
[3] *State University of New York at Albany, Albany, New York 12222*
[4] *Ohio State University, Columbus, Ohio 43210*
[5] *University of Oklahoma, Norman, Oklahoma 73019*
[6] *Purdue University, West Lafayette, Indiana 47907*
[7] *University of Rochester, Rochester, New York 14627*
[8] *Southern Methodist University, Dallas, Texas 75275*
[9] *Syracuse University, Syracuse, New York 13244*
[10] *Vanderbilt University, Nashville, Tennessee 37235*
[11] *California Institute of Technology, Pasadena, California 91125*
[12] *University of California, San Diego, La Jolla, California 92093*
[13] *University of California, Santa Barbara, California 93106*
[14] *Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213*
[15] *University of Colorado, Boulder, Colorado 80309-0390*
[16] *Cornell University, Ithaca, New York 14853*
[17] *University of Florida, Gainesville, Florida 32611*
[18] *Harvard University, Cambridge, Massachusetts 02138*
[19] *University of Illinois, Champaign-Urbana, Illinois, 61801*
[20] *Ithaca College, Ithaca, New York 14850*

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We have observed the decays $B^0 \to K^*(892)^0\gamma$ and $B^- \to K^*(892)^-\gamma$, which are evidence for the quark-level process $b \to s\gamma$. The average branching fraction is $(4.5 \pm 1.5 \pm 0.9) \times 10^{-5}$. This value is consistent with standard model predictions from electromagnetic penguin diagrams.

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One-loop, flavor-changing neutral current diagrams, known as penguins, were originally introduced into the theory of weak decays to explain the $\Delta I = \frac{1}{2}$ rule in K meson decays [1]. They were later identified as a possible source of direct CP violation in kaon decay, and hence as a contribution to ϵ'/ϵ [2]. Their importance in B meson

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decays has also been noted [3].

One of the clearest signatures for penguin diagrams is the radiative process $b \to s\gamma$ (Fig. 1). There are many calculations of the rate for this process, which depends on the as yet unknown mass of the top quark. After including substantial QCD corrections, the branching ratio for $b \to s\gamma$ is expected to be in the range $(2\text{–}4)\times10^{-4}$ [4]. Other standard model contributions have been considered, and found to be at least an order of magnitude smaller than the penguin contribution [5]. Observation of a rate much larger than 4×10^{-4} would be evidence for nonstandard-model contributions. In the recent literature possible contributions to $b \to s\gamma$ from supersymmetry, a fourth generation, and a charged Higgs boson have been discussed in some detail [6].

The fraction of $b \to s\gamma$ decays that hadronize to any exclusive final state is much less reliably predicted than the inclusive rate. Estimates for the fraction of $B \to K^*(892)\gamma$ range from 5% to 40% [7]. In this Letter, we report observation of the decay $B \to K^*\gamma$ [8], in both $B^0 \to K^{*0}\gamma$ and $B^- \to K^{*-}\gamma$ modes, at a rate that is consistent with the predictions from the penguin diagram.

The data sample used in this study was collected with the CLEO-II detector [9] at the Cornell Electron Storage Ring (CESR). It consists of 1377 pb^{-1} of integrated luminosity on the $\Upsilon(4S)$ resonance (1.39×10^6 $B\overline{B}$ events) and 633 pb^{-1} at a center-of-mass energy 55 MeV below the resonance. Charged particles are tracked using three nested cylindrical wire chambers operated in a 1.5 T magnetic field. The outer tracking chamber also measures specific ionization (dE/dx), which is used for particle identification. The tracking chambers are followed by time-of-flight (TOF) counters, which provide additional particle identification information. Beyond these counters but still inside the superconducting magnet coil is an electromagnetic calorimeter consisting of 7800 CsI crystals. Outside the coil is an iron yoke for field return, with chambers interspersed for muon identification.

The dominant experimental problem in identifying $B \to K^*\gamma$ is the large background from continuum (non-$B\overline{B}$) processes. We suppressed this background with a series of cuts determined from Monte Carlo studies. For $B^0 \to K^{*0}\gamma$, we selected events with at least 3 charged tracks and a visible energy of at least 30% of the center-of-mass energy. Our high energy photon candidates are clusters with energy E_γ satisfying $2.1 < E_\gamma < 2.9$ GeV, with polar angles θ (relative to the beam axis) satisfying $|\cos\theta| < 0.7$, not matched to charged tracks, and with shower shapes consistent with single photons. Photon candidates are rejected if they form π^0's (η's) when combined with another photon of energy greater than 30 (200) MeV.

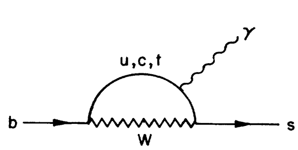

FIG. 1. Penguin diagram for $b \to s\gamma$. The photon may be radiated from any of the four lines.

There are two main sources of high energy photons from the continuum: initial state radiation (ISR) and fragmentation of non-$b\overline{b}$ quarks ($q\overline{q}$). Most continuum processes have a two-jet topology, which is used to distinguish them from the more spherical $B\overline{B}$ events with B mesons decaying almost at rest. We suppress $q\overline{q}$ backgrounds by applying cuts on the shape variables R_2, the normalized second Fox-Wolfram moment [10], and $S_\perp$, a measure of the momentum transverse to the photon direction [11]. We require $R_2 < 0.5$ and $0.25 < S_\perp < 0.60$ (the upper restriction on $S_\perp$ provides rejection of ISR). To further suppress the ISR background we use variables evaluated in the rest frame of the e^+e^- following the radiation of the high energy photon (the primed frame). In this frame we require $R_2' < 0.3$, where R_2' is evaluated excluding the photon, and $|\cos\theta'| > 0.5$, where θ' is the angle between the photon and the thrust axis of the rest of the event.

We look for K^{*0} candidates in the decay mode $K^{*0} \to K^+\pi^-$. Each charged track must pass standard track quality cuts, and must have a value of dE/dx and/or TOF which is within 2.5 standard deviations (σ) of that expected for the mass hypothesis. Particles lacking both TOF and dE/dx information are considered to be pions, but not kaons. A $K^+\pi^-$ pair must have an invariant mass $M_{K\pi}$ satisfying $821 < M_{K\pi} < 971$ MeV, and a decay helicity angle $\theta_{K\pi}$ satisfying $|\cos\theta_{K\pi}| < 0.8$, since K^*'s from $B \to K^*\gamma$ decay with a $\sin^2\theta_{K\pi}$ distribution, whereas the background is expected to have a flat distribution in $\cos\theta_{K\pi}$.

We combined the high energy photon and K^* candidates to form candidates for $B^0 \to K^{*0}\gamma$. Having made all particle assignments, we imposed two further cuts: (1) the angle θ_{thr} between the high energy photon direction and the thrust axis of the particles not from the B candidate, $|\cos\theta_{\text{thr}}| < 0.7$ (expected to be flat for signal, peaked at 1.0 for continuum background); (2) the production polar angle of the B, $|\cos\theta_B| < 0.85$ (expected to be $\sin^2\theta_B$ for signal, flat for background). Finally, we required that the B candidates have an energy close to the beam energy, $|\Delta E| < 90$ MeV (2.2σ), where $\Delta E = E_{\text{beam}} - E_{K^*\gamma}$. For candidates passing this cut, we scaled the photon energy to obtain $\Delta E = 0$, and computed $M_{K^*\gamma}$. The $M_{K^*\gamma}$ resolution of 2.8 MeV rms is dominated by the beam energy spread. The mass distribution for the B candidates is shown in Fig. 2. There are 8 events in the signal region, the mass interval 5.274–5.286 GeV.

The background is still mostly from the continuum, even after the continuum suppression cuts have been optimized. This background varies smoothly as a function

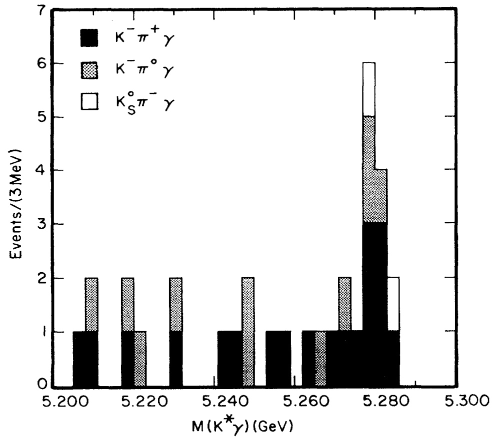

FIG. 2. The $K^*\gamma$ mass distributions for $B^0 \to K^{*0}\gamma$; $B^- \to K^{*-}\gamma$, $K^{*-} \to K^0_S\pi^-$; and $B^- \to K^{*-}\gamma$, $K^{*-} \to K^-\pi^0$ candidates.

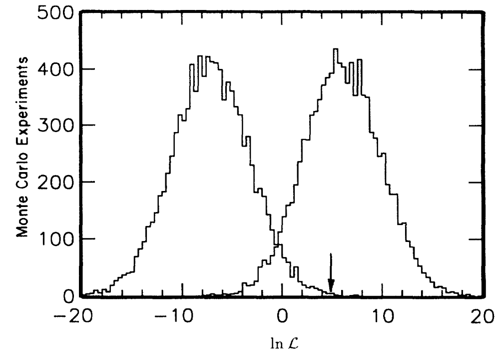

FIG. 3. The $\ln\mathcal{L}$ distributions for 10 000 "experiments" of 8 events each, drawn from $B^0 \to K^{*0}\gamma$ Monte Carlo (right curve) or continuum Monte Carlo (left curve) simulations. The value for the 8 $B^0 \to K^{*0}\gamma$ candidate events is indicated by an arrow.

of ΔE and $M_{K^*\gamma}$, so the amount of background in the signal region of the on-resonance data can be reliably estimated by scaling the events observed in sideband regions by an appropriate factor. For $B^0 \to K^{*0}\gamma$ the sideband was chosen to be $|\Delta E| < 280$ MeV and $M_{K^*\gamma} > 5.2$ GeV, excluding $|\Delta E| < 100$ MeV and $M_{K^*\gamma} > 5.274$ GeV (the signal region plus a narrow boundary in $|\Delta E|$). The relative population of the sideband and signal regions depends on the momentum distributions of the photon and two charged particles making up the $K^*\gamma$ candidate, and on their transverse momentum distributions relative to a common axis. Using Monte Carlo tuned to match the off-resonance data we determined the population ratio to be 25.4:1 with an error of ± 8%. For the actual background determination, we counted events in the sideband regions of the on- and off-resonance data samples, and the signal region of the off-resonance sample, and scaled the total of 41 events by a factor of 37.6 [12] to obtain a background estimate of 1.1 ± 0.2. The binomial probability [13] that 8 + 41 events in signal plus sideband regions would distribute themselves such that 8 or more were in the signal region, given that the intrinsic relative populations are 1:37.6, is 3.5×10^{-5}.

For $B^- \to K^{*-}\gamma$, we looked for K^{*-} candidates in both the $K^0_S\pi^-$ and the $K^-\pi^0$ modes. A $K^0_S \to \pi^+\pi^-$ decay is required to have a vertex more than 5 mm from the beam axis, a good χ^2 for the vertex fit, and a $\pi^+\pi^-$ mass within 10 MeV (2σ) of the K^0_S mass. The π^0's are selected from pairs of photons with an invariant mass within 15 MeV (2.5σ) of the π^0 mass. The photons are selected from showers in the calorimeter that are not matched to charged tracks, have shower shapes consistent with isolated photons, and have energies above 30 (50) MeV in the barrel (end-cap) regions. Other cuts [14] are similar to those described for $B^0 \to K^{*0}\gamma$. The $K^{*-}\gamma$ mass distributions for the two modes are shown in Fig. 2, and the numbers of signal events and estimated backgrounds are given in Table I. The combined probability of both K^{*-} results being fluctuations is 7.0×10^{-4}.

We obtain additional evidence that the signal events are not all continuum background by examining the distributions inside the cuts of the variables $M_{K^*\gamma}$, ΔE, $\cos\theta_B$, $\cos\theta_{K\pi}$, $M_{K\pi}$, R_2, and $\cos\theta_{\rm thr}$. We do this with a likelihood ratio test [15], which reduces the information contained in several variables to a single number. In Fig. 3 we show the distribution in log likelihood ratio ($\ln\mathcal{L}$) for two groups of 10 000 simulated experiments, one drawing 8 events from a sample of Monte Carlo $B^0 \to K^{*0}\gamma$ events, the other drawing from a sample of Monte Carlo

TABLE I. Summary of results for $B \to K^*\gamma$.

	$B^0 \to K^{*0}\gamma$ $K^{*0} \to K^+\pi^-$	$B^- \to K^{*-}\gamma$ $K^{*-} \to K^0_S\pi^-$	$K^{*-} \to K^-\pi^0$
Signal events	8	2	3
Sideband events	41	2	10
Sideband scale factor	37.6	40	12
Sideband background	1.1±0.2	0.05±0.03	0.8±0.3
Binomial probability	3.5×10^{-5}	3.7×10^{-3}	7.3×10^{-2}
Residual $B\overline{B}$ background	0.30±0.15	0.01±0.01	0.10±0.05
Efficiency	(11.9±1.8)%	(2.0±0.3)%	(3.1±0.5)%
Branching ratio	$(4.0\pm1.7\pm0.8)\times10^{-5}$	$(5.7\pm3.1\pm1.1)\times10^{-5}$	

continuum events. Only 0.11% of the 8-event continuum samples have values of $\ln \mathcal{L}$ as large as that of the 8 $B^0 \to K^{*0}\gamma$ candidate events, while about half of the signal samples do. Allowing for systematic and statistical errors, the probability of observing a value of $\ln \mathcal{L}$ this large from a sample of 8 continuum events is less than 1%. Similar studies for $B^- \to K^{*-}\gamma$ support the interpretation of a $K^{*-} \to K_S^0\pi^-$ signal, and are not inconsistent with a $K^{*-} \to K^-\pi^0$ signal.

We have assessed sources of background to $B \to K^*\gamma$ from other B decays. First, using a fast Monte Carlo that did not include a full detector simulation, we considered $b \to c$, $b \to u$, and $b \to sg$ decays, with particular attention to the $D^{*0}\gamma$, $\rho\pi^0$, $K^*\pi^0$, and $K^*\rho^-$ channels, which we anticipated might be troublesome. These sources accounted for < 0.11, < 0.06, and < 0.02 events as background to $K^-\pi^+\gamma$, $K^-\pi^0\gamma$, and $K_S^0\pi^-\gamma$, respectively. Then using techniques largely based on data, we studied possible sources of false 2–3 GeV photons such as random overlaps of uncorrelated photons, merging of photons from π^0's, clusters caused by K_L^0's, and clusters caused by antineutrons. These sources accounted for < 0.25, < 0.06, and < 0.02 events as background to $K^-\pi^+\gamma$, $K^-\pi^0\gamma$, and $K_S^0\pi^-\gamma$, respectively. A final contribution, from feeddown into $B \to K^*\gamma$ from other $b \to s\gamma$ modes, is estimated using the theoretical prediction of an inclusive rate of 4×10^{-4}, and a model for the hadronization. We find backgrounds of 0.4 and 0.1 events in $K^-\pi^+\gamma$ and $K^-\pi^0\gamma$, respectively. The feeddown into the $K_S^0\pi^-\gamma$ mode is negligible. Approximately half of the $B\overline{B}$ backgrounds are included in the background estimated from the sidebands. The residual backgrounds from $B\overline{B}$, not included in the sideband subtraction, are listed in Table I [16].

Table I summarizes our results. The net yield of $B^0 \to K^{*0}\gamma$ events is 6.6 ± 2.8. The efficiency for $B^0 \to K^{*0}\gamma$ decays, including K^* branching ratio, is $(11.9 \pm 1.8)\%$. The data sample contains 1.39×10^6 $B\overline{B}$ decays, which we assume to be half charged, half neutral. From this we obtain a branching ratio for $B^0 \to K^{*0}\gamma$ of $(4.0 \pm 1.7 \pm 0.8) \times 10^{-5}$, where the first error is statistical and the second is a $\pm$ 20% systematic error to account for uncertainties in efficiency and background. The net yield of $B^- \to K^{*-}\gamma$ events is 4.1 ± 2.3. The efficiencies for the $K_S^0\pi^-$ and $K^-\pi^0$ modes, including K^* and K^0 branching ratios, are 2.0% and 3.1%, respectively, giving an overall efficiency for the $B^- \to K^{*-}\gamma$ decay of 5.1%. From this we obtain a branching ratio for $B^- \to K^{*-}\gamma$ of $(5.7 \pm 3.1 \pm 1.1) \times 10^{-5}$.

In conclusion, we have obtained compelling evidence for the existence of the decay $B^0 \to K^{*0}\gamma$, and supporting evidence for the existence of the closely related decay $B^- \to K^{*-}\gamma$. If one makes the reasonable assumption that the branching ratios for these two decays are equal, then an average branching ratio of $(4.5 \pm 1.5 \pm 0.9) \times 10^{-5}$ is obtained. This is entirely consistent with the theoretical predictions from the penguin diagram which are in the range $(1\text{–}15) \times 10^{-5}$ [4,7]. Our result does not require any contributions beyond the standard model, but it is an order of magnitude larger than would be expected [5] if the penguin diagram were not present. This is strong evidence for the existence of the penguin diagram.

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* Permanent address: INP, Novosibirsk, Russia.
† Permanent address: Carleton University, Ottawa, Canada K1S 5B6.

[1] M.K. Gaillard and B.W. Lee, Phys. Rev. Lett. **33**, 108 (1974); G. Altarelli and L. Maiani, Phys. Lett. **52B**, 351 (1974); J. Ellis, M.K. Gaillard, and D.V. Nanopoulos, Nucl. Phys. **B100**, 313 (1975); A.I. Vainshtein, V.I. Zakharov, and M.A. Shifman, Pis'ma Zh. Eksp. Teor. Fiz. **22**, 123 (1975) [JETP Lett. **22**, 55 (1975)].

[2] F. Gilman and M.B. Wise, Phys. Lett. **83B**, 83 (1979).

[3] B.A. Campbell and P.J. O'Donnell, Phys. Rev. D **25**, 1989 (1982); M. Bander, D. Silverman, and A. Soni, Phys. Rev. Lett. **43**, 242 (1979). For a review, see J. Rosner, Enrico Fermi Institute Report No. EFI 90-63, 1990 (unpublished).

[4] S. Bertolini, F. Borzumati, and A. Masiero, Phys. Rev. Lett. **59**, 180 (1987); N.G. Deshpande *et al.*, Phys. Rev. Lett. **59**, 183 (1987); B. Grinstein, R. Springer, and M.B. Wise, Phys. Lett. B **202**, 138 (1988); R. Grigjanis *et al.*, Phys. Lett. B **213**, 355 (1988); A. Ali and C. Greub, Z. Phys. C **49**, 431 (1991).

[5] N.G. Deshpande *et al.*, Phys. Lett. B **214**, 467 (1988); P.Colangelo *et al.*, Z. Phys. C **45**, 575 (1990).

[6] S. Bertolini *et al.*, Nucl. Phys. **B353**, 591 (1991); J.L. Hewett, Phys. Rev. Lett. **70**, 1045, (1993); V. Barger *et al.*, Phys. Rev. Lett. **70**, 1368 (1993).

[7] T. Altomari, Phys. Rev. D **37**, 677 (1988); C.A. Dominguez *et al.*, Phys. Lett. B **214**, 459 (1988); N.G. Deshpande *et al.*, Z. Phys. C **40**, 369 (1988); T.M. Aliev *et al.*, Phys. Lett. B **237**, 569 (1990); P.J. O'Donnell and H. Tung, Phys. Rev. D **44**, 741 (1991); A. Ali and C. Greub, Phys. Lett. B **259**, 182 (1991); A. Ali, T. Ohl, and T. Mannel, Phys. Lett. B **298**, 195 (1993).

[8] We use K^* to denote $K^*(892)$ from here on.

[9] Y. Kubota *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 66 (1992).

[10] G. Fox and S. Wolfram, Phys. Rev. Lett. **41**, 1581 (1978).

[11] $S_\perp$ is defined as the sum of the magnitudes of the momenta transverse to the photon direction, summed over all particles more than 45° away from the photon axis, divided by the sum of the magnitudes of the momenta of all particles except the photon.

[12] This is $25.4 \times 1.464 + 0.464$, where 0.464 is the scale factor between off-resonance and on-resonance data samples.
[13] The Poisson probability that a mean of 1.1 gives rise to 8 or more events is 2.0×10^{-5}, but this estimate of significance does not consider the statistical error on the background, while the procedure with binomial probability does.
[14] Cuts that differ are at least 5 tracks, $|\cos\theta_{K\pi}| < 0.85$, $|\cos\theta_{\rm thr}| < 0.85$, $|\cos\theta_B| < 0.80$, $|\Delta E| < 0.75$, $R_2 < 0.35$, and no cuts on $S_\perp$, R_2', or $|\cos\theta'|$.
[15] The likelihood analysis is described in Cornell Laboratory of Nuclear Studies Report No. CLNS 93/1212 (unpublished).
[16] The binomial probabilities for continuum plus $B\overline{B}$ backgrounds fluctuating up to the numbers of observed signal events are larger than the probabilities for continuum background alone by at most a factor of 4 for the $K^{*0}\gamma$ mode, and a factor of 1.4 for the $K^{*-}\gamma$ modes.

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