11

The Fifth Quark

Discovery of the Υ and the B meson, 1977–1987.

The discovery of the J/ψ and charmed quark seemed to complete a family of fermions, (c, s, ν_μ, μ), entirely analogous to (u, d, ν_e, e). If this pattern were indicative, then the τ and its neutrino presaged a new pair of quarks. Both e^+e^- annihilation and hadronic production of lepton pairs, the techniques that had uncovered the charmed quark, were extended in the search for the next quark.

Leon Lederman and his co-workers **(Ref. 11.1)** pressed the search for peaks in the $\mu^+\mu^-$ spectrum to high energies by studying the collisions of 400 GeV protons on nuclear targets at Fermilab. Their apparatus was a double-arm spectrometer set to measure $\mu^+\mu^-$ pairs with invariant masses above 5 GeV with a resolution of 2%. Hadrons were eliminated by using long beryllium filters in each arm. In mid 1977, a clear, statistically significant $\mu^+\mu^-$ peak was observed in the 9.5 GeV region with an observed width of about 1.2 GeV. A more detailed analysis showed better agreement with two peaks at 9.44 and 10.17 GeV, respectively, which were given the names Υ and Υ'. It soon became evident that this was a repetition of the J/ψ and ψ' story.

With the help of an energy upgrade, in May 1978 two groups at the DORIS e^+e^- storage ring at DESY were able to observe the Υ in the PLUTO and DASP II detectors. The results of the experiments are reproduced here (Refs. **11.2**, 11.3) and in Figure 11.1. The determination of the mass of the resonance was greatly improved with the result $M_\Upsilon = 9.46 \pm 0.01$ GeV. Moreover, the observed width was limited only by the energy spread of the beams, so that it was less than 1/100 as much as that observed in hadronic production. Just as for the J/ψ, it was possible to infer the partial width for $\Upsilon \to e^+e^-$ from the area under the resonance curve, with the result $\Gamma_{e^+e^-}(\Upsilon) = 1.3 \pm 0.4$ keV. Using nonrelativistic potential models derived from the ψ system and the assumption that the potential was independent of the quark type, it was possible to predict the wave function at the origin and thus $\Gamma_{e^+e^-}(\Upsilon)$ for the cases of charge $-1/3$ and $+2/3$. The comparison indicated that the new quark had charge $-1/3$ rather than $+2/3$. The new quark was dubbed the b for "bottom," reflecting the practice of writing the quark pairs (u, d) and (c, s) with the charge $-1/3$ beneath the charge $2/3$ quark. Thus the sixth quark is referred to as t or "top."

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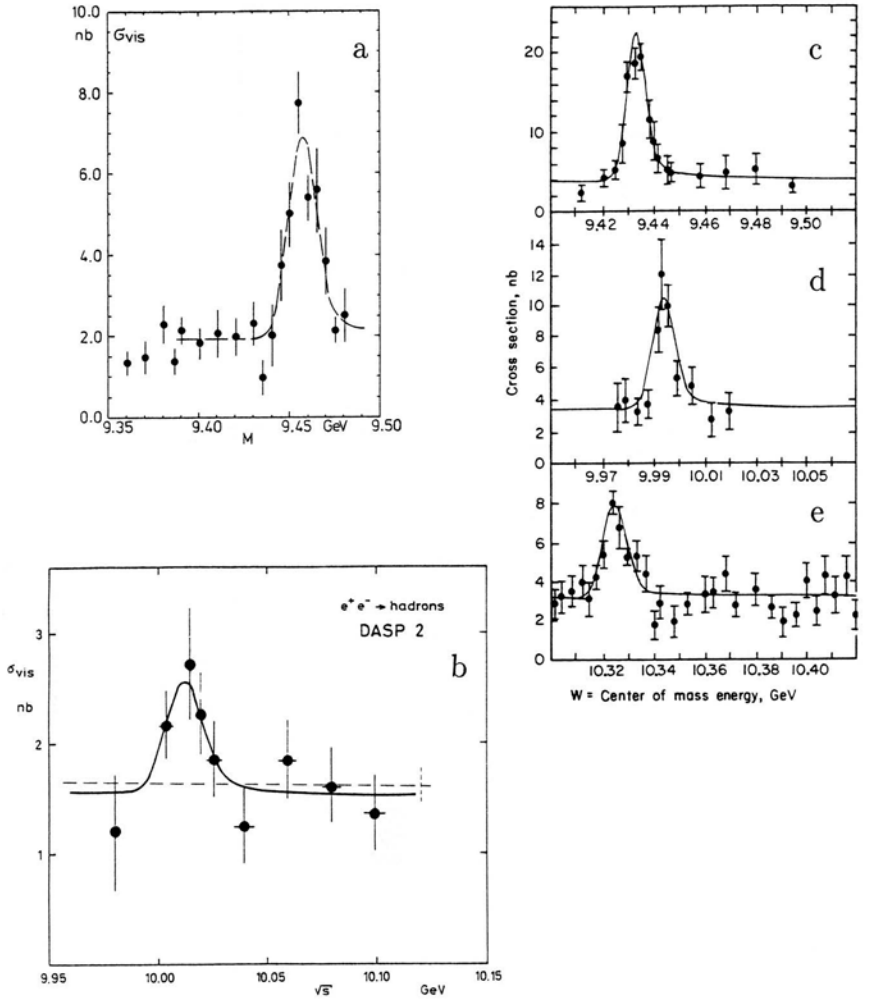


Figure 11.1. Measurements of the e^+e^- cross section at the lower Υ states. Measurements from the DASP II experiment at DORIS show (a) the Υ and (b) the Υ' (Ref. 11.3). Measurements by the CLEO group at CESR show (c) the Υ, (d) the Υ', and (e) the Υ''. Discrepancies between the mass measurements by the two groups were later resolved (Ref. 11.5).

After additional cavities were added to increase the energy of the DORIS ring, DASP II and the DESY–Heidelberg sodium-iodide and lead-glass detector were able to observe the Υ' (Refs. 11.3, **11.4**). The $\Upsilon' - \Upsilon$ splitting was found to be very nearly the same as that for $\psi' - \psi$.

By 1980, the Cornell Electron Storage Ring (CESR) with its two detectors, CLEO and CUSB, became operational. They both observed the Υ and Υ', and additional resonances, Υ'' and Υ''' (Refs. 11.5, 11.6, 11.7, **11.8**). The first three states, with masses 9.460, 10.023,

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and 10.355 GeV, are narrow, with observed widths consistent with the beam spread of the machine. They are analogous to the ψ and ψ', and correspond to 1^3S_1, 2^3S_1, and 3^3S_1 states of a $b\overline{b}$ system. Figure 11.1 shows the Υ and Υ' as observed by DASP II and the Υ, Υ', and Υ'' as observed by CLEO. The Υ''' at 10.577 GeV is a broader state, like the $\psi(3772) = \psi''$, and is interpreted as the 4^3S_1 state, lying above the threshold for $B\overline{B}$ production, where B represents a meson containing a $\overline{b}$ quark and a u or d quark. Thus $B^+ = \overline{b}u$, $B^0 = \overline{b}d$, $B^- = b\overline{u}$, $\overline{B}^0 = b\overline{d}$.

The existence of a series of s-wave bound states required that there be p-wave states as well. These were observed through radiative transitions from the s-wave states, $\Upsilon' \rightarrow \chi_b\gamma$, where χ_b represents a $C = +1$, $P = +1$ p-wave state. Evidence was obtained from the inclusive photon spectrum, $\Upsilon' \rightarrow \gamma +$ anything, and from the cascade $\Upsilon' \rightarrow \gamma\chi_b$, $\chi_b \rightarrow \gamma\Upsilon$, $\Upsilon \rightarrow l^+l^-$, where l represents e or μ. Measurements were carried out by CUSB and CLEO at CESR and by the Crystal Ball at DORIS II after the detector was shipped from Stanford to Hamburg. In Figure 11.2 some results from the Crystal Ball are shown.

What is the role of the b quark in weak interactions? Beta decay is described at the quark level by the transition $d \rightarrow ue^-\overline{\nu}$. Positron emission is the result of $u \rightarrow de^+\nu$. The strangeness-changing semileptonic weak decays (e.g. $\Lambda \rightarrow pe\overline{\nu}$) are described by $s \rightarrow ue^-\overline{\nu}$ whose inverse is $u \rightarrow se^+\nu$. The Cabibbo hypothesis is that the weak current is really $u \rightarrow (\cos\theta_c d + \sin\theta_c s)$. As discussed in Chapter 9, the introduction of a fourth

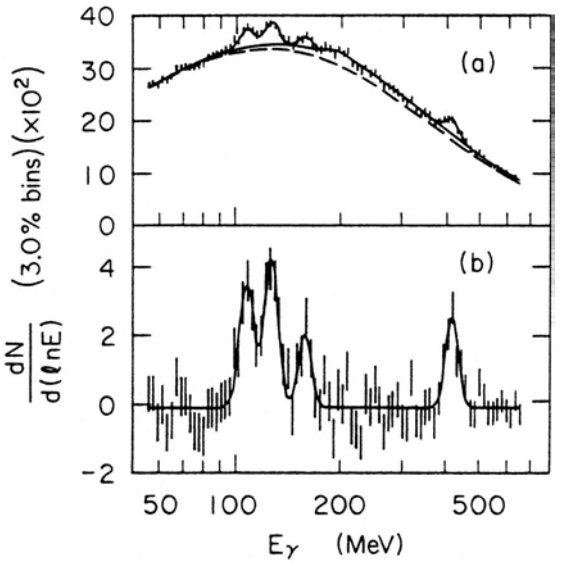


Figure 11.2. The photon spectrum from Υ' decays obtained by the Crystal Ball Collaboration at DORIS II. A triplet of lines corresponding to $\Upsilon' \rightarrow \gamma\chi_b(^3P_{2,1,0})$ is seen between 100 and 200 MeV. The decays $\chi_b \rightarrow \gamma\Upsilon$ produce the unresolved signal between 400 and 500 MeV [R. Nernst *et al.*, *Phys. Rev. Lett.* **54**, 2195 (1985)].

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quark makes the Cabibbo angle into a rotation, with the current described by

$$\begin{pmatrix} \overline{u} & \overline{c} \end{pmatrix} \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}. \tag{11.1}$$

The V-A structure $\gamma_\mu(1-\gamma_5)$ has been suppressed for clarity. The 2×2 matrix can be viewed either as a rotation of the charge $-1/3$ quarks or of the charge $+2/3$ quarks, though by convention it is usually the charge $-1/3$ quarks that are subjected to rotation.

With the discovery of the b quark it was apparent that the Cabibbo matrix would have to be expanded to a 3×3 matrix. Indeed this possibility had been anticipated by M. Kobayashi and T. Maskawa before the discovery of even the charmed quark. They observed that if there were a third generation, that is a third pair like (u, d) and (c, s), the 3×3 mixing matrix would allow for CP violation.

In order to provide for CP violation, we need a complex term in the interaction $J_\mu^\dagger J^\mu$ where $J_\mu = \overline{U}\gamma_\mu V(1-\gamma_5)D$ is the weak current. If there are n families, U represents the column of n charge $+2/3$ quarks and D the column of n charge $-1/3$ quarks. The matrix V is unitary and has n^2 complex or $2n^2$ real parameters. Unitarity imposes the conditions $V_{ij}V_{kj}^* = \delta_{ik}$, which give $n(n-1)/2$ complex constraints for $i \neq k$ and n real constraints for $i = k$. Altogether there are n^2 remaining free parameters in V.

It is possible to eliminate some of the complex phases in V by redefining the phases of the $2n$ quark fields. Changing all of the fields by the same phase changes nothing so $2n-1$ phases from V can be eliminated in this way. Thus the number of real parameters characterizing V is $n^2-2n+1 = (n-1)^2$. For two families this gives just one parameter, which is the Cabibbo angle. For three families there are four parameters. Now if V were purely real it would be a 3×3 rotation matrix, which is determined by three real parameters. Thus the fourth parameter of V must necessarily introduce a complex component into V, one that cannot be absorbed into a redefinition of the quark fields.

We can represent the Cabibbo–Kobayashi–Maskawa (CKM) matrix by

$$\begin{bmatrix} \overline{u} & \overline{c} & \overline{t} \end{bmatrix} \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}. \tag{11.2}$$

In principle, the squares of the various matrix elements can be measured by observing a variety of weak decays. The comparison of nuclear beta decay and muon decay indicates $|V_{ud}| \approx 0.97$, while the strangeness-changing decays give $|V_{us}| \approx 0.22$. These two are just $\cos\theta_c$ and $\sin\theta_c$ in the Cabibbo scheme. The production of charmed particles in neutrino (or antineutrino) nucleus scattering is proportional to $|V_{cd}|^2$. Data from the CDHS Collaboration led to a value $|V_{cd}| = 0.21 \pm 0.03$. The decay of mesons containing b quarks is controlled by V_{ub} and V_{cb}. The relative size of these elements determines the ratio of the semileptonic decays $\Gamma(b \to ul\nu)/\Gamma(b \to cl\nu)$. Because of the greater phase space available, the $b \to ul\nu$ decay produces leptons with higher momentum than does $b \to cl\nu$.

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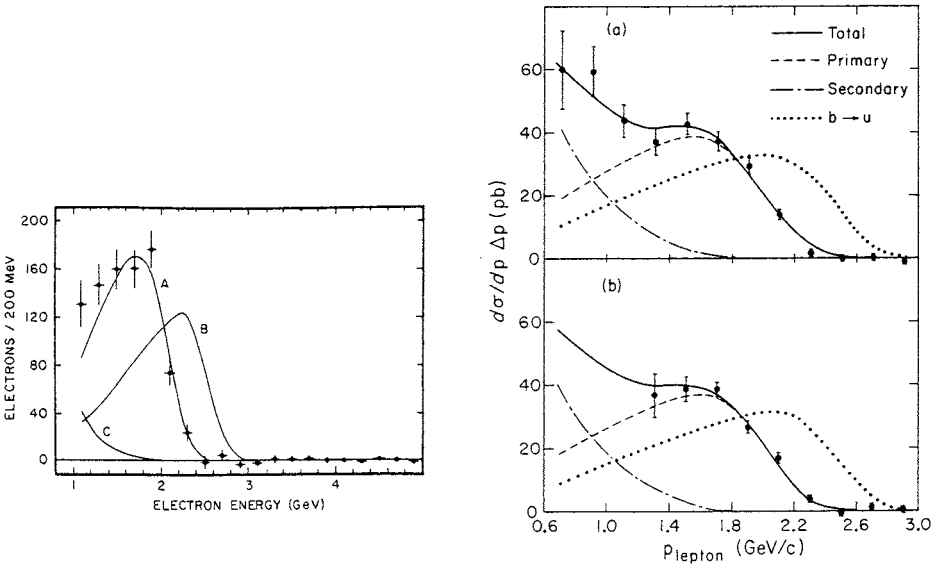


Figure 11.3. Lepton spectra for semileptonic B meson decays. Left, CUSB data from CESR together with the curves expected for (A) $b \to cev$, (B) $b \to uev$, and (C) $b \to cX$, $c \to sev$ [C. Klopfenstein *et al.*, *Phys. Lett.* **130B**, 444 (1983)]. Right, data from CLEO, also taken at CESR. The upper figure is for electrons and the lower for muons. The solid curves are predictions without any $b \to ulv$ while the dotted curves are predictions for purely $b \to ulv$ [A. Chen *et al.*, *Phys. Rev. Lett.* **52**, 1084, (1984)]. All the figures indicate that $\Gamma(b \to clv) >> \Gamma(b \to ulv)$. This Cabibbo–Kobayashi–Maskawa suppression is analogous to the Cabibbo suppression observed in the decays of charmed particles to states without strangeness.

In Figure 11.3 we show data from CUSB and CLEO for the lepton spectra. The evidence overwhelmingly supports $b \to clv$ as the dominant mode. Data indicated that

$$\frac{\Gamma(b \to ulv)}{\Gamma(b \to clv)} < 0.08. \tag{11.3}$$

Correcting for the difference in phase space available for the two modes gives

$$|V_{ub}/V_{cb}| < 0.22. \tag{11.4}$$

Actual identification of B meson decays promised to be a formidable task, even though some lessons had been learned from the study of charm. By focusing on the 4^3S_1 Υ''' it was possible to obtain a good sample of $\Upsilon(4S) \to B\overline{B}$ events **(Ref. 11.9)**. The technique used was to identify candidates for D^0 s and D^{*+} s, using only entirely charged decay modes, and combine these with either one or two charged pions. In analogy with the fundamental decay $c \to s$ leading to $D^+ \to K^-\pi^+\pi^+$, the transition $b \to c$ produces $B^- \to D^+\pi^-\pi^-$, $D^{*+}\pi^-\pi^-$. The combinations $B \to D\pi$ and $B \to D\pi\pi$ were required to produce B s with energy equal to the beam energy since the decay is $\Upsilon(4S) \to B\overline{B}$. An accumulation of events for mass near 5.275 GeV suggested the observation of exclusive B

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decays. Ultimately the branching fractions for these modes were determined to be an order of magnitude or more smaller than in this first report.

The CUSB Collaboration observed photons of energy about 50 MeV associated with $B\overline{B}$ production at energies above the $\Upsilon(4S)$, which they ascribed to the production of $B^*\overline{B}$ and the subsequent decay $B^* \to B\gamma$. The splitting between the spin-1 B^* and the pseudoscalar B was determined to be $52 \pm 2 \pm 4$ MeV. Some of the CUSB data are shown in Figure 11.4. Precision measurements later by CUSB and CLEO and by the LEP experiments, to be discussed in Chapter 12, refined the mass difference to 45.78 ± 0.35 MeV.

Semileptonic decays were exploited in several experiments to obtain B-enriched samples of events for B lifetime measurements. The Mark II Collaboration at PEP built a vertex detector using a precision drift chamber located close to the interaction point, which allowed measurements of the distance of closest approach of the lepton tracks to the beam–beam collision region. The experiment found a B lifetime of $1.2^{+0.45}_{-0.36} \pm 0.30$ ps.

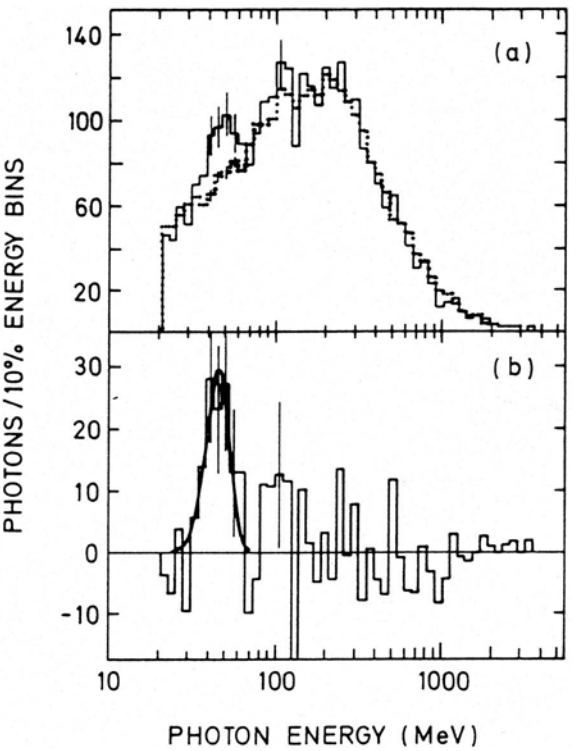


Figure 11.4. The photon energy spectrum obtained by the CUSB Collaboration for events with high energy leptons and thrust less than 0.88 (indicative of events more spherical than the ordinary two-jet events produced in e^+e^- annihilation). These criteria signal the presence of B mesons. The e^+e^- c.m. energy for the solid histogram in (a) is 10.62 – 25 GeV, above the $B^*\overline{B}$ threshold. The dotted histogram in (a) was taken at the $\Upsilon(4S)$, below the $B^*\overline{B}$ threshold. In (b) the spectrum with the background subtracted shows a line near 50 MeV, ascribed to $B^* \to B\gamma$ [K. Han *et al.*, *Phys. Rev. Lett.* **55**, 36 (1985)].

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A contemporaneous measurement by the MAC experiment at PEP found a similar result: $1.8 \pm 0.6 \pm 0.4$ ps. The surprisingly large value was confirmed subsequently by the DELCO experiment at PEP and TASSO and JADE experiments at PEP and PETRA. This unexpectedly long lifetime indicated that the V_{cb} matrix element is quite small, between 0.030 and 0.062. From the unitarity of the KM matrix, we conclude that $|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$, so $|V_{cs}| \approx 0.97$, assuming there are just three generations.

The pattern of decreasing CKM matrix elements – diagonal, first generation to second generation, second generation to third generation, first generation to third generation – led Lincoln Wolfenstein to propose a particularly convenient representation for the the matrix:

$$V = \begin{bmatrix} 1 - \lambda^2/2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1 - \rho - i\eta) & -\lambda^2 A & 1 \end{bmatrix} \tag{11.5}$$

where λ, ρ, η, and A are real parameters. This satisfies unitarity up to corrections of order λ^4 in the imaginary part and of order λ^5 in the real part.

The CKM picture predicts that the dominant B meson decays are due to $b \to c\overline{u}d$ and $b \to c\overline{c}s$. The CLEO Collaboration at CESR and ARGUS Collaboration at the DORIS storage ring at DESY identified decay modes modes of both categories. Each of the numerous final states of the form $D\pi$, $D^*\pi$, $D^*\pi\pi$, etc. accounts for less than 2% of the total, but together they constitute the vast majority of decays. The final state like $c\overline{d}\overline{c}s$ can appear as $D^+D_s^-$ or alternatively as $J/\psi K^0$, and similar states with additional pions. The decay to $J/\psi K_S^0$ with a branching fraction of about 0.45×10^{-3} has a spectacular signal when the J/ψ decays to e^+e^- or $\mu^+\mu^-$ and was destined to play a central role in future studies.

An upgraded detector, CLEO II, featured greatly improved tracking and particle identification. As the number of accumulated events increased, it became possible to search for rarer decays. Of particular importance was the observation in 1993 of $B^0 \to K^{*0}\gamma$ and $B^+ \to K^{*+}\gamma$ (**Ref. 11.10**). The decay $B \to K\gamma$ is forbidden since the final state necessarily has a component of angular momentum along the γ direction of ± 1. The signal was isolated by requiring the photon to have a laboratory energy between 2.1 GeV and 2.9 GeV and demanding that there be a $K\pi$ with an invariant mass consistent with that of the K^*. The dominant background, from non $B - \overline{B}$ events, was suppressed by excluding events with a two-jet appearance, characteristic of the production of lower mass quarks. The final signals were 6.6 ± 2.8 events in the $B^0 \to K^{*0}\gamma$ channel and 4.1 ± 2.3 in the $B^+ \to K^{*+}\gamma$ channel, resulting in branching fractions $(4.0 \pm 1.7 \pm 0.8) \times 10^{-5}$ and $(5.7 \pm 3.1 \pm 1.1) \times 10^{-5}$. The significance of these decays is that they establish the existence of the whimsically named "penguin" process, shown in Fig. 11.5.

The discovery of the b quark provided an excellent opportunity to test the models proposed to explain the phenomena associated with the charmed quark. These tests have been quite successful in a qualitative and semiquantitative way. The general spacing of bound-state levels in the two systems can be understood from a single potential. The systematics of the fine structure (the splitting of the p-wave states) is in accord with expectations. The rates for radiative decays are in general agreement with the nonrelativistic model. The b

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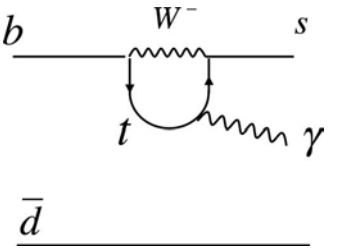


Figure 11.5. A penguin process, in which the decaying quark emits a W boson, then reabsorbs it, is responsible for the class of decays $b \to s\gamma$, and in particular for $B \to K^*\gamma$. Analogous decays occur with the γ replaced by a gluon. Since the gluon carries no isospin, the penguin process $s \to dg$ is purely $\Delta I = 1/2$ and explains, in part, the $\Delta I = 1/2$ rule. All charge 2/3 quarks contribute to the loop, but the t quark makes the dominant contribution because of its large mass.

quark provided, as well, a possible explanation for CP violation through the complex phase in the Cabibbo–Kobayashi–Maskawa matrix.

Exercises

11.1 Suppose the quark–antiquark potential obeys the power law $V(r) = ar^{\nu}$. Show that the binding energies vary with the quark mass as $E \propto m^{-\nu/(\nu+2)}$ and that the density at the origin $|\phi(0)|^2$ for an s-wave state varies as $m^{3/(\nu+2)}$. Given that the splitting $\Upsilon' - \Upsilon$ is nearly identical to that for $\psi' - \psi$, predict $\Gamma(\Upsilon \to e^+e^-)$ from $\Gamma(\psi \to e^+e^-)$ if the charge of the new quark is $-1/3$ or is $+2/3$.

11.2 Show that $|\phi(0)|^2$, the s-wave wave function at the origin squared, is related to the average force by

$$|\phi(0)|^2 = \frac{m}{2\pi} < F > .$$

Hint: write the Schrödinger wave equation for the radial wave function, u and multiply by u'. Integrate the result from $r = 0$ to $r = \infty$.

11.3 Use the results of Exercise 6.5 to determine the e^- spectrum in the decays $b \to ce^-\overline{\nu}$, $b \to ue^-\overline{\nu}$. Take $m_b = 5$ GeV, m_c= 1.5 GeV, m_u= 0.3 GeV.

11.4 * Suppose that the $b\overline{b}$ or $c\overline{c}$ interaction can be represented approximately by a non-relativistic Schrödinger equation:

$$\left[-\frac{1}{2m_{red}}\nabla^2 + V(r)\right]\psi = E\psi$$

where $m_{red} = m/2$ is the reduced mass. Then the energy levels are spin-independent so $^3S_1$ and $^1S_0$ are degenerate, as are $^3P_{2,1,0}$ and $^1P_1$, etc. Now consider as perturba-

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tions the spin dependent forces

$$\mathbf{L}\cdot\mathbf{S}\,V_{so}(r)$$
$$\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2}\,V_{spin-spin}(r)$$
$$\frac{3\,\boldsymbol{\sigma_1}\cdot\mathbf{r}\,\boldsymbol{\sigma_2}\cdot\mathbf{r}-\boldsymbol{\sigma_1}\cdot\boldsymbol{\sigma_2}r^2}{r^2}V_{tensor}(r)\equiv S_{12}V_{tensor}(r).$$

Here $\mathbf{S}=\frac{1}{2}(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)$ is the total spin, and $\boldsymbol{\sigma}_1$ and $\boldsymbol{\sigma}_2$ are the quark and antiquark spin operators.

a. Which degenerate states are split by each of the interactions? Which nondegenerate state are mixed by the interactions?
b. Use the relations (try to prove them, too)

$$\begin{aligned}
&<J,L=J+1,\quad S=1,M|S_{12}|J,L=J+1,\quad S=1,M>=-2\frac{L+1}{2L-1}\\
&<J,L=J,\qquad\ S=1,M|S_{12}|J,L=J,\qquad\ S=1,M>=+2\\
&<J,L=J-1,\quad S=1,M|S_{12}|J,L=J-1,\quad S=1,M>=-2\frac{L}{2L+3}
\end{aligned}$$

to analyze the observed splittings of the ^3P states in the Υ and ψ systems. Here $|J,L,S,M>$ is a state with total angular momentum J, orbital angular momentum L, total spin angular momentum S, and $J_Z=M$. [See J. D. Jackson, "Lectures on the New Particles" in *Proc. of Summer Institute on Particle Physics*, Stanford, CA, Aug. 2-13, 1976, M. Zipf, ed.]

11.5 * The relation between the standard relativistic Lorentz invariant amplitude, $\mathcal{M}$, (the usual Feynman rules generate $-i\mathcal{M}$) and the conventional scattering amplitude of potential theory is

$$f=-\frac{1}{8\pi\sqrt{s}}\mathcal{M}$$

where s is the square of the center-of-mass energy. The center-of-mass differential cross section is $d\sigma/d\Omega=|f|^2$. In potential theory, the Born value for f is

$$f=-\frac{m}{2\pi}\int d^3r e^{-i\mathbf{p}'\cdot\mathbf{r}}V(r)e^{i\mathbf{p}\cdot\mathbf{r}}$$

where $\mathbf{p}$ and $\mathbf{p}'$ are the initial and final momenta. Two body scattering can be treated analogously with the modification $m\rightarrow m_{reduced}$. If the particles have spin 1/2, we generalize the wave function to $\psi(r)\chi_1\chi_2$, where χ_1 and χ_2 are two-component spinors. Thus

$$f=-\frac{m_{red}}{2\pi}\int d^3r\,\chi_2^{\prime\dagger}\,\chi_1^{\prime\dagger}e^{-i\mathbf{p}'\cdot\mathbf{r}}V(r)e^{i\mathbf{p}\cdot\mathbf{r}}\chi_1\chi_2.$$

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Suppose $\mathcal{M}$ has the form of vector exchange but with some more general dependence on momentum transfer:

$$\mathcal{M} = \overline{u}(p_4)\gamma_\mu u(p_2)\,\overline{u}(p_3)\gamma^\mu u(p_1)\;\tilde{V}(p_1 - p_3).$$

Show that the spin dependent potential is, to leading order

$$V(r) = V_0(r) + \frac{3}{2m^2}\frac{1}{r}\frac{dV_0}{dr}\mathbf{L}\cdot\mathbf{S} + \frac{1}{12m^2}S_{12}\left(\frac{1}{r}\frac{dV_0}{dr} - \frac{d^2V_0}{dr^2}\right) + \frac{\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2}{6m^2}\nabla^2 V_0$$

where $\mathbf{S} = \frac{1}{2}(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)$ is the total spin and

$$\int d^3r\; V_0(r)e^{i\mathbf{q}\cdot\mathbf{r}} = \tilde{V}(q).$$

Further Reading

For a discussion of the Cabibbo–Kobayashi–Maskawa matrix see the article in the current edition of the *Review of Particle Physics*.

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Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

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Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

We have observed a strong enhancement at 9.5 GeV in the mass spectrum of dimuons produced in 400-GeV proton-nucleus collisions. Our conclusions are based upon an analysis of 9000 dimuon events with a reconstructed mass $m_{\mu^+\mu^-}$ greater than 5 GeV corresponding to 1.6×10^{16} protons incident on Cu and Pt targets:

$$p + (\mathrm{Cu, Pt}) \rightarrow \mu^+ + \mu^- + \text{anything}.$$

The produced muons are analyzed in a double-arm magnetic-spectrometer system with a mass resolution $\Delta m/m$ (rms) $\approx 2\%$.

The experimental configuration (Fig. 1) is a modification of an earlier dilepton experiment in the Fermilab Proton Center Laboratory.[1-3] Narrow targets (~0.7 mm) with lengths corresponding to 30% of an interaction length are employed.

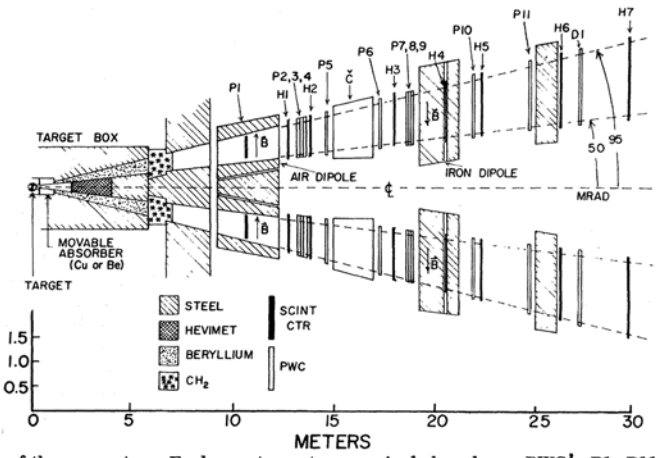


FIG. 1. Plan view of the apparatus. Each spectrometer arm includes eleven PWC's P1–P11, seven scintillation counter hodoscopes H1–H7, a drift chamber D1 and a gas-filled threshold Čerenkov counter Č. Each arm is up/down symmetric and hence accepts both positive and negative muons.

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TABLE I. Yield of muon pairs for various running conditions.

Analyzing-magnet current (A)	Target	First 30 cm absorber	No. of incident protons	No. of events $m_{\mu^+\mu^-} \geq 5$ GeV
1500	Cu	Cu	8.1×10^{15}	4093
1500	Pt	Cu	4.1×10^{15}	2076
1250	Cu	Cu	2.5×10^{15}	1891
1250	Pt	Be	1.6×10^{15}	911

Beryllium (18 interaction lengths) is used as a hadron filter, covering the 50–95-mrad (70–110° c.m.) horizontal and ± 10-mrad vertical aperture in each arm. The Be is closely packed against steel and tungsten which minimize particle leakage from outside the aperture, especially from the tungsten beam dump located 2.2 m downstream of the target. Polyethylene (1.5 m) and a 2.2-m steel collimator complete the shielding. The first 30 cm of beryllium (starting 13 cm downstream of the target center) can be remotely exchanged for 30 cm of copper.

The spectrometer dipoles deflect vertically, decoupling the production angle of each muon from its momentum determination. At full excitation (1500 A), the magnets provide a transverse momentum kick $p_t \approx 1.2$ GeV. In order to maximize the usable luminosity, no detectors are placed upstream of the magnet. Conventional proportional wire chambers (PWC's) and scintillation hodoscopes serve to define the muon trajectory downstream of the air dipole. Following the PWC's is a solid iron magnet (1.8 m long, energized to 20 kG) used to refocus partially the muons vertically and to redetermine the muon momentum to ± 15%. A threshold Čerenkov counter on each arm also helps prevent possible low-momentum muon triggers. The apparatus is ar-

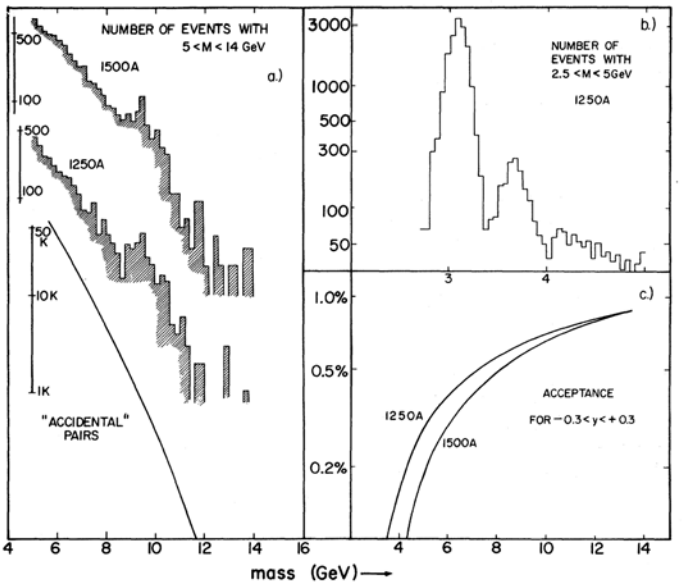


FIG. 2. (a) Dimuon yield at 1500 and 1250 A; the data with Cu and Pt targets have been combined. Also shown is the mass spectrum generated by combining two muons from different events. (b) Excess of opposite-sign over equal-sign muon pairs in the ψ, ψ' region. (c) Dimuon mass acceptance for the two excitations of the air dipole.

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ranged symmetrically with respect to the horizontal median plane in order to detect both μ^+ and μ^- in each arm.

The data sets presented here are listed in Table I. Low-current runs produced ~15 000 J/ψ and 1000 ψ' particles which provide a test of resolution, normalization, and uniformity of response over various parts of the detector. Figure 2(b) shows the 1250-A J/ψ and ψ' data. The yields are in reasonable agreement with our earlier measurements.[2]

High-mass data (1250 and 1500 A) were collected at a rate of 20 events/h for $m_{\mu^+\mu^-} > 5$ GeV using $(1.5-3)\times 10^{11}$ incident protons per accelerator cycle. The proton intensity is limited by the requirement that the singles rate at any detector plane not exceed 10^7 counts/sec. The copper section of the hadron filter has the effect of lowering the singles rates by a factor of 2, permitting a corresponding increase in protons on target. The penalty is an ~15% worsening of the resolution at 10 GeV mass. Figure 2(a) shows the yield of muon pairs obtained in this work.

At the present stage of the analysis, the following conclusions may be drawn from the data [Fig. 3(a)]:

(1) A statistically significant enhancement is observed at 9.5-GeV $\mu^+\mu^-$ mass.

(2) By exclusion of the 8.8–10.6-GeV region, the continuum of $\mu^+\mu^-$ pairs falls smoothly with mass. A simple functional form,

$$[d\sigma/dmdy]_{y=0} = Ae^{-bm},$$

with $A = (1.89 \pm 0.23)\times 10^{-33}$ cm^2/GeV/nucleon and $b = 0.98 \pm 0.02$ GeV^{-1}, gives a good fit to the data for 6 GeV $< m_{\mu^+\mu^-} <$ 12 GeV ($\chi^2 = 21$ for 19 degrees of freedom).[4,5]

(3) In the excluded mass region, the continuum fit predicts 350 events. The data contain 770 events.

(4) The observed width of the enhancement is greater than our apparatus resolution of a full width at half-maximum (FWHM) of 0.5 ± 0.1 GeV. Fitting the data minus the continuum fit [Fig. 3(b)] with a simple Gaussian of variable width yields the following parameters (B is the branching ratio to two muons):

$$\text{Mass} = 9.54 \pm 0.04 \text{ GeV},$$

$$[Bd\sigma/dy]_{y=0} = (3.4 \pm 0.3)\times 10^{-37} \text{ cm}^2/\text{nucleon},$$

with FWHM = 1.16 ± 0.09 GeV and $\chi^2 = 52$ for 27 degrees of freedom (Ref. 5). An alternative fit with two Gaussians whose widths are fixed at the resolution of the apparatus yields

$$\text{Mass} = 9.44 \pm 0.03 \text{ and } 10.17 \pm 0.05 \text{ GeV},$$

$$[Bd\sigma/dy]_{y=0} = (2.3 \pm 0.2) \text{ and } (0.9 \pm 0.1) \times 10^{-37} \text{ cm}^2/\text{nucleon},$$

with $\chi^2 = 41$ for 26 degrees of freedom (Ref. 5).

The Monte Carlo program used to calculate the acceptance [see Fig. 2(c)] and resolution of the

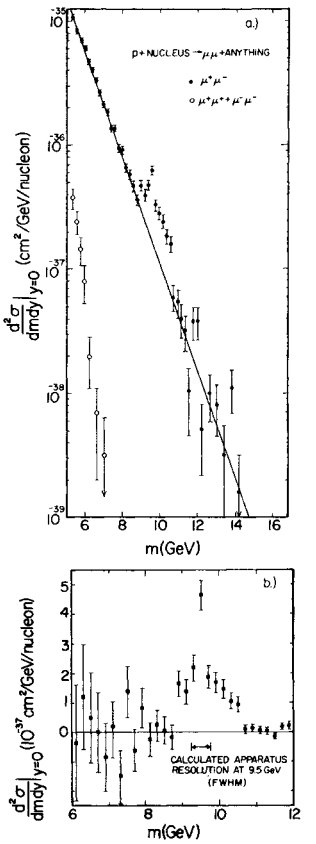


FIG. 3. (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign–dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 9–10-GeV region in more detail.

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apparatus assumed a mass, p_t, rapidity and decay angular distribution of the $\mu^+\mu^-$ pair consistent with these data and previously published dilepton searches. It also included all multiple-scattering effects in the hadron absorber and detector resolutions. The conclusions stated above are insensitive to these assumptions. In particular we note that the acceptance is relatively flat in the 9–10-GeV region.

The following checks have been made to verify the validity of the conclusions reached above:

(1) The spectrum of $\mu^+\mu^+$ and $\mu^-\mu^-$ events in Fig. 3(a) constitute an upper limit on the combined effects of accidental coincidences and hadronic decays. Misidentified $\psi \to \mu^+ + \mu^-$ decays are prevented from producing background at high mass by the remeasurement of the muon momenta both downstream by the second magnet and also by the PWC at the center of the first magnet. This is confirmed by the clean separation of the ψ and ψ' peaks in Fig. 2(a). Their widths agree with the calculated apparatus resolution.

(2) Various subsets of the data were studied in order to search for possible apparatus bias. In addition to the subsets shown in Table I, data were studied as a function of magnet polarity and magnetic bend direction. All fits showed enhancements consistent with the values quoted above.

(3) To check our analysis software (and as a further check of the apparatus), we mixed muons from different events, yielding the smooth mass spectrum shown in Fig. 2(a). The geometrical distribution of events in the 9–10-GeV region at the various detector planes in the apparatus is consistent with that of events in neighboring mass bins.

(4) The longitudinal distribution of muon-pair vertices at the target (FWHM = 16 cm) is cleanly separated from events generated in the beam dump, 220 cm downstream. A separate target-out run with 6×10^{14} incident protons produced no acceptable $\mu^+\mu^-$ candidates above 6 GeV (an equivalent run with a Cu or Pt target would have yielded about 200 events with 25 of these in the 9–10-GeV region).

In conclusion, the measured spectrum of $\mu^+\mu^-$ pairs produced in proton-nucleus collisions shows significant structure[6] in the 9–10-GeV region on an exponentially falling continuum. The structure is wider than the apparatus resolution. The 9.5-GeV enhancement and the continuum are in agreement with our previous measurements.[7]

We owe much to Ken Gray, Karen Kephart, Frank Pearsall, and S. Jack Upton for technical assistance, and to F. William Sippach for our electronic systems design. We also thank Brad Cox, William Thomas, and the staffs of the Fermilab Proton Department and Accelerator Division for their efforts. The work at Columbia University and at the State University of New York at Stony Brook was supported by the National Science Foundation, and that at the Fermi National Accelerator Laboratory by the U. S. Energy Research and Development Administration.

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[4]Cu and Pt yields were reduced to cross sections per nucleon by assuming an atomic-number dependence of $A^{1.0}$.

[5]The errors quoted on the magnitude of the continuum and resonance cross sections and the resonance masses are statistical only. Systematic normalization effects are probably less than 25% and do not affect the conclusions drawn here. Systematic errors on the mass calibration are probably less than 1%.

[6]Following Ref. 1, a reasonable designation for this enhancement is Υ(9.5).

[7]We note that the 9–10-GeV mass bin in the e^+e^- and $\mu^+\mu^-$ spectra previously published by this group (Ref. 3) shows an excess of events, consistent with the statistically more significant results here. If we add our preliminary unpublished e^+e^- data to our published e^+e^- yield (Ref. 1), the spectrum contains a cluster of 6 e^+e^- events near 9.5 GeV where ~5 events would be expected on the assumption of μ-e universality.

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Volume 76B, number 2 PHYSICS LETTERS 22 May 1978

OBSERVATION OF A NARROW RESONANCE FORMED IN e^+e^- ANNIHILATION AT 9.46 GeV

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An experiment using the PLUTO detector has observed the formation of a narrow, high mass, resonance in e^+e^- annihilations at the DORIS storage ring. The mass is determined to be 9.46 ± 0.01 GeV which is consistent with that of the Upsilon. The gaussian width σ is observed as 8 ± 1 MeV and is equal to the DORIS energy resolution. This suggests that the resonance is a bound state of a new heavy quark-antiquark pair. An electronic width Γ_{ee} = 1.3 ± 0.4 keV was obtained. In standard theoretical models, this favors a quark charge assignment of −1/3.

The existence of the Upsilon particle recently discovered in proton interactions by Herb et al. [1] is of considerable interest. Not only is it exceptionally massive (9.4 GeV), but its observed decay to muon pairs implies that it is probably quite narrow. The observed width of about 500 MeV is consistent with their experimental resolution. The situation is analogous to that of the J/ψ and suggests that the Upsilon is a bound state of a new heavy quark-antiquark pair [2]. We report on an experiment, which has observed the formation of the Upsilon, using the PLUTO detector at the electron positron storage ring DORIS. It sets a substantially lower upper limit on the total width. From our measurement of the Upsilon production cross section we obtain Γ_{ee} – its electronic partial width. Γ_{ee} in turn may be used to determine the charge of the constituent quark-antiquark pair.

The energy of the storage ring DORIS has recently

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Volume 76B, number 2 PHYSICS LETTERS 22 May 1978

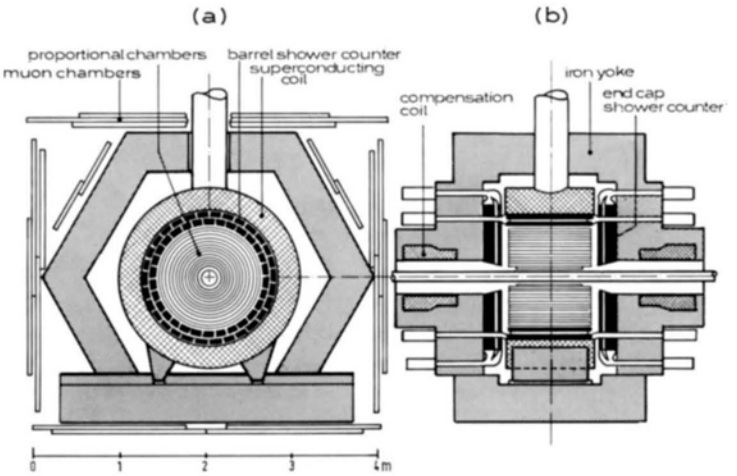


Fig. 1. Schematic views of the PLUTO detector. Sections (a) perpendicular to and (b) containing the beam axis.

been upgraded to make possible measurements for center of mass energies up to 10 GeV. In order to achieve this goal the machine was modified to operate in a single ring, single bunch mode. The detector PLUTO [3], see fig. 1, has also been improved by installing a cylindrical array (barrel) of shower counters (8.6 radiation lengths) and proportional tubes and by covering the ends of the cylindrical detector by a second set of shower counters (10.5 radiation lengths) and proportional wire chambers. These improvements bring the total gamma and electron coverage to approximately 94% of 4π. Cylindrical proportional wire chambers covering 92% of 4π and operating in a field of 1.69 T are used for track recognition and momentum measurement. The detector was triggered either by the presence of tracks in the wire chambers, by sufficient detected energy in the shower counters, or by a combination of the two. The luminosity was monitored by a set of shower counter telescopes which record Bhabha scatters at an angle to the beam of about 7°. We find good agreement between this monitor and the rate of large angle Bhabhas observed in the barrel shower counters. Reference points were taken at center of mass energies of 9.20 GeV and 9.30 GeV. The resonance search was made from 9.35 GeV upwards in steps of either 5 or 10 MeV. The average integrated luminosity per 10 MeV was $\sim 20\ \mathrm{nb}^{-1}$.

In order to obtain substantial background reduction and fast feedback during the energy scan we analysed in the first off-line pass only those events with energy equivalent in the shower counters greater than 2 GeV. The bulk of the data reported here are subject to this restriction. Cosmic ray background was further reduced by making use of the bunch crossing time.

To obtain the total cross section for hadron production, we selected events with at least two charged tracks having a vertex within the prescribed interaction region. QED events were removed by the combined usage of a coplanarity cut and a shower recognition algorithm. To remove beam gas interactions cuts were imposed on the total visible energy and the missing mass in the final state. Remaining beam gas events were removed if they showed a substantial excess of positive charge. The effect of the energy cut was studied by analysing a subsample completely. We estimate that 51% of the hadronic events are being detected and analysed in the first off-line step.

Fig. 2 shows the total cross section for hadron production as a function of the center of mass energy. In addition to the statistical errors, shown in the figure, there is an overall estimated systematic uncertainty of 20%. Radiative corrections have not been applied. A resonance is seen in the region of 9.5 GeV. Fitting a gaussian to the peak on a 1/s background we obtain a

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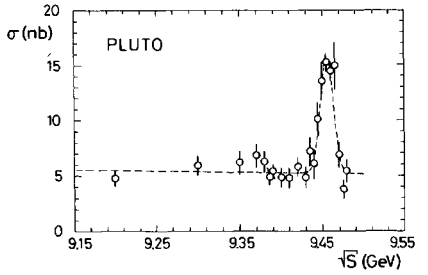


Fig. 2. Total cross section for hadron production in e^+e^--annihilation as a function of center of mass energy. There is an additional systematic error (not shown) of 20%. Contributions from the heavy lepton are included.

mass of 9.46 ± 0.01 GeV. The error in mass comes from the 0.1% uncertainty in the absolute calibration of DORIS energy. Our mass value is in agreement with the value of 9.40 GeV measured by Innes et al. [1], when their quoted systematic uncertainty of less than 1% is considered [4]. The gaussian width σ is 7.8 ± 0.9 MeV which is consistent with the theoretically estimated energy spread [5] of 8 MeV in the storage ring. The actual resonance width is therefore less than 18 MeV (FWHM). This adds weight to the supposition that the Upsilon is a bound state of a new quark-antiquark pair.

The relation between the integral over the cross section for resonant hadronic production σ_h, the resonance mass M_R, the electronic width Γ_{ee}, the hadronic width Γ_h, and the total width Γ_{tot} is given by

$$\int \sigma_h \, dM = \frac{6\pi^2}{M_R^2} \frac{\Gamma_{ee}\Gamma_h}{\Gamma_{tot}}.$$

On the standard assumption that the hadronic width dominates the total width, ($\Gamma_h \approx \Gamma_{tot}$) one obtains Γ_{ee} directly from the measured integral and the mass. Our result is $\Gamma_{ee} = 0.8 \pm 0.2$ keV. An estimate of the radiative corrections raises this to 1.3 ± 0.4 keV. Models for quark binding in nonrelativistic potentials relate Γ_{ee} to the charge of the constituent quarks. In the standard model [6] our measurement implies a charge of $-1/3$ for the new heavy quark.

In summary we have observed the formation of a high mass, narrow resonance in e^+e^- annihilation at DORIS. We determine the mass to be (9.46 ± 0.01) GeV and therefore associate it with the Upsilon resonance seen by Herb et al. [1]. We observe a gaussian width of 7.8 MeV which is consistent with the energy resolution of the storage ring and supports the interpretation that the Upsilon is a bound state of a new heavy quark-antiquark pair. Our determination of Γ_{ee} as 1.3 ± 0.4 keV favors an assignment of $-1/3$ for the charge of the new quark.

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Volume 78B, number 2,3 PHYSICS LETTERS 25 September 1978

OBSERVATION OF A NARROW RESONANCE AT 10.02 GeV IN e^+e^- ANNIHILATIONS

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The Υ′ state has been observed as a narrow resonance at $M(\Upsilon') = 10.02 \pm 0.02$ GeV in e^+e^- annihilations, using a NaI and lead-glass detector in the DORIS storage ring at DESY. The ratio $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ of electronic, hadronic, and total widths has been measured to be 0.32 ± 0.13 keV. The parameters of the Υ particle have also been determined to be $M(\Upsilon) = 9.46 \pm 0.01$ and $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot} = 1.04 \pm 0.28$ keV. The mass difference is $M(\Upsilon') - M(\Upsilon) = 0.56 \pm 0.01$ GeV.

The two massive particles Υ(9.4) and Υ′(10.0) discovered by Herb et al. [1] were produced in 400 GeV proton nucleus collisions and were observed in their $\mu^+\mu^-$ decay with a mass resolution of about 200 MeV (rms). It was thought that they could be bound states of a quark–antiquark pair in analogy to the J/Ψ(3.1) and Ψ′(3.7) states, but composed of a new type of quark. In this context it is essential to establish a narrow width, and to measure the mass difference accurately. In the framework of such quarkonium models [2], the charge of the new quark is related to the electronic partial widths Γ_{ee} which are, therefore, of considerable interest. These quantities can most conveniently be determined if the Υ resonances are formed in e^+e^- annihilations, a process expected to occur since they decayed into $\mu^+\mu^-$.

This had prompted the efforts of the DORIS machine group to extend the energy range of the storage ring beyond its original limits. DORIS was modified to operate as a single-ring single-bunch machine, and in April 1978 it had reached energies up to 9.6 GeV. Using this modified machine the existence of the Υ resonance was confirmed by the PLUTO [3] and DASP II [4] groups. The mass of the resonance was found to be 9.46 ± 0.01 GeV, and $\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}$ was measured to be 1.3 ± 0.4 keV. In July 1978 additional cavities were installed in the DORIS ring, which allowed a search for the Υ′ resonance expected above 10 GeV.

Here we present the results of measurements performed with the DESY–Heidelberg NaI and lead-glass detector in June and August 1978. During the first period the Υ resonance was measured, whereas during the second period the 10 GeV region was scanned and the Υ′ resonance observed.

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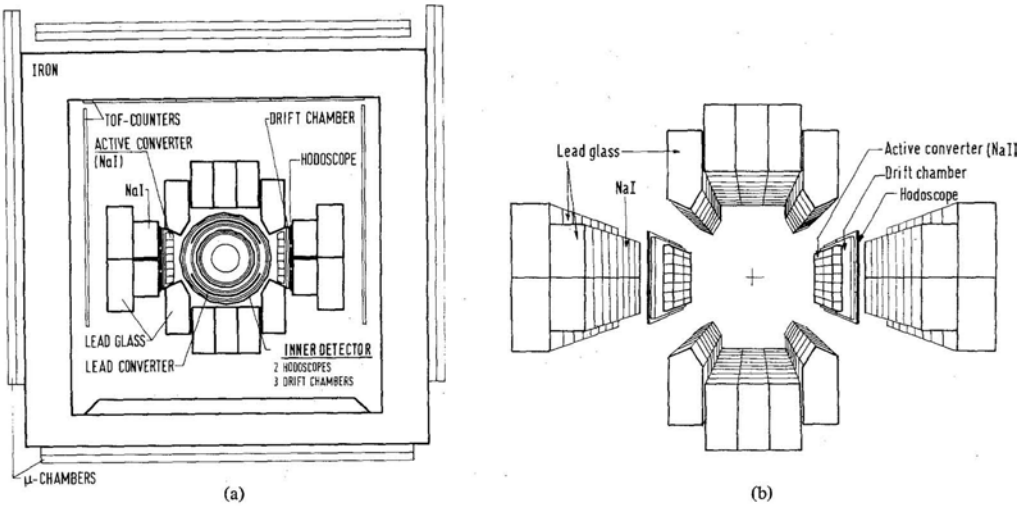


Fig. 1. Layout of the NaI lead-glass detector: (a) cross section perpendicular to the e^+e^- beam directions; (b) "exploded view" of the arrangement of energy detectors.

The layout of the apparatus is shown in fig. 1. This non-magnetic detector was described in detail in ref. [5]. For the measurements presented here, use has been made of the following parts: an inner detector measures the directions of charged particles; it has three cylindrical double-drift chambers and two scintillation hodoscopes. An outer box of energy counters (NaI and lead glass) determines the energy and direction of photons and electrons originating from the interaction point. The side walls have a total thickness of 15.2 X_0 (radiation lengths). The lead glass at top and bottom has 12.7 X_0. The lead converter between the second and third drift chamber of the inner detector has a thickness of 1 X_0. Minimum ionizing particles deposit about 200 MeV energy. The inner detector, as well as the energy counters, cover a solid angle of 86% of 4π.

The trigger consisted of several combinations of charged track multiplicities and a minimum total deposited energy as described in ref. [5]. An on-line filter eliminated beam–gas interactions that were easily recognized by their oblique incidence in the chambers. In the data reduction the following cuts were applied in order to isolate events of the type $e^+e^- \to$ hadrons: more than 1.8 GeV seen in the energy detector; at least three charged tracks recognized; at least 10% of the energy seen in the energy detector correlated with charged tracks. In a hand-scan, all events were eliminated which had drift chamber timing information inconsistent with the geometry of beam-beam interactions. Table 1 shows the breakdown of the events as they pass through the filtering procedure.

The "visible cross section" σ_{vis} was obtained by dividing the number of observed hadronic events by the time-integrated luminosity measured with the large-angle ($\alpha > 36°$) Bhabha events in the same apparatus for each energy point. The luminosity was also measured in a set of four counter telescopes for Bhabha scattering under 7°. Both measurements agreed within ±10%.

Fig. 2 shows how σ_{vis} depends on the centre-of-mass energy $\sqrt{s}$. The Υ is seen near 9.46 GeV above a

Table 1
Number of events in the filtering procedure and luminosity.

	Υ region	Υ' region
Triggers	3.4×10^6	5.1×10^6
Left after on-line filter	4.6×10^5	9.1×10^5
Left after off-line filter	2500	770
Left after hand-scan	1200	420
Integrated luminosity (nb^{-1})	173	120

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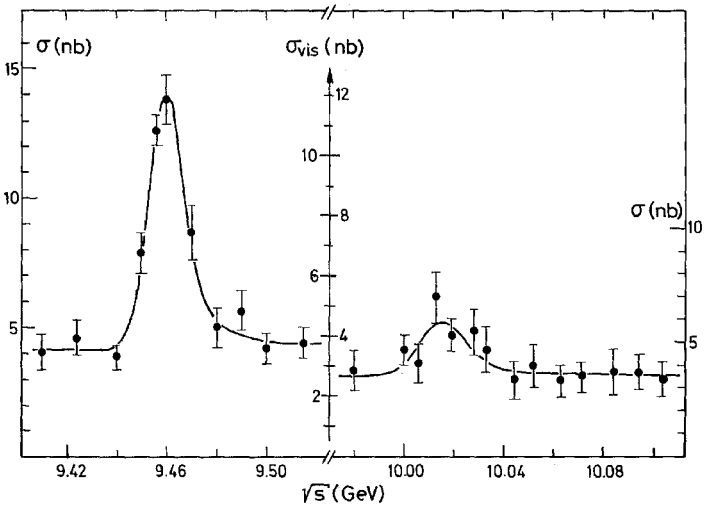


Fig. 2. Observed cross section $\sigma_{vis}(e^+e^- \to \text{hadrons})$ in the Υ and Υ′ regions (centre scale common to both measurements). The two outer scales represent the data after normalization to the expected level of continuum based on $R = 4.7$ (see text). The two outer scales are different by ≈10%, reflecting the systematic errors between the independent normalizations of the two measurements.

nearly constant continuum of 3.7 nb, and the Υ′ resonance is seen for the first time to be formed in e^+e^- annihilations, above a continuum of 2.7 nb. We note that the Υ′ signal is also very clearly visible in the event sample defined by the off-line filter.

The energy dependence of σ_{vis} was fitted around each resonance by a radiatively corrected gaussian resolution function (according to ref. [6]) over a background proportional to $1/s$. At the present time we are not able to calculate the exact amount of losses of hadronic events due to our filtering procedure. They are probably between 10% and 30% and are roughly independent of s. The visible cross section was normalized to 4.16 nb at 9.4 GeV and to 3.68 nb at 10.0 GeV to correspond to a value of $R = \sigma_{had}/\sigma_{\mu\mu}$ of 4.2 derived from $R(\sqrt{s} = 5\ \text{GeV}) = 4.7$ [7] minus 0.5 units for undetected heavy-lepton decays due to our event selection. R was assumed to be energy independent between 5 and 10 GeV.

We foudn the resonances at masses of $M(\Upsilon) = 9.46 \pm 0.01$ GeV, $M(\Upsilon') = 10.02 \pm 0.02$ GeV; $\Delta M = 0.56 \pm 0.01$ GeV where the errors are from the machine [8]. The mass difference is only 29 ± 10 MeV less than the one between J/Ψ and Ψ′, contrary to expectations based on universal potentials, "Coulomb + linear" [2], for the charmed and the new quarks.

The observed widths were found to be $\sigma(\Upsilon) = (7.1 \pm 0.8)$ MeV and $\sigma(\Upsilon') = (12 \pm 4)$ MeV. These are consistent with the energy resolution of the storage ring calculated to be $\sigma(9.5) = (7.8 \pm 0.8)$ MeV at the Υ and $\sigma(10.0) = (8.7 \pm 0.9)$ MeV at the Υ′. The machine value was used in the following determination of the area under the Υ′.

The areas under the normalized resonance curves were $A(\Upsilon) = 208 \pm 25$ MeV nb and $A(\Upsilon') = 59 \pm 15$ MeV nb, which turned into $A_0(\Upsilon) = 267 \pm 32$ MeV nb and $A_0(\Upsilon') = 74 \pm 19$ MeV nb after radiative corrections. We assume the Υ and Υ′ are $J^P = 1^-$ objects, for which the ratio of electronic, hadronic, and total widths is

$$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot} = (E_{res}^2/6\pi^2)A_0 \approx \Gamma_{ee}.$$

We obtained:

$$\Gamma_{ee}\Gamma_{had}/\Gamma_{tot} = (1.04 \pm 0.28)\ \text{keV for the } \Upsilon,$$
$$(0.32 \pm 0.13)\ \text{keV for the } \Upsilon',$$

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thus confirming the earlier measurement of the Υ [3,4], whereas the Υ'-value is new. The errors contain a statistical contribution of ± 0.13 keV (Υ) and ± 0.08 keV (Υ'), and a common systematic contribution of $\pm 15\%$. The ratio 0.32/1.04 is, therefore, known with a precision of $\pm 28\%$. In the quarkonium picture [2] such values of Γ_{ee} favour the assignment of charge 1/3 to the new quark. Our small $\Gamma_{ee}(\Upsilon')$ seems to exclude a charge of 2/3 [9].

This work would not have been possible without the successful operation of the DORIS storage ring, which the machine group was able to run far beyond its original specifications. We are very grateful to the old DESY–Heidelberg group, who built the experiment and let us use their software. We are indebted to all the service groups who supported the experiment, i.e. the computer centre, the synchrotron staff, and the vacuum group as well as our technicians. The non-DESY members of our collaboration want to thank the DESY directorate for their hospitality.

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VOLUME 45, NUMBER 4 PHYSICAL REVIEW LETTERS 28 JULY 1980

Observation of the Υ''' at the Cornell Electron Storage Ring

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During an energy scan at the Cornell Electron Storage Ring, with use of the Columbia University–Stony Brook NaI detector, an enhancement in $\sigma(e^+e^- \to \text{hadrons})$ is observed at center-of-mass energy ~10.55 GeV. The mass and leptonic width of this state (Υ''') suggest that it is the 4^3S_1 bound state of the b quark and its antiquark. After applying to the data a cut in a (pseudo) thrust variable, the natural width is measured to be $\Gamma = 12.6 \pm 6.0$ MeV, indicating that the Υ''' is above the threshold for $B\bar{B}$ production.

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In the quarkonium model,[1] vector mesons are considered to be triplet S states of a quark-antiquark system in a "Coulombic-plus-confining" potential, with the number of quasistable radial excited states increasing with the mass of the quark. In particular, for the b quark ($M \sim 5$ GeV) the 1^3S_1, 2^3S_1, and 3^3S_1 states (Υ, Υ', and Υ'') have been observed as narrow enhancements in $\sigma(e^+e^- \to \text{hadrons})$,[2-4] as well as in proton-nucleon scattering.[5] A 4^3S_1 state should also exist, with an excitation energy of ~1.15 GeV. The 4^3S_1 state is expected to be close to the threshold for $B\bar{B}$ production,[6] where B is a pseudoscalar bound system of b and $\bar{u}$ or $\bar{d}$ quarks. If the 4^3S_1 state lies below the $B\bar{B}$ threshold, its natural width would be well below 1 whereas if it lies above the $B\bar{B}$ threshold, the opening up of decay channels would result in a natural width which increases rapidly with $M(4^3S_1) - 2M(B)$.[7]

We report here on the production of a new state in the Υ family, the Υ''', which we identify, from a measurement of its leptonic width Γ_{ee}, with the 4^3S_1 $b\bar{b}$ state. In addition, we observe a total width $\Gamma_{\text{obs}}(4^3S_1) \sim 19$ MeV; unfolding the contribution ($\Gamma \sim 10.8$ MeV) due to the Cornell Electron Storage Ring (CESR) beam-energy spread gives a natural width $\Gamma \sim 12.6$ MeV. This suggests that this state is above the $B\bar{B}$ threshold. We also obtain the (pseudo) thrust distribution for this new state and compare it with the corresponding distribution obtained for the continuum and for the $\Upsilon(1^3S_1)$.

These results were obtained in a twenty-day run covering the energy range 10.46 to 10.60 GeV, with an integrated luminosity of 1100 nb^{-1}. We had seen preliminary evidence for the new state during a run covering 10.55 to 10.80 GeV with a total integrated luminosity of 400 nb^{-1}. During the present run, we also collected data at the $1^3S_1(\Upsilon)$ with 300 nb^{-1} and at the $3^3S_1(\Upsilon'')$ with 150 nb^{-1}.

The principle of the Columbia University–Stony Brook layered NaI detector has been described in our previous Letter,[4] in which we reported the first measurements of the Υ, Υ', and Υ'' at CESR. For the present run, the complete NaI array was available, and for half of the run, in three of the four quadrants, drift chambers between the beam pipe and the NaI array were in operation. The NaI array consists of five radial layers, each subdivided into two polar halves and 32 azimuthal sectors (see Fig. 1). In contrast to its earlier configuration, our detector now covers the polar angle range $45° < \theta < 135°$ and a solid angle of approximately two-thirds of 4π, with each of the 64 sectors covering ~1% of 4π. In the following, we consider the detector as being composed of eight octants, four with $90° < \theta < 135°$ (West) and four with $45° < \theta < 90°$ (East), each spanning $\Delta\varphi$ intervals of 90°.

The operation of the detector was also described in Ref. 4. All NaI signals are integrated every

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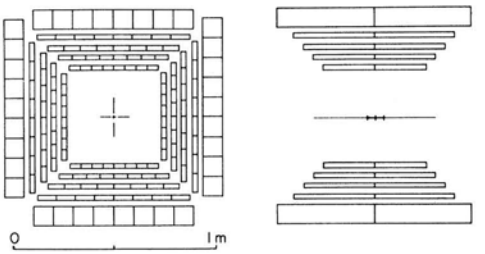


FIG. 1. A front view and a cut-away side view of the NaI array. An error bar shows the length of the interaction region.

machine cycle (2.56 μs) but are digitized only if a trigger is present. Only a single total-energy trigger is used, requiring $\geq$ 700 MeV to be deposited in the outer three layers of the NaI array. Hadronic and large-angle Bhabha-scattering yields in the detector are monitored on line by counting on scalers events satisfying appropriate criteria. The hadronic criterion requires that the total energy deposited in the outer three NaI layers, E_{NaI}, be in the range 1.2 GeV $< E_{\mathrm{NaI}} <$ 3.6 GeV, that two or more octants in each half have $\geq$ 100 MeV deposited in the outer four layers, and that two such octants be collinear with the interaction point. The hadron monitor sensitivity is such that the Υ and Υ'' signals are clearly visible in a few hours' run (~15 nb^{-1}); this monitor also provided an on-line indication of the Υ'''. The Bhabha-scattering criterion requires that $E_{\mathrm{NaI}} > 5.4$ GeV, and that two collinear octants each have $\geq$ 100 MeV in the outer four layers. These on-line "Bhabhas" comprise approximately 80% of those found later in off-line analysis and serve as an on-line consistency check of the beam luminosity measurement obtained from the luminosity counters (which detect small-angle Bhabha scatterings). Additional electronic criteria were used to monitor and veto poor beam conditions. Typically we write 150 events on tape per inverse nanobarn of integrated luminosity, of which, at the Υ, about 15% are hadronic events and 10% are large-angle Bhabha scattering events. The live time of our detection system is 99.0%.

"e^+e^- $\rightarrow$ hadrons" events are recognized clearly in our detector. Photons from π^0 and η decay are detected as electromagnetic showers. Charged particles which do not shower electromagnetically nevertheless leave a clear signature since the five layers of NaI give five independent measurements of dE/dx. Recognition of "tracks" left in the NaI by minimum-ionizing particles is central to our hadronic-event-selection algorithms. Events containing at least one "track" pointing towards the beam and some additional energy deposition are hadronic candidates. Additional criteria imposed at succeeding levels of analysis include requirements that additional "tracks" or showers be present, and that energy be deposited in both the East and West halves of the detector.

Several independent hadronic-event-selection computer algorithms were developed. To guide us in this process, one or more physicists have examined over 95% of the hadronic-event candidates in the Υ''' energy scan. The various algorithms have efficiencies for continuum events of from 60 to 75% and background contaminations between 1 and 5%. The inefficiencies include loss of events due to detector solid angle. The background estimates are obtained from single-beam runs, and from reconstructed vertex position for those events having drift-chamber information. While the numbers of events found by the various algorithms and the on-line hadron monitor differ, the determinations of masses, widths, and relative cross sections of the resonances are in good agreement.

The present run yielded 5000 hadronic events at the Υ, 450 at the Υ'', and 3000 in the region around the Υ''', for a total 1550 nb^{-1} of integrated luminosity. The data are shown in Fig. 2(a). They have been normalized with use of the measured small-angle and large-angle Bhabha yields. Comparison of our observed cross sections with those measured at DORIS[2] and by CLEO[3] indicates that the product of acceptance by efficiency for our detector is approximately 73% for the continuum and 82% for the Υ.

A peak in the cross section is visible at a mass of 10.55 GeV. As has been shown in the DORIS experiments,[8] the spatial distributions of the continuum and Υ decay events are different. We choose here to test this difference using a simplified thrust variable, T', defined as the maximum of $\sum|\vec{E}_{\mathrm{NaI}}\cdot\hat{n}|/\sum E_{\mathrm{NaI}}$ over all possible $\hat{n}$ perpendicular to the beam axis. The distributions of T' for Υ and continuum events are given in Fig. 3. The difference between the two cases is quite evident and agrees with the conjecture that continuum events have a two-jet-like structure while resonance decays have a more spherical distribution. A cut at $T' < 0.85$ has been made for all the data and the result is shown in Fig. 2(b).

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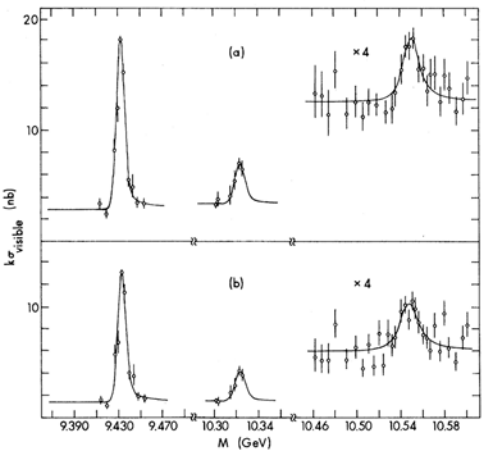


FIG. 2. (a) The observed cross section for e^+e^- → hadrons multiplied by $k = (M/M_\Upsilon)^2$. M is the e^+e^- invariant mass. (b) The same cross section after removing events with $T \geq 0.85$. The lines are fitted to the data including machine energy spread and radiative corrections. See text for explanation.

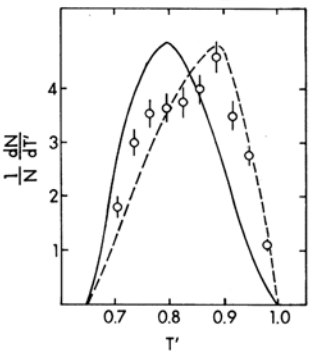


FIG. 3. Solid line, pseudothrust (see text) distribution for events in the Υ region; dashed line, distribution for continuum events. Data points are for events from the Υ''' region, showing contributions from both distributions.

The cut removes 52% of the continuum events but only 26% of resonance events.

We determine the parameters of the Υ''' by fitting the data sample with $T' < 0.85$; the uncut data give similar results but with less statistical significance. A fit to a constant continuum plus a Gaussian with radiative corrections gives an apparent machine energy spread of $\Gamma = 19 \pm 4$ MeV. We have also fitted the parameters of the Υ using our data from this running period, cut on $T' < 0.85$. This gives a full width at half maximum (FWHM) machine energy spread at the Υ of 8.7 ± 0.7 MeV. Scaling this by the expected $(E_{beam})^2$ dependence yields a FWHM at the Υ''' of $\Gamma = 10.8 \pm 0.9$ MeV. This is inconsistent with the observed result by 2 standard deviations. We therefore assume a Breit-Wigner, rather than Gaussian, resonance shape for the enhancement, fold in the machine energy spread and radiative corrections, and fit the Υ''' data with the resulting curve. The mass values are calculated from the CESR energy calibration, which gives a mass for the Υ 0.3% below the DORIS values.[2-4] The mass difference is $M(\Upsilon''') - M(\Upsilon) = 1114 \pm 2$ MeV with systematic uncertainty of 5 MeV. The ratio of leptonic widths calculated from the fitted areas is $\Gamma_{ee}(\Upsilon''')/\Gamma_{ee}(\Upsilon) = 0.25 \pm 0.07$. Both the mass difference and the ratio of leptonic widths are in excellent agreement with many phenomenological calculations for the 4^3S_1 state of $b\bar{b}$.[1,6,9] Therefore, we conclude that the enhancement observed at $M = 10.547$ GeV is most likely that state.

The natural width of the enhancement is also of great interest. Our fit gives a natural width $\Gamma = 12.6 \pm 6.0$ MeV. If we constrain the natural width to be much smaller than the machine energy spread, χ^2 increased by 8.3, from 40.3 for thirty degrees of freedom to 48.6 for 29 degrees of freedom. Thus, our value for the natural width is inconsistent with the expected width of less than 1 MeV for a resonance below $B\bar{B}$ threshold. A similar result has been obtained by the CLEO collaboration at CESR.[10] This implies that Υ''' is above threshold and that the mass of the B is less than 5.275 GeV. It also implies a production rate for B mesons which is greatly enhanced above the level in the neighboring continuum. If this is confirmed, the study of the Υ''' events should contribute enormously toward our understanding of the B meson.

We gratefully acknowledge the assistance of the CESR operating staff and again thank the people who assisted in the design, construction, and installation of our detector. One of us (S.W.H.) acknowledges the support of the Sloan Foundation. This research was supported in part by the National Science Foundation, and in part by the U. S. Department of Energy.

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VOLUME 50, NUMBER 12 PHYSICAL REVIEW LETTERS 21 MARCH 1983

Observation of Exclusive Decay Modes of *b*-Flavored Mesons

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B-meson decays to final states consisting of a D^0 or $D^{*\pm}$ and one or two charged pions have been observed. The charged-B mass is $5270.8 \pm 2.3 \pm 2.0$ MeV and the neutral-B mass is $5274.2 \pm 1.9 \pm 2.0$ MeV.

PACS numbers: 14.40.Jz, 13.25.+m, 13.65.+i

The upsilon states[1] are interpreted as q-q resonances of a new quark, the b quark. The first three resonances are narrow,[2,3] implying bound b flavor and a suppressed strong decay. The large width of the $\Upsilon(4S)$ resonance discovered at the e^+e^- storage ring CESR[4] (Cornell Electron Storage Ring) and the observation that the decay products from the $\Upsilon(4S)$ include high-momentum leptons[5] imply that the $\Upsilon(4S)$ decays strongly into $B\bar{B}$ meson pairs, which then decay weakly. Until now, however, the b-flavored mesons themselves had not been found. Here we report that

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discovery.

The b quark has been shown to decay predominantly to the c quark.[6] Thus the principal decay mode of the B meson will be to a charmed meson plus pions. Since the high multiplicity in $\Upsilon(4S)$ decay[7] leads to large combinatorial background, we have restricted our search to low-multiplicity decay modes, D^0 or $D^{*\pm}$ plus one or two charged pions.

The data sample used is 40.7 pb^{-1} of $\Upsilon(4S)$ data and 19.6 pb^{-1} of continuum data taken with the CLEO detector at CESR. The $\Upsilon(4S)$ cross section is a 1.0-nb enhancement above a 2.5-nb continuum contribution. The detector has been described in detail elsewhere.[8] In this work we have used the cylindrical drift chamber inside a 1.0-T solenoid magnet to determine momenta of charged particles. In addition we have used the dE/dx-measuring wire proportional chambers and the time-of-flight scintillation counters located outside the solenoid magnet to identify charged kaons over a momentum range from 0.45 to 1.0 GeV/c.

The two-body decay modes, $D^0 \to K^-\pi^+$ and its charge conjugate, were used to find D^0 mesons. Identified kaons were paired with each oppositely charged particle in the event (assumed to be a pion). The combination was kept only if its momentum was below 2.6 GeV/c, since D^0's from B decay cannot exceed this momentum. The resulting $K^\pm\pi^\mp$ mass distribution is shown in Fig. 1(a). Mass combinations within ± 40 MeV of the D^0 mass were kept as D^0 candidates.

We looked for charged D^* mesons through the cascade $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ and its charge conjugate. We did not require that the charged kaon be identified as such. Rather we first formed mass combinations of all pairs of oppositely charged particles in an event, assuming that each particle in turn is a kaon. We then added an additional particle (assumed to be a pion) of charge opposite to that of the assumed kaon. We kept as D^* candidates the combinations for which the $[K\pi\pi, K\pi]$ mass difference was within ± 3.0 MeV of the $[D^{*\pm}, D^0]$ mass difference of 145.4 MeV,[9] and $K\pi$ masses within ± 80 MeV of the D^0 mass. We further required that the D^* candidate have momentum below 2.6 GeV/c, eliminating the high-momentum D^* contribution from the continuum. With these requirements the $D^{*\pm}$ signal is hidden under considerable background. By demanding a more restrictive set of conditions [see Fig. 1(b)], we demonstrate that the $\Upsilon(4S)$ decays contain a $D^{*\pm}$ signal. Because these latter restrictions lower

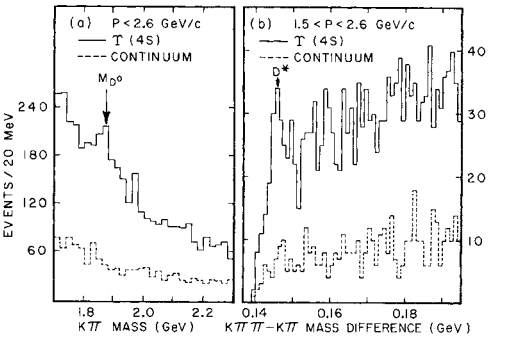


FIG. 1. (a) Mass distribution of $K^\pm\pi^\mp$, for $K\pi$ momenta below 2.6 GeV/c, using identified kaons. The solid line shows data from 40.7 pb^{-1} of $\Upsilon(4S)$ running; the dashed line is from 19.6 pb^{-1} of continuum running at energies just below the $\Upsilon(4S)$. A D^0 signal at 1.86 GeV is evident in the 4S data. (b) $(K^\pm\pi^\mp\pi^\mp)$-$(K^\pm\pi^\mp)$ mass-difference distribution, for $K\pi\pi$ momenta between 1.5 and 2.6 GeV/c and $K\pi$ masses within 20 MeV of the D^0 mass. Kaons were not directly identified. Curves are as in (a). The signal at the $D^{*\pm}$-D^0 mass difference (145.4 MeV) is evidence of $D^{*\pm}$ production in $\Upsilon(4S)$ decay.

the $D^{*\pm}$ detection efficiency they were not used in the search for B mesons.

Each event containing a D^0 or $D^{*\pm}$ candidate was fitted to the following hypotheses[10] (or their charge conjugates):

$$B^- \to D^0\pi^-, \quad (1)$$

$$\bar{B}^0 \to D^0\pi^+\pi^-, \quad (2)$$

$$\bar{B}^0 \to D^{*+}\pi^-, \quad (3)$$

$$B^- \to D^{*+}\pi^-\pi^-. \quad (4)$$

We considered only these charge combinations, since they preserve the quark decay scheme $b \to c \to s$. In making the fit, we constrained the B-meson energy to the beam energy and constrained the D^0 or $D^{*\pm}$ decay products to the known D^0, $D^{*\pm}$ masses, respectively. This fitting procedure measures the B mass relative to the CESR beam energy, which is scaled to agree with the VEPP4 measurement of the $\Upsilon(1S)$ mass.[11] Since the threshold for $B\bar{B}$ production is known to lie between the $\Upsilon(3S)$ and $\Upsilon(4S)$ resonances, we considered B-meson mass combinations between half the $\Upsilon(3S)$ and $\Upsilon(4S)$ resonance masses (i.e., 5180 and 5290 MeV). Candidate fits were required to have a χ^2 value less than 14. If an event had two acceptable fits in this mass inter-

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VOLUME 50, NUMBER 12 PHYSICAL REVIEW LETTERS 21 MARCH 1983

val we took the hypothesis with the lower χ^2. Each successful fit was examined visually to reject B candidates involving incorrectly fitted drift-chamber tracks (a 15% rejection).

The B masses for all successful fits are shown in Fig. 2. The 18 events in the peak near 5275 MeV are divided 2, 5, 5, and 6 for reactions (1)–(4), respectively. The width of the mass peak is consistent with the resolution expected from Monte Carlo studies. We have estimated the background under the mass peak in several ways. (1) We changed our selection criteria to accept $K^{\mp}\pi^{\pm}$ mass combinations that differed from the D^0 mass by ± 200 MeV. The spectrum of reconstructed "B-meson" masses for this "sideband" search is shown in Fig. 3(a). (2) We considered wrong charge combinations, which corresponded to doubly charged B's, or corresponded to decay sequences other than $b \to c \to s$. The mass spectrum for wrong charge combinations is shown in Fig. 3(b). Both distributions in Fig. 3 have been normalized so that the vertical scales are directly comparable with Fig. 2. (3) We performed Monte Carlo studies of background from $B\bar{B}$ events and from continuum events, to determine how the background in Fig. 2 should be extrapolated from lower masses to the peak region. (4) We searched 19.6 pb^{-1} of data accumulated just below the $\Upsilon(4S)$ for apparent B's, finding two in the region of the mass peak. These studies lead to estimates of the background under the peak at 5275 MeV which lie between 4 and 7 events.

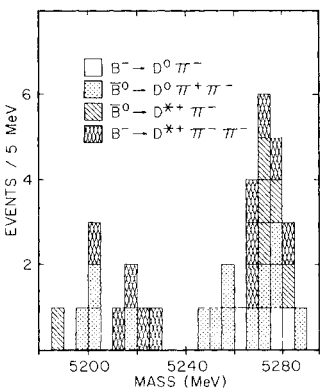


FIG. 2. Mass distribution of B-meson candidates. The $B \to$ final-state decay labels should be interpreted as including the charge-conjugate reaction.

If a B decay contains a low-energy particle that escapes detection, the remaining particles from that B may still be consistent with the beam-energy constraint and give an acceptable fit. We frequently cannot distinguish reactions (1) and (2) from similar reactions with the D^0 replaced by D^{*0}, where $D^{*0} \to D^0\pi^0$ or $D^0\gamma$. Similarly, the decay $\bar{B}^0 \to D^{*+}\pi^-$, $D^{*+} \to D^0\pi^+$ (π^+ not detected), can masquerade as $B^- \to D^0\pi^-$, causing us to assign an incorrect charge to the B. Monte Carlo studies show that the reconstructed mass is shifted down a few megaelectronvolts from the true B mass, and the mass resolution is worsened slightly. The problem of missed low-energy particles is *not* important for reactions (3) and (4), and therefore we use only these to determine the B mass.

We find a mass of $5274.2 \pm 1.9 \pm 2.0$ MeV for the neutral B, and $5270.8 \pm 2.3 \pm 2.0$ MeV for the charged B, where the first error is statistical and the second error systematic. The $[\bar{B}^0, B^-]$ mass difference is $3.4 \pm 3.0 \pm 2.0$ MeV, consistent

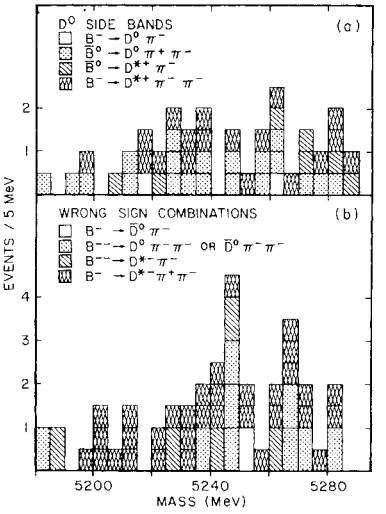


FIG. 3. Mass distribution for two estimates of the background to the B-meson candidates of Fig. 2. (a) D^0's chosen from sidebands. The events shown are plotted with a weight of $\frac{1}{2}$ event, since there are approximately twice as many events in the sidebands as in the D region. (b) Wrong charge combinations. The events shown in this distribution have been scaled to account for the difference in the number of combinations leading to a wrong-sign B compared to those leading to the correct-sign charged B.

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with the theoretical prediction[12] of 4.4 MeV. The average of charged and neutral B masses is $5272.3 \pm 1.5 \pm 2.0$ MeV. This corresponds to a mass difference ΔM of $32.4 \pm 3.0 \pm 4.0$ MeV between the mass of the $\Upsilon(4S)$ and twice the B-meson mass. If the $[B^*, B]$ mass difference is ~ 50 MeV as expected theoretically,[12] the $\Upsilon(4S)$ must decay exclusively to $B\bar{B}$, with no contribution from $B^*\bar{B}$. Previous experimental information on ΔM comes from the fact that Schamberger *et al.* do not observe monochromatic photons from $B^* \to \gamma B$ decay.[13] Their experiment sets an upper limit of 50 MeV on ΔM. Theoretical calculations of ΔM using the width and the height of the $\Upsilon(4S)$ fall either above[12] or below[14] our result. Using our measured value for ΔM and the theoretical value of 4.4 MeV for the $[\bar{B}^0, B^-]$ mass difference, we obtain the branching fractions $B(\Upsilon(4S) \to B^+B^-) = 0.60 \pm 0.02$ and $B(\Upsilon(4S) \to B^0\bar{B}^0) = 0.40 \pm 0.02$. We estimate branching ratios of $4.2 \pm 4.2\%$, $13 \pm 9\%$, $2.6 \pm 1.9\%$, and $4.8 \pm 3.0\%$ for reactions (1)–(4), respectively.[15,16]

In conclusion, we have explicitly demonstrated the existence of the B meson through its decay into exclusive final states and have measured its mass.

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VOLUME 71, NUMBER 5 PHYSICAL REVIEW LETTERS 2 AUGUST 1993

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

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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.

PACS numbers: 13.40.Hq, 14.40.Jz

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 $(2\text{–}4)\times 10^{-4}$ [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.

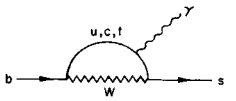


FIG. 1. Penguin diagram for $b \to s\gamma$. The photon may be radiated from any of the four lines.

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 $\theta_{\rm thr}$ between the high energy photon direction and the thrust axis of the particles not from the B candidate, $|\cos\theta_{\rm thr}| < 0.7$ (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 $\Delta E = E_{\rm beam} - E_{K^*\gamma}$. 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

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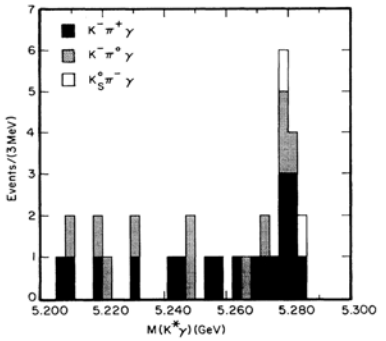


FIG. 2. The $K^*\gamma$ mass distributions for $B^0 \to K^{*0}\gamma$; $B^- \to K^{*-}\gamma$, $K^{*-} \to K^0_S\pi^-$; and $B^- \to K^{*-}\gamma$, $K^{*-} \to K^-\pi^0$ candidates.

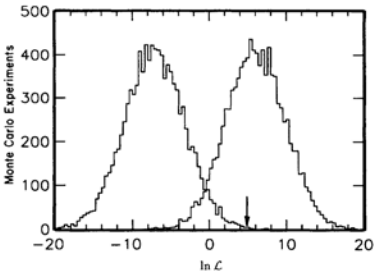


FIG. 3. The $\ln \mathcal{L}$ distributions for 10 000 "experiments" of 8 events each, drawn from $B^0 \to K^{*0}\gamma$ Monte Carlo (right curve) or continuum Monte Carlo (left curve) simulations. The value for the 8 $B^0 \to K^{*0}\gamma$ candidate events is indicated by an arrow.

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 $\pm$ 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 $B \to K^*\gamma$.

	$B^0 \to K^{*0}\gamma$	$B^- \to K^{*-}\gamma$	
	$K^{*0} \to K^+\pi^-$	$K^{*-} \to K^0_S\pi^-$	$K^{*-} \to K^-\pi^0$
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	$(4.0\pm1.7\pm0.8)\times10^{-5}$	$(5.7\pm3.1\pm1.1)\times10^{-5}$	

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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 $K^{*-} \to K^0_S\pi^-$ 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 $K^0_S\pi^-\gamma$, 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^0_L'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 $K^0_S\pi^-\gamma$, 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 $K^0_S\pi^-\gamma$ 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 $K^0_S\pi^-$ and $K^-\gamma^0$ 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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[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.

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[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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