Search for Isolated Photons from Flavor-Changing Neutral-Current Decay of a New Quark at the KEK e^+e^- Collider TRISTAN

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A search for a new charge $-\frac{1}{3}$ quark has been carried out at the KEK e^+e^- collider TRISTAN under the assumption of its photonic decay through a flavor-changing neutral current (FCNC). The observed number of multihadronic events with isolated photons is consistent with that expected from the known five quark flavors. Including the usual charged-current decays, limits on the absolute photonic branching ratio and FCNC processes were obtained.

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One crucial problem in elementary-particle physics concerns the number of generations of quarks and leptons. It is widely known that the so-called standard model successfully describes the behavior of elementary particles, but does not answer questions concerning why and how many generations exist. It would therefore be important to find a new particle which belongs to the next generation. Searches for new quark flavors in recent e^+e^- experiments at the KEK collider TRISTAN [1] have excluded a fourth-generation quark with an electric charge of $-\frac{1}{3}$ (hereafter, called b') with a mass $(m_{b'})$ up to 27.5 GeV/c^2. Analyses were made by studying isolated lepton (e/μ) events under the assumption that b' decays mainly into a c quark through a charged current (CC). However, it has been pointed out[2] that if b' is lighter than top quark, the usual CC decay might be suppressed and that it is very likely for b' to decay through a flavor-changing neutral current (FCNC). If this is indeed the case, previous searches for b' have been ineffective, and the analysis including both FCNC and CC processes is necessary. In recent theoretical studies, aside from a possible decay to a Higgs particle,[3] it was suggested[4] that b' decays into a b quark by emitting a gluon or a photon, and that the ratio of photonic to

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gluonic decays amounts to an order of 10%. If the b' quark exists within the TRISTAN energy region, it would be lighter than the t quark. The sizable rate of the estimated photonic decay indicates that it could easily be found by the signal of isolated hard photons. Since a photon is not affected by hadronization processes we can make a clean search for b', compared with a search by more abundant gluonic decays.

The present analysis was made with multihadronic events from a $21.1 \pm 0.1(\text{stat}) \pm 0.6(\text{syst})\text{-pb}^{-1}$ data sample taken with the VENUS detector at c.m. energies[5] between 55.0 and 60.8 GeV. The VENUS detector[6] is a general purpose magnetic spectrometer. The main components are a central drift chamber (CDC), a lead-glass (LG) barrel and liquid-argon (LA) end-cap calorimeters, and muon chambers. With no gaps between the calorimeters, LG and LA form a uniform, hermetic calorimeter which covers 99% of 4π. This feature provides excellent detection capabilities for isolated photons.

Multihadronic events are selected according to the following criteria: (i) There exist at least five good tracks[7] with $|\cos\theta| < 0.85$, having a minimum distance from the interaction point of less than 2.0 cm in the r-ϕ (Ref. 8) plane and 20 cm in the r-z plane and a transverse momentum greater than 0.2 GeV/c; (ii) the total energy in the calorimeter system for $|\cos\theta| < 0.9$ is greater than 5 GeV; (iii) the visible energy (E_{vis}), defined as the sum of cluster energies in the calorimeter and the momenta of the good tracks, is greater than the beam energy (E_{beam}); (iv) the sum of the longitudinal component of the cluster energies and momenta of good tracks lie between ± 0.4 times E_{vis}. A total of 2702 events remained.

Events with isolated photons were selected with further conditions: (v) There exists a cluster with $|\cos\theta| < 0.7$ whose energy is greater than 0.1 times E_{beam}; and (vi) inside a cone around the cluster, with a half angle of 30°, there exist no other clusters exceeding 1 GeV, nor good tracks. Figure 1(a) shows the energy spectrum of the isolated photons for the remaining 50 events. Estimation of the π^0 background was carried out by studying isolated charged pions in the same data sample. This was done with the same selection criteria as described above. Muon contamination was rejected by requiring less than four hit layers in the six-layer muon chambers along the extrapolated track. The momenta of the remaining tracks are plotted in the figure, where they are multiplied by a factor of 0.5, assuming an equal production rate of π^+, π^-, and π^0. A Monte Carlo simulation was carried out using LUND 5.3 (Ref. 9) with five known quark flavors at a c.m. energy of 60 GeV. The result is indicated by a solid line. The simulated number of events was 49.5 ± 1.0 in total. The contribution of the π^0 background is indicated by a dashed line. We can say that the agreement with data is pretty good.

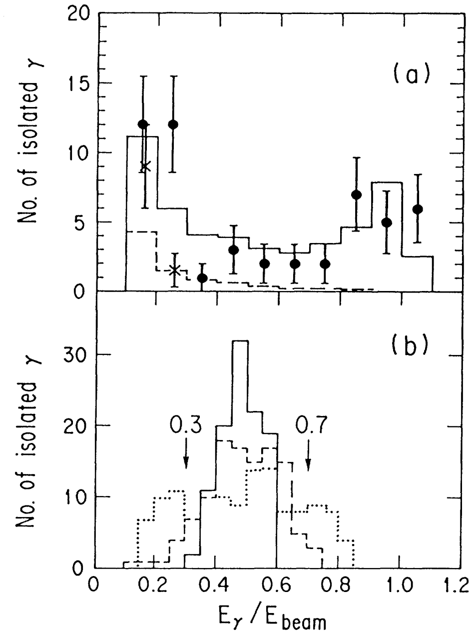

FIG. 1. (a) Energy spectrum of isolated photons. Closed circles show the real data. Crossed points show the estimated π^0 background from isolated charged pions. The histogram with a solid line is the Monte Carlo simulation with five quark flavors. The contribution of the π^0 background is shown by a dashed line. (b) Monte Carlo simulation of the photon spectrum from b' decay with masses of 29 (solid line), 26 (dashed line), and 20 GeV/c^2 (dotted line). The signal region for b' candidates is indicated by arrows.

The photon spectra expected from b' quarks with masses of 29, 26, and 20 GeV/c^2 at a c.m. energy of 60 GeV are presented in Fig. 1(b). Candidate b' events were selected with the signal region defined by photon energies between 0.3 and 0.7 times E_{beam}, which is shown in the figure. The lower cut reduces the π^0 background and the upper one reduces the contribution of the initial-state radiation. After the cut eight candidates remained. If we neglect the small contribution of the π^0 background, the number is in agreement with the Monte Carlo estimation (11.8 ± 0.5) of the initial-state radiation.

The upper limit was obtained on any excess over the initial-state radiation in the signal region. From a conservative point of view the π^0 background is included in the excess. In order to avoid ambiguities from b'-quarkonium effects, only data at c.m. energies greater than 2 times the given $m_{b'}$ plus 1 GeV were used. The upper limit at a 95%-confidence level lies between 4.0 and 7.8 (Fig. 2).

The expected number of events from b' production ($N_{b'}$) was calculated including both FCNC and CC decay processes of b'; that is b' decays into $b+\gamma$ and $b+$gluon through FCNC, and $c+$virtual W through

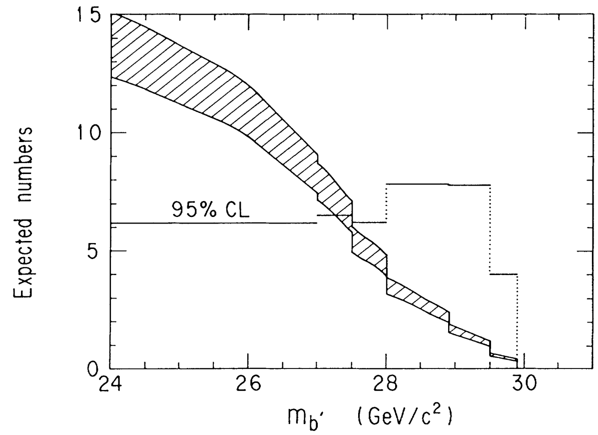

FIG. 2. Expected number of b' events for $r=0.1$. The hatched area indicates the ambiguities. The horizontal lines show the upper limits on excess above initial-state radiation at a 95%-confidence level.

CC. The expression of $N_{b'}$ is given by

$$N_{b'}=\sum \sigma_{i,b'}L_i[2\rho^2\xi(1-\xi)\epsilon^{\gamma g}+\rho^2\xi^2\epsilon^{\gamma\gamma}+2\rho(1-\rho)\xi\epsilon^{\gamma W}]\,, \quad (1)$$

where $\sigma_{i,b'}$ is the total cross section of b' production given by the standard electroweak theory at the ith c.m. energy, including the mass effect and the radiative corrections[10] of the order α; L_i is the corresponding luminosity; ρ and ξ are the ratios of the FCNC decay width ($\Gamma_{\rm FCNC}$) to the total width ($\Gamma_{\rm tot}=\Gamma_{\rm FCNC}+\Gamma_{\rm CC}$) and the photonic decay width $\Gamma(b'\to\gamma b)$ to $\Gamma_{\rm FCNC}$, respectively: $\epsilon^{\gamma g}$, $\epsilon^{\gamma\gamma}$, and $\epsilon^{\gamma W}$ are the acceptance times detection efficiencies for b' events in which one b' decays into $\gamma+b$ and the other into gluon$+b$, $\gamma+b$, and $c+$virtual W, respectively. The efficiencies were evaluated by a Monte Carlo simulation, all of them increasing with the value of $m_{b'}$: typical values are 0.4 for $\epsilon^{\gamma g}$ and $\epsilon^{\gamma W}$, and 0.7 for $\epsilon^{\gamma\gamma}$ at $m_{b'}$ greater than 26 GeV/c^2. The increase with $m_{b'}$ reflects the fact that the decay of the heavier b' gives better isolation and a smaller energy spread of the emitted photons. It was found that $\epsilon^{\gamma W}$ is nearly equal to $\epsilon^{\gamma g}$, independent of $m_{b'}$. Thus, $N_{b'}$ can be approximated by

$$N_{b'}=\sum \sigma_{i,b'}L_i[2r(1-r)\epsilon^{\gamma g}+r^2\epsilon^{\gamma\gamma}]\,, \quad (2)$$

where $r\equiv\rho\xi$ [$=\Gamma(b'\to\gamma b)/\Gamma_{\rm tot}$] is the absolute photonic branching ratio of the b' quark. We conservatively used the lower values of $\epsilon^{\gamma g}$ and $\epsilon^{\gamma W}$ at given $m_{b'}$ for the value of $\epsilon^{\gamma g}$ in Eq. (2). The calculated $N_{b'}$ for $r=0.1$ are shown in Fig. 2. The hatched area indicates the ambiguity from a luminosity measurement (3%), radiative correction (2%), the estimated efficiency of event selection (3%) and its dependence on c.m. energy (4%), and the systematics of detector response (3%). Considering other systematic uncertainties from a fragmentation model and its parameters we used a combined systematic error of $\pm10\%$ over the whole mass region. Figure 3(a) shows the excluded region in the plane of $m_{b'}$ and r at a 95%-confidence level. Assuming the dominant FCNC decay ($\rho=1$) and the typical value of $\xi=0.1$, a b' mass between 11.4 and 27.3 GeV/c^2 has been excluded. Also obtained are the limits at a 95%-confidence level on the FCNC processes at different values of ξ. They are presented by solid lines in Fig. 3(b). Another excluded region was obtained from the previous study[1] on isolated e/μ events at c.m. energy between 56 and 57 GeV, where no candidate b' events were found. Considering both CC and FCNC decays of b', and using the same selection criteria as in Ref. 1, the expected numbers of b' events were calculated at given values of $m_{b'}$ and ρ. The limits obtained at a 95%-confidence level are shown by a dashed line in the figure. Combined with the results from isolated photons at $\xi=0.1$, we can exclude b' with masses between 13.0 and 25.6 GeV/c^2 without depending on the decay processes.

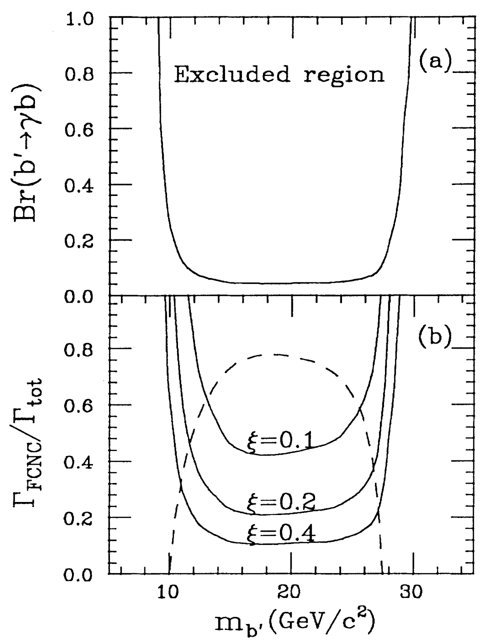

FIG. 3. Excluded region at a 95%-confidence level of (a) the absolute photonic branching ration, and (b) $\Gamma_{\rm FCNC}/\Gamma_{\rm tot}$ obtained from the isolated photon events at $\xi=0.1$, 0.2, and 0.4 (solid lines) and from the isolated e/μ events (dashed line).

In summary, we searched for the b' quark by studying isolated photons in multihadronic events from 21.1-pb^{-1} data taken at c.m. energies of e^+e^- between 55.0 and 60.8 GeV. The observed spectrum is in good agreement with that expected from the known five quark flavors. Considering both FCNC and CC decay processes, limits on the b' mass and the absolute photonic branching ratio at a 95%-confidence level were obtained. Also obtained was the excluded region of the FCNC processes from the analysis of isolated leptons as well as isolated photons.

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[5]The c.m. energies (luminosities) of the data sample are 55 GeV (1.7 pb^{-1}), 56 (5.3), 57 (5.1), 58.8 (2.9), 60 (3.2), and 60.8 (2.8). The luminosities are given by LA and the errors are about 1% in statistical and 2.7% in systematic. The values at 57 and 58.8 GeV are combined ones at neighboring energies.

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[7]A good track is reconstructed from eight or more hit points in axial layers and four or more ones in slant layers in CDC and satisfies the conditions described in the text.

[8]r-ϕ and r-z indicate planes which contain the interaction point and whose normal lines are parallel and perpendicular to the beam direction, respectively.

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