Search for Isolated Leptons in Low-Thrust e^+e^- Annihilation Events at $\sqrt{s}=50$ and 52 GeV

S. Igarashi,[1] S. S. Myung,[17] R. Chiba,[1] K. Hanaoka,[1] M. Miyashita,[1] H. Murata,[1] H. Yokota,[1] A. Bacala,[2] R. Imlay,[2] P. Kirk,[2] R. R. McNeil,[2] W. Metcalf,[2] C. P. Cheng,[3] Z. P. Mao,[3] Y. Yan,[3] Y. T. Xu,[3] H. S. Zhou,[3] Y. C. Zhu,[3] A. Abashian,[4] K. Gotow,[4] F. Kajino,[4] F. Naito,[4] R. Childers,[5] C. Darden,[5] J. Edwards,[5] S. Lusin,[5] C. Rosenfeld,[5] S. Wilson,[5] D. Johnson,[6] M. Frautschi,[6] H. Kagan,[6] R. Kass,[6] C. G. Trahern,[6] H. Y. Lee,[7] Winston Ko,[8] R. L. Lander,[8] K. Maeshima,[8] R. L. Malchow,[8] K. Sparks,[8] M. C. S. Williams,[8] K. Abe,[9] S. Chakrabarti,[9] Y. Fujii,[9] Y. Higashi,[9] S. Ishimoto,[9] Y. Kurihara,[9] A. Maki,[9] T. Nozaki,[9] T. Omori,[9] P. Perez,[9] H. Sagawa,[9] Y. Sakai,[9] Y. Sugimoto,[9] Y. Takaiwa,[9] S. Terada,[9] K. Tsuchiya,[9] R. Poling,[11] A. Aldritch,[12] J. Green,[12] I. H. Park,[12] S. Sakamoto,[12] F. Sannes,[12] S. Schnetzer,[12] R. Stone,[12] S. Trentalange,[12] D. Zimmerman,[12] K. Miyano,[13] H. Miyata,[13] M. Ogawa,[13] Y. Yamashita,[14] D. Blanis,[15] A. Bodek,[15] H. Budd,[15] R. Coombes,[15] S. Eno,[15] C. A. Fry,[15] H. Harada,[15] Y. H. Ho,[15] Y. K. Kim,[15] T. Kumita,[15] T. Mori,[15] S. L. Olsen,[10,15] N. M. Shaw,[15] A. Sill,[15] E. H. Thorndike,[15] K. Ueno,[15] H. W. Zheng,[15] H. Asakura,[16] K. Eguchi,[16] H. Itoh,[16] S. Kobayashi,[16] A. Murakami,[16] K. Toyoshima,[16] J. S. Kang,[17] H. J. Kim,[17] S. K. Kim,[17] M. H. Lee,[17] E. J. Kim,[18] G. N. Kim,[18] D. Son,[18] H. Kozuka,[19] S. Matsumoto,[19] T. Sasaki,[19] T. Takeda,[19] R. Tanaka,[19] Y. Ishi,[20] T. Ishizuka,[20] T. Maruta,[20] and K. Ohta[20]

(The AMY Collaboration)

[1]*Tokyo Institute of Technology, Tokyo 152*
[2]*Louisiana State University, Baton Rouge, Louisiana 70803*
[3]*Institute for High Energy Physics, Beijing*
[4]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[5]*University of South Carolina, Columbia, South Carolina 29208*
[6]*Ohio State University, Columbus, Ohio 43210*
[7]*Chungnam National University, Daejeon 300-31*
[8]*University of California, Davis, Davis, California 95616*
[9]*KEK, National Laboratory for High Energy Physics, Ibaraki 305*
[10]*Tsukuba University, Ibaraki 305*
[11]*University of Minnesota, Minneapolis, Minnesota 55455*
[12]*Rutgers University, New Brunswick, New Jersey 08854*
[13]*Niigata University, Niigata 950-21*
[14]*Nihon Dental College, Niigata 951*
[15]*University of Rochester, Rochester, New York, 14627*
[16]*Saga University, Saga 840*
[17]*Korea University, Seoul 132*
[18]*Kyungpook National University, Taegu 635*
[19]*Chuo University, Tokyo 112*
[20]*Saitama University, Urawa 338*
(Received 29 December 1987)

Multihadronic e^+e^- annihilation events containing final-state leptons have been investigated with a 4.7-pb^{-1} data sample at c.m. energies of 50 and 52 GeV. The number of low-thrust events ($T \leq 0.8$) with isolated leptons is consistent with the expectation of the standard model with five quark flavors. Limits on the production of new quarks and leptons are reported.

PACS numbers: 13.65.+i

At e^+e^- energies just above production threshold, the decays of new heavy quarks, which are nearly at rest, result in isotropic event topologies that are quite distinct from the two-jet structure characteristic of lighter-quark production. Quarks carrying a new flavor quantum number would have three-body semileptonic weak decays with branching fraction of $\frac{1}{9}$ for each of the e, μ and τ channels. The kinematics of the semileptonic decay process results in final-state leptons that are usually well separated from the associated hadrons. Similarly, a new sequential lepton would have decays $L \to l\nu_L\bar{\nu}_l$ with a branching fraction $\frac{1}{9}$ each to $l=e,\mu,\tau$, and decay $L \to \nu_L$+hadrons with branching fraction $\frac{2}{3}$, resulting in events with a primary electron or muon well isolated from hadrons. Thus, multihadronic e^+e^- annihilation events with final-state isolated leptons are a good signature for the production of new particles. The observation[1] at c.m. energies $46.3 \leq \sqrt{s} < 46.8$ GeV of events with low thrust containing muons at wide angles relative to the thrust axis by the Mark J and JADE experiments at the DESY e^+e^- storage ring PETRA has been interpreted as an indication of the production of a new charge $-\frac{1}{3}$ quark.[2] However, since an excess of such muon events has not been seen by the CELLO experiment at PETRA,[3] and since none of the PETRA experiments have seen similar events with electrons, the experimental situation remains unsettled. In this communication we report on a search for such events at $\sqrt{s}=50$ and 52 GeV in the AMY detector at the KEK storage ring TRISTAN.

The AMY detector[4] is a compact, high-resolution detector based on a 3-T solenoid and optimized for lepton detection. Charged particle tracking is done by a four-layer tube-type inner tracking chamber (ITC) at a radius of 13 cm followed by a cylindrical drift chamber (CDC) with 25 axial and 15 stereo layers extending to an outer radius of 67 cm. Charged tracks are detected efficiently over the polar-angle region $|\cos\theta| \leq 0.87$; transverse momenta (p_t) are determined with a precision $\Delta p_t/p_t \simeq (0.9\ \mathrm{GeV}^{-1})cp_t\,\%$. The small size of the central tracking region minimizes the number of muons from kaon and pion decays in flight. Outside of the CDC and inside the coil is a finely segmented 14.4-radiation-length cylindrical electromagnetic calorimeter (SHC) covering the region $|\cos\theta| \leq 0.73$. The SHC is constructed from twenty alternating layers of lead and gas proportional tubes. The signals induced on orthogonal cathode strips, located on each side of an anode wire, are tower ganged into five depth segments. The position of the centroid of electromagnetic showers is determined with a precision of ± 3 mm. This fine spatial resolution minimizes the misidentification of pions as electrons due to accidental overlap of photon and charged-particle tracks. The energy resolution of the SHC is $\sigma_E/E \simeq [(23\ \mathrm{GeV}^{1/2})/\sqrt{E}+6]\%$. In the end-cap region are lead/scintillator calorimeters covering the region $15° \leq \theta \leq 39.5°$. The integrated luminosity is determined from the number of Bhabha-scattering ($e^+e^- \rightarrow e^+e^-$) events detected in the end-cap calorimeters, as described in Ref. 4.

The SHC chamber, coil, and iron flux return act as a hadron filter with an average thickness equivalent to 1.65 m of iron. Outside of the iron flux return is a five-layer muon detector consisting of two orthogonal double-layer planar drift chambers follows by scintillation counters providing timing information to within ± 3 ns. The muon detector covers the region $|\cos\theta| \leq 0.74$. A p_t of 1.9 GeV/c is needed for muons to penetrate the hadron absorber; the penetration efficiency reaches 100% for p_t greater than 2.5 GeV/c.

The detector is triggered by energy deposition in the barrel or end-cap calorimeters, and by a variety of track patterns from the ITC and CDC chambers. The latter includes two-track and multitrack triggers. Multihadronic annihilation events were selected with use of the criteria described in Ref. 4; namely, (a) five or more charged tracks in the CDC with $|\cos\theta| \leq 0.85$; (b) the total visible energy (E_{vis}) in the CDC and SHC in excess of half the total CM energy; (c) the total longitudinal momentum imbalance less than $0.4E_{\mathrm{vis}}$; and (d) at least 3 GeV of energy deposited in the SHC. These cuts reduce the contamination from two-photon–initiated processes, τ pairs, and beam-gas interactions to a level of less than 2%. The 0.7-pb^{-1} data sample at $\sqrt{s}=50$ GeV and the 4.0-pb^{-1} data sample at $\sqrt{s}=52$ GeV contain 95 and 473 hadronic events, respectively.

Muons in multihadronic events are selected by the requirement of hits in any three of the four muon-chamber layers and matching of the hits to an extrapolated CDC track. The muon-counter timing information is used to reject cosmic-ray tracks that are out of time with the beam crossing. In order to maintain high efficiency, we impose a matching requirement of 1 m which is loose as compared with the present extrapolation uncertainty from multiple scattering and CDC track reconstruction. From low-momentum muons in $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ events and high-momentum muons in $e^+e^- \rightarrow \mu^+\mu^-$ events, it is determined that 94% of muons penetrating the absorber satisfy the tracking and matching requirements. A total of 38 events (5 at $\sqrt{s}=50$ GeV and 33 at $\sqrt{s}=52$ GeV) with a matching CDC track of momentum greater than 1.9 GeV/c are selected. Since two of the events have two muons, a total of forty inclusive muon tracks are observed.

Electrons in the multihadronic events are selected by their energy deposition in the SHC ($|\cos\theta| \leq 0.71$). A shower in the SHC is defined as an energy cluster greater than 0.2 GeV within the region of $\pm 3°$ in both θ and ϕ directions. Charged tracks with momentum greater than 2.5 GeV/c and within $\pm 2°$ (in ϕ and θ) of a shower are classified as electron candidates if (a) the ratio of the energy measured in the calorimeter to the momentum of the charged track is between 0.7 and 1.5 and (b) the longitudinal shape of the shower is consistent with that of an electromagnetic shower. The efficiency for selection of isolated electrons is determined to be 86% for $p > 2.5$ GeV/c, by application of the electron-selection requirements to a sample of electrons from $e^+e^- \rightarrow e^+e^-e^+e^-$ events. Although further cuts could be imposed to improve pion rejection, these are not applied in order to maintain high efficiency. The number of electron events selected is 6 and 38 for the 50- and 52-GeV data samples, respectively. Since three events have two electrons, the total sample of electron tracks is 47.

For the events with final-state leptons, we perform an

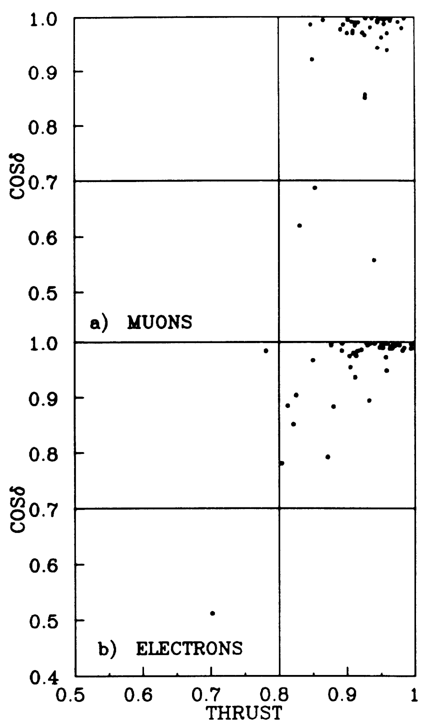

FIG. 1. The distribution of T and $\cos\delta$ for (a) the 40 inclusive muons and (b) the 47 inclusive electrons at $\sqrt{s}=50$ and 52 GeV.

analysis similar to that done by the PETRA experiments.[1,3] The value of the thrust[5] (T) and the direction of the thrust axis are calculated with the lepton excluded, and the isolation angle δ is defined to be the angle between the lepton and the thrust axis of the remaining particles. The region of low thrust is defined as $T \leq 0.8$ and the region of large isolation angle as $\cos\delta \leq 0.7$. In order to ensure that only particles that could be reconstructed with precision are used, only the energy of particles in the CDC and SHC are included in the thrust calculation. The energy from the end caps is excluded from both data and Monte Carlo analysis. We address the effect of our including the end-cap energy in a later section.

The backgrounds to the muon and electron samples are calculated for each of the regions of thrust and isolation angle by use of all of the charged tracks in the multihadron-event sample that satisfy the momentum and geometrical requirements. The background to the muon sample is calculated by our weighting each charged track by momentum-dependent decay and punch-through probabilities.[6] The muon sample is thus determined to be 65% prompt, where prompt is defined as originating from heavy flavors. For the calculation of background to the electron sample, the number of charged tracks is multiplied by a misidentification probability determined from tests in a hadron beam. Background due to the overlap of charged tracks and photons is determined by our varying the accepted region of a match between the SHC cluster and the CDC track. An additional background of nonprompt electrons from π^0 and kaon decays and from photon conversions in the beam pipe is estimated by means of a Monte Carlo simulation. With the present loose selection cuts, the background level in the electron sample is about 75% overall.

TABLE I. Comparison of lepton numbers for various thrust and isolation regions in the data and Monte Carlo (MC) simulations for five quark flavors and new heavy quark (t or b') with full excitation (see text). The errors include only statistical errors. The background-subtracted data numbers have been rounded to the nearest positive integer.

	Total	$T<0.8$	$\cos\delta<0.7$	$T<0.8$, $\cos\delta<0.7$
		No. of muons		
Expt. data	40 ± 7	0 ± 1	3 ± 1.7	0 ± 1
Prompt μ	28 ± 7	0 ± 1	3 ± 1.7	0 ± 1
MC				
Five-quark	24.9 ± 2.1	2.7 ± 0.7	1.3 ± 0.5	0.9 ± 0.4
Full open t	50.3 ± 2.3	33.5 ± 1.9	26.6 ± 1.7	18.5 ± 1.4
Full open b'	10.6 ± 0.6	6.6 ± 0.5	6.1 ± 0.5	3.8 ± 0.4
		No. of electrons		
Expt. data	47 ± 7	2 ± 1.4	1 ± 1	1 ± 1
Prompt e	11 ± 7	0 ± 1.4	0 ± 1	1 ± 1
MC				
Five-quark	18.7 ± 1.8	1.0 ± 0.4	0.6 ± 0.3	0.2 ± 0.2
Full open t	42.0 ± 2.0	28.0 ± 1.6	24.6 ± 1.5	15.9 ± 1.3
Full open b'	7.6 ± 0.5	4.8 ± 0.4	4.4 ± 0.4	2.7 ± 0.3

Figure 1 shows the scatter plot of $\cos\delta$ versus thrust for the muon and electron candidate events. Table I lists the total number ($\sqrt{s}=50$ and 52 GeV combined) of electrons and muons in each region of thrust and isolation angle. The background-subtracted prompt lepton numbers are to be compared with expectations from the LUND 6.3 Monte Carlo[7] program with five quark flavors, and also for a sixth flavored quark which is given a mass of 25 GeV and a production rate corresponding to full open quark production (the new quark only contributes to the 4 pb^{-1} at 52 GeV). The measured number of prompt leptons in all regions is in agreement with the expectation of the five-quark model. There is no anomalous excess of low-thrust events with isolated muons or electrons.

With full excitation, the production of t quarks ($q=\frac{2}{3}$) is expected[8] to result in an increase in R, the ratio of $e^+e^- \rightarrow$ hadrons to the QED cross section for $e^+e^- \rightarrow \mu^+\mu^-$, of $\Delta R_t = 1.5$. The corresponding expectation for the production of a new b' quark ($q=-\frac{1}{3}$) is $\Delta R_{b'}=0.48$ If $\sqrt{s}=52$ GeV were well above threshold for production of a new sequential lepton, the total cross section would be $\sigma_{e^+e^-\rightarrow L^+L^-}=34.5$ pb including weak interference effects.[8]

From Monte Carlo studies, it is determined that the best limit on new-quark production is obtained with use of the number of low-thrust lepton events without the imposition of isolation requirements. Using the combined muon- and electron-data sample, we observe two low-thrust electron events. Under the conservative assumption that these events are all due to a new quark, we obtain the 95%-confidence-level (C.L.) limits $\Delta R(t$ quark$) \leq 0.15$ and $\Delta R(b'$ quark$) \leq 0.26$, ruling out t-quark production with $\geq 10\%$ excitation, and b' quarks with $\geq 54\%$ excitation. The threshold behavior for heavy-quark production is believed to resemble a step function, because of QCD effects,[9] rather than the $\beta(3-\beta^2)/2$ threshold factor expected for the production of pointlike spin-$\frac{1}{2}$ particles (where β is the c.m. velocity of the produced particles). Our data indicate that the position of such a steplike threshold for either t or b' quarks must be higher than 52 GeV. Under the conservative assumption that the pointlike spin-$\frac{1}{2}$ threshold factor is applicable, 95%-C.L. lower mass limits of 25.9 GeV/c^2 for $q=\frac{2}{3}$ and 24.4 GeV/c^2 for $q=-\frac{1}{3}$ quarks are obtained, ruling out 23-GeV/c^2 $q=-\frac{1}{3}$ charged quark production as an explanation for the low-thrust isolated muon events at PETRA.

Heavy-lepton decays would result in large amounts of energy carried by neutrinos. For this reason, selection requirements designed to be efficient for $e^+e^- \to q\bar{q}$ events are inefficient for $e^+e^- \to L^+L^-$ events. The efficiency for heavy-lepton events is improved by our relaxing the hadronic-event charged-track requirement to a minimum of four tracks, changing the total visible energy requirement to $0.3 \leq E_{\text{vis}}/\sqrt{s} \leq 0.85$, and discarding the longitudinal-momentum–balance requirement. To reduce the background from quark-pair production, a minimum missing transverse momentum requirement of $0.3E_{\text{vis}}$ is imposed. Monte Carlo studies indicate that high sensitivity to heavy-lepton detection is obtained by the additional requirement of an isolated electron or muon. The total number of isolated lepton events in the data satisfying the above requirements is one electron event. As we expect 5.5 such events from a Monte Carlo simulation of 25-GeV/c^2 lepton-pair production, a mass limit is obtained for new sequential heavy-lepton production of 25.0 GeV/c^2 at 95% C.L.[10]

With use of a Monte Carlo generator, the sensitivity to new phenomena with isolated low-thrust lepton events as the signature was studied for the AMY detector at $\sqrt{s}=52$ GeV and the Mark J detector[1] at $\sqrt{s}=46.7$ GeV. Monte Carlo events were generated according to three different production models: $e^+e^- \to b'\bar{b}'$, where b' is a charge $-\frac{1}{3}$ quark of mass 23 GeV/c^2; $e^+e^- \to \gamma H$ ($H \to$ leptons$+X$), where H is a Higgs particle of mass 30 GeV/c^2; and $e^+e^- \to L^+L^-$, where L is a lepton of mass 23 GeV/c^2. These three reactions span a wide range of different production kinematics. Since AMY is sensitive to these processes using both muons and electrons, and because AMY has accumulated 4.7 pb^{-1} of luminosity compared with 2.8 pb^{-1} at Mark J, AMY would expect to observe about 3 times as many low-thrust isolated lepton events for these processes as Mark J observe low-thrust isolated muon events.

Several of the Mark J and JADE isolated low-thrust muon events are accompanied by large electromagnetic energy deposits.[1] As a check of whether we would miss observing these events because of a more restrictive geometrical acceptance than Mark J or JADE, we repeat the analysis and include the electromagnetic energy in the end caps in the calculation of the thrust and in the hadronic-event selection cuts. This increases the inclusive lepton sample to 42 muons and 53 electrons. The number of muon events in the region of low thrust and large isolation increases to one, and the number of electrons in this region remains one. The expected number of isolated low-thrust lepton events in the five-quark Monte Carlo simulation increases from 1.1 to 1.3 events because of increased hadronic-event acceptance and initial-state radiation. Our result is still consistent with the prediction of the standard model with five quark flavors and no significant excess of isolated low-thrust lepton events is observed.

We thank the TRISTAN staff for the rapid commissioning and excellent operation of the storage ring. In addition we acknowledge the strong support and enthusiastic assistance provided by the staffs of our home institutions. This work has been supported by the Japan Ministry of Education, Science and Culture (Monbusho), the U.S. Department of Energy and National Science Foundation, the Korean Science and Engineering Foundation and Ministry of Education, and the Academia Sinica of the People's Republic of China.

[1]B. Adeva *et al.* (MARK J Collaboration), Phys. Rev. D **34**, 681 (1986); W. Bartel *et al.* (JADE Collaboration), Z. Phys. C **36**, 15 (1987).

[2]F. Cornet *et al.*, Phys. Lett. B **174**, 224 (1986); V. Barger, R. J. N. Philips, and A. Soni, Phys. Rev. Lett. **57**, 1518 (1986).

[3]H. J. Behrend *et al.* (CELLO Collaboration), Phys. Lett. B **193**, 157 (1987).

[4]H. Sagawa *et al.* (AMY Collaboration), Phys. Rev. Lett. **60**, 93 (1988).

[5]E. Farhi, Phys. Rev. Lett. **39**, 1587 (1977).

[6]F. A. Harris *et al.*, Nucl. Instrum. Methods **103**, 345 (1972); A. Bodek, University of Rochester Report No. UR911, 1985 (unpublished).

[7]T. Sjostrand, Comput. Phys. Commun. **43**, 367 (1987).

[8]Here we have used $\sin^2\theta_W=0.23$, $M_Z=92.0$ GeV/c^2, and $\Lambda_{\overline{\text{MS}}}=0.2$ GeV.

[9]J. Jersak, E. Laermann, and P. M. Zerwas, Phys. Rev. D **25**, 1218 (1982); T. Appelquist and H. D. Politzer, Phys. Rev. D **12**, 1404 (1975).

[10]An analysis using selection requirements optimized (including additional decay modes) for a heavy-lepton search can improve the mass limit. This analysis will be the subject of a future paper.