Measurement of $e^+e^- \to b\bar{b}$ Forward-Backward Change Asymmetry between $\sqrt{s}=52$ and 57 GeV

H. Sagawa,[1] J. Lim,[2] K. Abe,[1] Y. Fujii,[1] Y. Higashi,[1] S. K. Kim,[1] Y. Kurihara,[1] A. Maki,[1] T. Nozaki,[1] T. Omori,[1] Y. Sakai,[1] Y. Sugimoto,[1] Y. Takaiwa,[1] S. Terada,[1] R. Imlay,[2] P. Kirk,[2] R. R. McNeil,[2] W. Metcalf,[2] S. S. Myung,[2] C. P. Cheng,[3] P. Gu,[3] J. Li,[1,3] Y. K. Li,[3] Z. P. Mao,[3] Y. T. Xu,[3] Y. C. Zhu,[3] A. Abashian,[4] K. Gotow,[4] K. P. Hu,[4] E. H. Low,[4] M. E. Mattson,[4] L. Piilonen,[4] K. L. Sterner,[4] S. Lusin,[5] C. Rosenfeld,[5] A. T. M. Wang,[5] S. Wilson,[5] M. Frautschi,[6] H. Kagan,[6] R. Kass,[6] C. G. Trahern,[6] G. N. Kim,[7] Winston Ko,[7] R. L. Lander,[7] K. Maeshima,[7] R. L. Malchow,[7] J. R. Smith,[7] K. Sparks,[7] D. Stuart,[7] M. C. S. Williams,[7] F. Kajino,[9] D. Perticone,[10] R. Poling,[10] T. Thomas,[10] A. Bacala,[11] I. H. Park,[11] F. Sannes,[10] S. Schnetzer,[11] R. Stone,[11] J. Vinson,[11] Y. Ishi,[12] K. Miyano,[12] H. Miyata,[12] T. Sasaki,[12] Y. Yamashita,[13] D. Blanis,[14] A. Bodek,[14] H. Budd,[14] S. Eno,[14] C. A. Fry,[14] H. Harada,[14] Y. H. Ho,[14] Y. K. Kim,[14] T. Kumita,[14] T. Mori,[14] S. L. Olsen,[8,14] P. Perez,[14] N. M. Shaw,[14] A. Sill,[14] E. H. Thorndike,[14] K. Ueno,[14] H. W. Zheng,[14] H. Itoh,[15] H. Ichinose,[15] S. Kobayashi,[15] A. Murakami,[15] K. Toyoshima,[15] J. S. Kang,[16] H. J. Kim,[16] M. H. Lee,[16] D. H. Han,[17] E. J. Kim,[17] D. Son,[17] H. Kozuka,[18] S. Matsumoto,[18] T. Takeda,[18] R. Tanaka,[18] H. Yokota,[19] T. Ishizuka,[20] and K. Ohta[20]

[1]*National Laboratory for High Energy Physics (KEK), Ibaraki 305*
[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]*University of California, Davis, California 95616*
[8]*Tsukuba University, Ibaraki 305*
[9]*Konan University, Kobe 658*
[10]*University of Minnesota, Minneapolis, Minnesota 55455*
[11]*Rutgers University, Piscataway, New Jersey 08854*
[12]*Niigata University, Niigata 950-21*
[13]*Nihon Dental College, Niigata 951*
[14]*University of Rocheter, Rochester, New York 14627*
[15]*Saga University, Saga 840*
[16]*Korea University, Seoul 132*
[17]*Kyungpook National University, Taegu 635*
[18]*Chuo University, Tokyo 112*
[19]*Tokyo Institute of Technology, Tokyo 152*
[20]*Saitama University, Urawa 338*
(Received 17 July 1989)

Using 123 multihadronic inclusive muon-production e^+e^- annihilation events at an average c.m. energy of 55.2 GeV, we extracted the forward-backward charge asymmetry of the $e^+e^- \to b\bar{b}$ process and the R ratio for $b\bar{b}$ production. We used an analysis method in which the behavior of the c quark and lighter quarks is assumed, with only that of the b quark left indeterminate. The results, $A_b = -0.72 \pm 0.28(\text{stat}) \pm 0.13(\text{syst})$ and $R_b = 0.57 \pm 0.16 \pm 0.10$, are consistent with the standard model.

PACS numbers: 13.65.+i, 12.15.Ff

In the standard model of electroweak interactions, the quarks and leptons form left-handed doublets and right-handed singlets in the weak-isospin representation. While there is as yet no direct evidence for the sixth quark (t quark),[1] the scheme with three families of doublets of leptons and quarks, including the t quark as a counterpart of the b quark, has been successful in explaining a wide range of experimental phenomena. It is therefore generally accepted that the t quark will eventually be found as higher-energy accelerators become operational. Meanwhile, in the absence of direct experimental evidence for the t quark, it is an important test of the standard model to continue to check whether the properties of the b quark are consistent with the interpretation of the b quark as a $T_3 = -\frac{1}{2}$ member of a $(t,b)_L$ weak-isospin doublet, where T_3 is the third component of weak isospin. Production of $b\bar{b}$ in e^+e^- annihilation at c.m. energies with significant contributions from the Z^0 provides an excellent testing ground for this interpretation. The coupling of the $b\bar{b}$ pair to the Z^0, expressed in terms of the vector and axial-vector coupling constants g_V^b and g_A^b depends on T_{3L} and T_{3R}, where L and R stand for left handed and right handed, respectively. Thus, the coupling varies depending on whether the b quarks are assigned to a doublet or singlet. While this difference has some effect on R_b (the b-quark contribution to the total hadronic cross section in units of the lowest-order QED cross section for $e^+e^- \to \mu^+\mu^-$), its effect on the forward-backward charge asymmetry in the $e^+e^- \to b\bar{b}$ process, A_b, is rather dramatic. The angular distribution for the $e^+e^- \to b\bar{b}$ is described by

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s} R_b (1 + \cos^2\theta + \tfrac{8}{3} A_b \cos\theta) , \qquad (1)$$

where α is the fine-structure constant, s is the square of the c.m. energy, and θ is defined as the angle of the outgoing b ($\bar{b}$) with respect to the incoming e^- (e^+) direction. Ignoring the QCD corrections, which amount to about 5% in our energy region, R_b and A_b are expressed as

$$R_b = 3\{Q_b^3 - 8Q_b g_V^e g_V^b \,\mathrm{Re}(\chi) + 16[(g_V^e)^2 + (g_A^e)^2 (g_V^b)^2 + (g_A^b)^2] |\chi|^2\} , \qquad (2)$$

$$A_b = 3[-6Q_b g_A^e g_A^b \,\mathrm{Re}(\chi) + 48 g_V^e g_V^b g_A^e g_A^b |\chi|^2]/R_b , \qquad (3)$$

where Q_b is the charge of the b quark and χ is the contribution from the Z^0 given by

$$\chi = \frac{1}{16\sin^2\theta_W \cos^2\theta_W} \frac{s}{s - M_Z^2 + i\Gamma_Z M_Z} . \qquad (4)$$

As can be seen in the above formula, the asymmetry A_b strongly depends on g_A^b, which in the standard model is simply T_{3L}. The asymmetry is expected to reach maximum at TRISTAN energies. As an example, using $\sqrt{s} = 55.2$ GeV, $M_Z = 91$ GeV, $\Gamma_Z = 2.5$ GeV, $\sin^2\theta_W = 0.230$, and including QCD corrections up to third order, the standard-model prediction for A_b is -0.55. Here $g_A^b = -\frac{1}{2}$, corresponding to the left-handed and right-handed b quarks belonging to a doublet and singlet, respectively. For the simplest alternative model without a t quark, in which both left-handed and right-handed b quarks are assigned to singlets,[2] we have $g_A^b = 0$ and, consequently, A_b becomes zero. On the other hand, changing g_A^b from $-\frac{1}{2}$ to 0 changes R_b from 0.55 to 0.38; a difference that is not as striking as that for A_b.

We have extracted the forward-backward of the charge asymmetry of the $e^+e^- \to b\bar{b}$ process using multihadronic inclusive muon events accumulated by the AMY detector at the KEK e^+e^- storage ring TRISTAN. The AMY detector[3] is a compact detector based on a 3-T solenoidal magnet and is optimized for lepton identification. Charged particles are detected by a tube-type inner tracking chamber (ITC) and a cylindrical drift chamber (CDC). Between the CDC and the magnet coil is a finely segmented electromagnetic shower counter (SHC). Outside the coil and the iron flux return, which also serve as a 1.6-m-iron-equivalent hadron filter, are drift chambers and scintillation counters for muon identification (MUO). These detectors cover the region $|\cos\theta| \leq 0.74$. The end-cap region is covered by simple calorimeters and is used for detecting Bhabha events to measure the luminosity.

The presence of prompt muons within hadronic jets indicates that the events originated either from c or b quarks. The charge of each muon reflects the sign of the parent quark charge. In selecting inclusive muon events, we imposed the standard AMY hadronic event criteria[3] with the additional requirement of the presence of at least one muon hit. A muon hit requires a track in the muon drift chamber consisting of at least three out of a total of four planes, with timing, measured by scintillation counters, consistent with the beam crossing, and a matching with the extrapolated position of one of the CDC tracks. When a track is within a hadronic jet, the CDC reconstruction efficiency is about 95%. The reconstruction efficiency of the muon detection system was determined to be 98% from a study of cosmic rays. Backgrounds to the muon signal (hadron fakes) arise principally from hadron showers in the hadron filter, where the debris reaches the muon chamber (punch-throughs), or from the decay of $\pi^\pm$ and $K^\pm$ mesons, before they are absorbed in the hadron filter, to a muon that reaches the muon chamber (decay). The matching distance cut, which was determined from a study of true muons (from the $e^+e^-\mu^+\mu^-$ data sample and those in the prompt muon fraction originating from the c- and b-flavor hadrons in a Monte Carlo simulation), is a smoothly varying function of the extrapolated track momentum at the muon chamber, becoming almost constant (at 14 cm) above 5 GeV/c. About 88% of the true muons that are reconstructed by the CDC and the muon chamber system satisfy the matching distance cut. A minimum momentum of 1.9 GeV/c is required for the muons. The overall detection efficiency for muons above 3 GeV/c in the angular region of $|\cos\theta| \leq 0.74$ is 82%.

In a data sample corresponding to an integrated luminosity of 18.6 pb^{-1} accumulated between $\sqrt{s} = 52$ and 57 GeV, we find 123 events passing the multihadronic inclusive muon selection criteria. This data sample contains events of interest, namely $e^+e^- \to b\bar{b}$ with subsequent semileptonic decay either directly, $b \to \mu^-$ ($\bar{b} \to \mu^+$), or by the cascade decay, $b \to c \to \mu^+$ ($\bar{b} \to \bar{c} \to \mu^-$).[4] It also contains additional prompt muons coming from $e^+e^- \to c\bar{c}$, followed by $c \to \mu^+$ ($\bar{c} \to \mu^-$), and hadron fakes. For the determination of the forward-backward charge asymmetry for $e^+e^- \to b\bar{b}$, we assume that the yield and asymmetry of $e^+e^- \to c\bar{c}$ is correctly described by the standard model. We estimate the contributions from the $c\bar{c}$ production as well as those from hadron fakes by using a Monte Carlo simulation, where five flavors are generated according to the standard model using the LUND 6.3 event generator.[5] We subtract these contributions from the data in order to obtain the $e^+e^- \to b\bar{b}$ sample. Estimation of the fraction of hadron fakes coming from b-flavored hadrons requires knowledge of $e^+e^- \to b\bar{b}$, which we are trying to determine. While such an assumption is not strictly valid, we apply it to the present case because the fraction of hadron fakes coming from the b-flavor hadrons is only $\sim \frac{1}{10}$ of those originating from u-, d-, s-, and c-flavor hadrons. The Monte Carlo simulation is also used for estimating the ratio of muons from $b\bar{b}$ cascade decays to those from direct decays. This is justified because this ratio depends only on the decay kinematics of the b quark and not on the dynamics of the $b\bar{b}$ pair production. The cascade decay produces muons with charge opposite to those produced by direct decay, and thus contributes oppositely to the asymmetry. We use our estimated ratio of the cascade decay to direct decay to correct for this effect. The estimated hadron fakes amount to about 35% of the data sample, of which 60% are punch-throughs and 40% are decays. Even though our punch-through calculation, which is based on the GHEISHA program,[6] agrees well with available experimental data for the pions, data for kaons is not available in our energy range. We estimate that about half of the punch-throughs are induced by K^+ mesons, mainly because of its smaller absorption cross section in the iron. This is the main source of the systematic uncertainty in this analysis.

The Monte Carlo study indicates that we can maximize the fraction of b quark by applying a cut of p_T greater than 0.7 GeV/c, where p_T is the transverse momentum of muons with respect to the event thrust axis. Thus, we divide the data into two p_T regions, below and above $p_T = 0.7$ GeV/c. The distributions for muon p_T and $\cos\theta$ of the data are shown in Figs. 1 and 2 together with the estimated contributions of $c\bar{c}$, hadron fakes, and the $b\bar{b}$ contribution obtained in this analysis. The muons from $\bar{b}$ extend toward higher-p_T values compared with those from $c\bar{c}$ and hadron fakes. This is expected because the muons from the semileptonic decays of b-flavored hadrons tend to have larger-p_T values, reflecting the fact that these hadrons are heavier than those of other flavors. The angle θ used in Fig. 2 is defined as the direction of the thrust axis associated with μ^- (μ^+) with respect to the incoming e^- (e^+) direction. As expected, the angular distribution for hadron fakes does not show any asymmetry, while the $c\bar{c}$ contribution has a positive asymmetry.

We have extracted A_b and R_b using the distributions for $p_T \geq 0.7$ GeV/c. After subtracting $c\bar{c}$ hadron fakes from the data sample, the resulting distribution was converted to the $e^+e^- \to b\bar{b}$ differential cross section by first correcting for (1) the effect of different θ definitions; (2) the efficiency for detecting the b quark by requiring a muon; (3) the effect of the cascade decay $b \to c \to \mu$; and (4) the muon detection efficiency of 82%, and then normalizing to the luminosity. We obtained a θ-dependent correction factor by dividing a Monte Carlo-generated $e^+e^- \to b\bar{b}$ angular distribu-

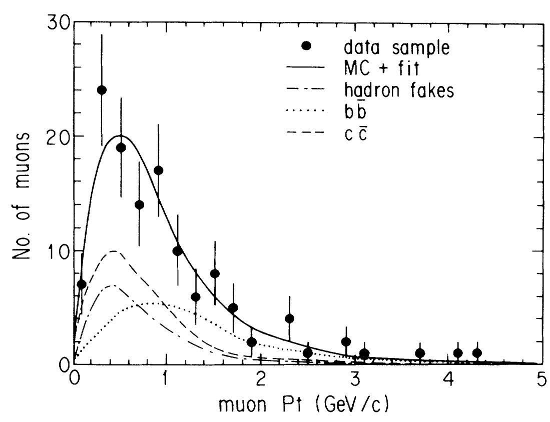

FIG. 1. The transverse momentum distribution of the muons with respect to the thrust axis for all multihadronic events including muons. Estimated contributions from $c\bar{c}$ and hadron fakes were determined from a Monte Carlo simulation. The $b\bar{b}$ was obtained from the analysis described in the text. The solid line is a sum of these three processes.

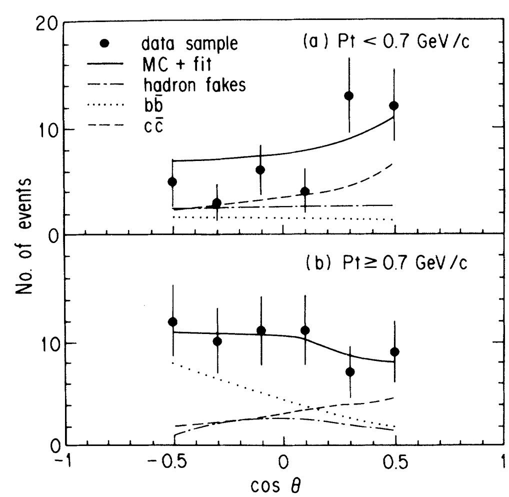

FIG. 2. The angular distribution $dN/d\cos\theta$ for the multihadronic events including muons. The data are divided into two separate regions, p_T (a) below and (b) above 0.7 GeV/c. Estimated contributions from $c\bar{c}$, hadron fakes, $b\bar{b}$, and their sum are also shown as in Fig. 1.

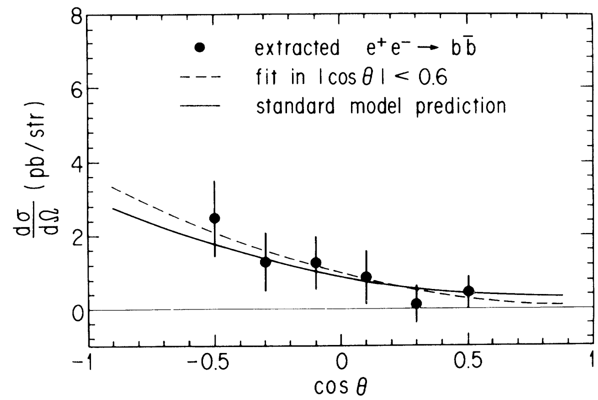

FIG. 3. $d\sigma/d\Omega$ of $e^+e^- \rightarrow b\bar{b}$ with the results of the fit. The standard-model prediction is also shown.

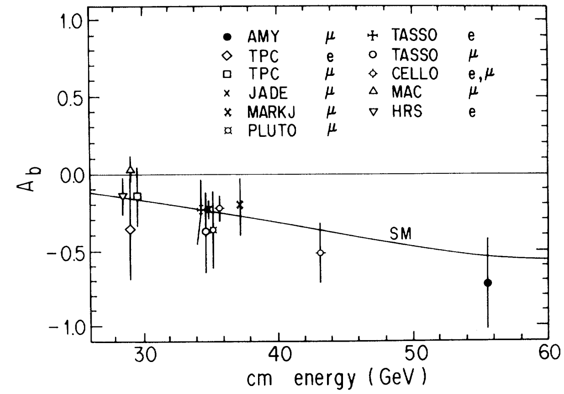

FIG. 4. The forward-backward charge asymmetry for $e^+e^- \rightarrow b\bar{b}$ as a function of the center-of-mass energy. The result of this experiment at a mean $\sqrt{s}=55.2$ GeV is compared with previous measurements at lower energies. The solid-line curve is the standard-model prediction using $M_Z=92$ GeV, $\Gamma_Z=2.5$ GeV, and $\sin^2\theta_W=0.230$.

tion, where θ was defined as the direction of the b quark, by an angular distribution of simulated $b\bar{b}$ events in which θ was defined as the direction of the thrust axis. We first used a $1+\cos^2\theta$ angular distribution. The observed asymmetry using this correction factor was then used in the Monte Carlo generator and a new correction factor was calculated. Unlike the first, which is symmetric in $\cos\theta$, the second correction factor has a slight $\cos\theta$ asymmetry which is caused by a combination of the nonzero asymmetry for $e^+e^- \rightarrow b\bar{b}$ and the nonzero ratio for $b \rightarrow c \rightarrow \mu/b \rightarrow \mu$. This second factor incorporates the effects described in items (1) through (4) listed above. The $e^+e^- \rightarrow b\bar{b}$ differential cross section was fitted by Eq. (1) in the region of $|\cos\theta| \leq 0.6$ and the asymmetry parameter A_b was obtained. The R ratio of the $b\bar{b}$ production, R_b, was also obtained from the fit. The results are shown in Fig. 3. In order to estimate systematic uncertainties, we repeated the analysis by varying the hadron-fake contribution by $\pm 30\%$, which corresponds to the fraction contributed by the K^+-induced punchthroughs. We use the largest shift in this analysis as our estimate of the systematic error.

Our final results, measured at an average c.m. energy of $\sqrt{s}=55.2$ GeV, are $A_b=-0.72\pm0.28\pm0.13$ and $R_b=0.57\pm0.16\pm0.10$, where the first and the second errors are statistical and sytematic, respectively. The effect of B^0-$\bar{B}^0$ mixing[7] is to reduce the observed asymmetry by an amount ranging from 6% to 36%.[8] The amount of this reduction depends on poorly known processes such as B_s^0-$\bar{B}_s^0$ mixing and the semileptonic branching ratios for all b mesons. We did not make any correction. These observed results are consistent with the standard-model predictions of $A_b=-0.56$ and $R_b=0.51$. Figure 4 compares our result for A_b with those from previous measurements at lower energies,[1,9] which are also not corrected for the B^0-$\bar{B}^0$ mixing. The measurements are consistent with the standard-model prediction throughout the energy region explored so far. Thus, the axial-vector coupling of the $b\bar{b}$ to the Z^0 is consistent with being $g_A^b=-\frac{1}{2}$.

We thank the TRISTAN staff for the 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) and Society for the Promotion of Science, 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] T. Kamae, in *Proceedings of the Twenty-Fourth International Conference on High Energy Physics, Munich, 1988,* edited by R. Kotthaus and J. H. Kuhn (Springer-Verlag, Berlin, 1989); UA1 Collaboration, C. Albajar *et al.*, Z. Phys. C **37**, 505 (1988).

[2] Various theoretical models of this type and their consequences were studied by several authors; see, for example, G. L. Kane and M. E. Peskin, Nucl. Phys. **B195**, 29 (1982). The most striking feature of the simplest of these models is the appearance of the flavor-changing neutral current (FCNC), which was subsequently ruled out experimentally; see P. Avery *et al.*, Phys. Rev. Lett. **53**, 1309 (1984). Various schemes to suppress the FCNC were proposed. References may be found in Kane and Peskin. For a more recently proposed model, based on supersymmetry, see Ernest Ma, Phys. Rev. D **35**, 851 (1987).

[3] AMY Collaboration, H. Sagawa *et al.* Phys. Rev. Lett. **60**, 93 (1988); AMY Collaboration, S. Igarashi *et al.*, Phys. Rev. Lett. **60**, 2359 (1988).

[4] The expression $b \rightarrow \mu^-$ is used for the process $B \rightarrow X_\mu^- \bar{\nu}_\mu$, where B is the b-flavor hadron. The other expressions follow this notation.

[5] T. Sjöstrand and M. Bengtsson, Comput. Phys. Commun. **43**, 367 (1987).

[6] H. Fesefeldt, Nucl. Instrum. Methods Phys. Res., Sect. A **263**, 114 (1987).

[7] ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. B

192, 245 (1987); CLEO Collaboration, M. Artuso *et al.*, Phys. Rev. Lett. **62**, 2233 (1989).

[8]K. Hagiwara *et al.*, Phys. Lett. B **219**, 369 (1989).

[9]JADE Collaboration, W. Bartel *et al.*, Phys. Lett. B **146**, 437 (1984); TASSO Collaboration, M. Althoff *et al.*, Phys. Lett. B **146**, 443 (1984); C. Kiesling, in Proceedings of the Twenty-Ninth Recontre de Moriond Conference, March 1989 (to be published); F. Ould-Saada, DESY Report No. 88-177, 1988 (unpublished); MAC Collaboration, H. R. Band *et al.*, Phys. Lett. B **218**, 369 (1989); HRS Collaboration, C. R. Ng *et al.*, ANL Report No. ANL-HEP-PR-88-11 (unpublished); S. L. Wu, Nucl. Phys. B (Proc. Suppl.) **3** (1988).