Observation of Charge Asymmetry in Hadron Jets from e^+e^- Annihilation at $\sqrt{s}=29$ GeV

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A charge asymmetry has been observed in final-state jets from e^+e^- annihilation into hadrons at $\sqrt{s}=29$ GeV. The measured asymmetry is consistent with the prediction of electroweak theory. The product of axial-vector weak coupling constants, averaged over all quark flavors, is determined to be $\langle g_A^e g_A^q \rangle = -0.34 \pm 0.06 \pm 0.05$.

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The electroweak theory is now well established in e^+e^- annihilation for the reactions $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \tau^+\tau^-$ through observation of the charge asymmetry in the angular distribution.[1] In contrast to these purely leptonic reactions, the weak neutral couplings of the quarks are not well determined experimentally because of complications introduced by final-state hadronization of the quarks and the large cancellation of the angular asymmetry between u-type quarks (u and c quarks) and d-type quarks (d, s, and b quarks). The weak neutral couplings of charm and bottom quarks have been measured via semileptonic decays of heavy flavored mesons or reconstructed charmed mesons.[2] Although flavor-tagging methods allow the study of these two heavy quarks separately, the statistical significance of the measurements is limited because of the low tagging efficiencies. In this paper the charge asymmetry of jets in inclusive hadronic events is used to study the weak neutral coupling of all quarks.

The measurement of a jet-charge asymmetry was first reported by Fernandez *et al.* for hadronic events accompanied by a hard photon in the reaction $e^+e^- \rightarrow q\bar{q}\gamma$.[3] In this reaction the charge asymmetry is largely a QED effect and the emphasis was primarily to measure quark charges. In the present study the jet-charge-asymmetry measurements have been extended to all two-jet events, and in this case the charge asymmetry is expected to result primarily from electroweak effects.

The measurement of jet charge has also been reported in deep inelastic lepton scattering[4] and neutrino scattering.[5] Since only u- or d-quark-initiated hadronic jets are produced in these reactions in contrast to the e^+e^- case, the quark fragmentation process and charge flow can be studied. In these measurements and in the previous work,[3] it has been shown that (1) jet-charge measurements provide a reliable method to tag the charge of the parent quarks; (2) the leading hadron in the jet has a high probability of containing the parent quark as a constituent; and (3) currently available Monte Carlo models of quark fragmentation reproduce the data quite well.

The parent data sample consists of approximately 10^5 multihadron events collected with the MAC detector at the Stanford Linear Accelerator Center storage ring PEP. The integrated luminosity of the sample is 220 pb^{-1} at a center-of-mass energy of 29 GeV. The MAC detector and the multihadron-event-selection criteria have been described previously.[6] The following additional requirements are imposed to select two-jet events: (1) At least five charged tracks per event are required, with at least two in each hemisphere defined by the plane perpendicular to the thrust axis calculated from the calorimeter energy deposition. (2) The thrust is required to be greater than 0.8 with $|\cos\theta| < 0.8$, where θ is the polar angle of the thrust axis. (3) To reduce $e^+e^- \rightarrow \tau^+\tau^-$ background in events with fewer than seven tracks, the tracks in at least one hemisphere are required to have an invariant mass greater than 1.78 GeV/c^2. A total of 80 380 events satisfy these requirements.

The jet charge Q_{jet} in each hemisphere is determined by

$$Q_{\mathrm{jet}} = \sum Q_i \eta_i^{\kappa},$$

where Q_i is the charge of the ith charged particle of the hemisphere, η_i is the rapidity of the ith particle, and κ is a constant.[7] The simple sum of the charges corresponds to $\kappa=0$. The sum is taken over all the charged tracks with momentum greater than 100 MeV/c that have at least six drift-chamber hits, and over all tracks with momentum greater than 500 MeV/c that have only five drift-chamber hits. The weight η_i^κ is introduced since particles with larger rapidity are expected to have a higher probability of carrying the parent-quark flavor. With this rapidity weight, neutral jets occur only with $\kappa=0$.

Various jet-charge combinations are observed. In a perfect detector events would contain either two neutral (for $\kappa=0$) or oppositely charged jets. Loss of tracks due to detector acceptance and drift-chamber inefficiency results in some events having jets with the same sign of charge. Moderately small values of κ give a higher efficiency for yielding events with oppositely charged jets. The value $\kappa=0.2$ was chosen to maximize the number of these events. With use of these 49402 events with oppositely charged jets, the jet-charge asymmetry is measured from the polar-angle distribution of the thrust axis, where the polar angle is defined to be the angle between the direction of the incident positron and the thrust axis, taken in the direction of the positively charged jet.

The charge asymmetry can also be measured by other techniques for determination of the jet charge. For example, the jet-charge asymmetry may be measured with only the leading particle in each jet to assign the jet charge. Also, rather than the charge asymmetry of the jets, the charge asymmetry may be determined with use of individual high-rapidity charged hadrons. These methods have been examined, and yield consistent results, but the expected and measured charge asymmetries are smaller.[7]

A Monte Carlo event sample was generated on the basis of the standard electroweak theory. Events were generated with the program of Berends, Kleiss, and Jadach for $e^+e^-\to q\bar{q}(\gamma)$,[8] and the quark fragmentation and QCD corrections were subsequently simulated with the Lund program.[9,10] These events were then processed through a detector simulation program and subjected to the same analysis procedure described above. A small charge asymmetry is expected to arise from QED as a result of interference between lowest-order and higher-order QED diagrams. This asymmetry was determined from the Monte Carlo event sample and found to be negligible compared with the electroweak contribution.

If we neglect quark masses and radiative effects, the differential cross section for quark-pair production is given in the electroweak theory as

$$\frac{d\sigma^q}{d\cos\theta}=\frac{\pi\alpha^2}{2s}R_{q\bar{q}}(1+\cos^2\theta+\tfrac{8}{3}A_{q\bar{q}}\cos\theta).$$

$R_{q\bar{q}}$ is the ratio of the total quark-pair cross section to the lowest-order QED muon-pair cross section, and is given by

$$R_{q\bar{q}}=3[Q_q^2-2Q_q g_V^e g_V^q \mathrm{Re}\chi + (g_V^{e2}+g_A^{e2})(g_V^{q2}+g_A^{q2})|\chi|^2],$$

where Q_q is the quark charge and $g_V^{e,q}$ and $g_A^{e,q}$ are the vector and axial-vector electroweak coupling constants of the electron and quark, respectively. $A_{q\bar{q}}$ is the forward-backward asymmetry for full acceptance and is given by

$$A_{q\bar{q}}=3(-\tfrac{3}{2}Q_q g_A^e g_A^q \mathrm{Re}\chi+3g_V^e g_V^q g_A^e g_A^q|\chi|^2)/R_{q\bar{q}}.$$

The quantity χ is given by

$$\chi=s/4\sin^2\theta_W\cos^2\theta_W(s-M_Z^2+iM_Z\Gamma_Z),$$

where θ_W is the Weinberg angle. The general formula for massive-quark production is too lengthy to be given here,[11] but the following calculation is based on the complete formula with the quark masses $m_u=m_d=0.3$ GeV/c^2, $m_s=0.5$ GeV/c^2, $m_c=1.5$ GeV/c^2, and $m_b=5.0$ GeV/c^2.

If the forward direction ($\theta=0$) is defined for the positive-charge quark with respect to the incident positron direction, the expected charge asymmetries are $A_{u\bar{u}}=A_{c\bar{c}}=+0.09$, $A_{d\bar{d}}=A_{s\bar{s}}=-0.18$, and $A_{b\bar{b}}=-0.16$. The resulting average charge asymmetry $\langle A\rangle$ of all flavors with proper production weights is $\langle A\rangle=+0.018$ at the quark level. However, the detection efficiency of events with oppositely charged jets is higher for the u-type quarks than for the d-type quarks, and the quark-charge misidentification probability is lower for the u-type quarks than for the d-type quarks. Since these two factors both favor the u-type quarks, a jet-charge asymmetry of about +0.02 is expected. In order to compare the prediction with the observed angular distribution, radiative corrections, detection efficiencies, and quark-charge misidentification probabilities were evaluated with the Monte Carlo method described above. According to these calculations, the detection efficiency of events with oppositely charged jets coming from the u-type quarks is about 10% higher than that of events from d-type quarks, and the quark-charge misidentification probability is about 20% for the u-type quarks and about 29% for the d-type quarks. The Monte Carlo–simulated events give a jet-charge asymmetry $\langle A\rangle=+0.022\pm0.005$, where the error is purely statistical. This simulation was based on standard electroweak theory with $\sin^2\theta_W=0.22$.

The measured differential cross section after efficiency and radiative corrections is shown in Fig. 1(a), with the dotted curve representing the pure QED distribution. The overall normalization of the data was adjusted to agree with the theoretical prediction. The difference between the measured cross section and that expected from pure QED, normalized to the total QED cross section, is

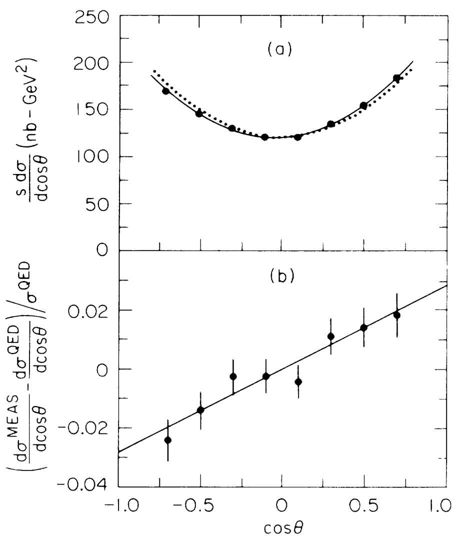

FIG. 1. (a) The measured differential cross section after efficiency and radiative corrections. The results of a one-parameter fit as described in the text are shown as the solid curve, together with the lowest-order QED cross section shown as the dotted curve. (b) The difference between the measured cross section and the QED cross section, divided by the total QED cross section. The solid line represents the fit to the angular distribution.

shown in Fig. 1(b). The data clearly show the expected linear dependence on $\cos\theta$. The average charge asymmetry determined by a maximum-likelihood fit is $\langle A \rangle = +0.028 \pm 0.005$ where the error is statistical. The fit is shown by the solid lines in Figs. 1(a) and 1(b). In order to minimize any bias introduced by the magnetic field, the magnetic field polarity was reversed periodically. The data samples for each polarity were examined separately and found to be consistent.

At the energy of the data presented here, the contribution of the second and third terms in $R_{q\bar{q}}$ is negligible (0.2% of the first term for $\sin^2\theta_W = 0.22$), in agreement with measurements of the hadronic cross section.[12] Since the second term of $A_{q\bar{q}}$ is also negligible, $A_{q\bar{q}}$ depends mostly on $g_A^e g_A^q$. If universality among different quark flavors is assumed, with the axial-vector electroweak coupling of the quarks defined as $g_A^u = -g_A^d = -g_A^s = g_A^c = -g_A^b \equiv g_A^q$, one parameter $\langle g_A^e g_A^q \rangle$ can be determined from the average charge asymmetry obtained from the data and the quark-charge misidentification probabilities evaluated by the Monte Carlo event sample. The coupling constant determined from the data is $\langle g_A^e g_A^q \rangle = -0.34 \pm 0.06$. As a consistency check, the maximum-likelihood fit has been applied to the Monte Carlo events based on the standard electroweak theory. The coupling constant obtained for this sample is $\langle g_A^e g_A^q \rangle = -0.27 \pm 0.06$, consistent with the input value $g_A^e g_A^q = -0.25$.

The procedure used for this analysis has been checked empirically with two different methods. The first method used flavor-separated heavy-quark jets which have a tagged charge from a semileptonic decay. This tagged charge can be compared to the jet charge and a quark-charge misidentification probability can be determined from the data and compared to the Monte Carlo prediction. A sample of 857 semileptonic events are selected from the same multihadron sample as the present analysis by the requirement of a muon with momentum greater than 2 GeV/c and momentum transverse to the thrust axis greater than 1 GeV/c.[13] According to a Monte Carlo calculation, this b-enriched event sample consists of 58% b-quark events, 10% c-quark events, and 32% light-quark events. The jet selection criteria described above have been applied to these events yielding 402 events with oppositely charged jets. The muon charge has been compared with the jet charge in the hemisphere which contains the muon. The signs of the muon charge and the jet charge disagree for $(32.3 \pm 2.3)\%$ of events. This comparison is a quantitative demonstration that the jet charge and the muon charge are correlated and that the jet charge carries the quark-charge information. The same comparison has been made for the Monte Carlo events. For this sample, the signs of the muon charge and the jet charge disagree for $(32.7 \pm 2.0)\%$ of events. This value is in excellent agreement with the data, indicating that the Monte Carlo modeling is quantitatively reliable.

The second method uses the measurement of the jet-charge asymmetry for hadronic events accompanied by a hard photon.[3] The charge asymmetry is predominantly of QED origin because of the interference between photon radiation from initial-state electrons and final-state quarks, and hence calculable independent of weak effects. In contrast with the electroweak asymmetry, there is no cancellation of the angular asymmetry between u-type quarks and d-type quarks and therefore a large charge asymmetry is expected. The events were selected from the same multihadron sample as before by the requirement of an isolated photon with energy greater than 3 GeV and less than 10 GeV. A sample of 1049 direct photon candidates was found with about 22% background coming from π^0 decays. The charge asymmetry observed for the data was $A = -0.123 \pm 0.035$, consistent with the Monte Carlo prediction $A = -0.117 \pm 0.026$. This comparison can be interpreted as a quantitative test of the charge assignment procedure.

The systematic errors on the coupling constant have been estimated as follows. Based on the above-mentioned check with lepton-tagged events, the quark-charge misidentification probability of the b quark is modeled properly by the Monte Carlo sample with an uncertainty of about 2%. If the same error is assumed for other quarks and the errors are assumed to contribute independently, the systematic error on the coupling constant is estimated to be about 9%. If the errors of different quarks are assumed to be correlated, the resulting error on the coupling constant would be negligible because of the cancellation of errors between the u-type and d-type quarks. The systematic errors are also estimated with the Monte Carlo sample by a change in the quark fragmentation function and parameters of the Lund program. The most sensitive parameter is found to be the fraction of sea quarks, $s\bar{s}/u\bar{u}$. A change in this fraction by $\Delta(s\bar{s}/u\bar{u})=0.1$ produces about a 10% change in the coupling-constant product. The systematic error due to the particular choice of κ to measure the jet charge has been estimated to be 5%. Systematic effects due to differences in the fragmentation models have been studied by comparison of the results with those obtained from the Webber Monte Carlo simulation.[14] This fragmentation model is quite different from that of Lund and provides a check of the procedure used to determine the jet charge. Since the results from the Webber simulation are consistent with the Lund model, systematic errors introduced by the choice of fragmentation model are estimated to be small compared to the systematic errors discussed above. With systematic errors, the result is

$$\langle g_A^e g_A^q \rangle = -0.34 \pm 0.06 \pm 0.05.$$

In conclusion, this experiment has measured for the first time an electroweak interference effect sensitive to contributions from all the quarks. The value determined for the product of electron and quark electroweak axial-vector couplings is consistent with the standard-model prediction, $g_A^e g_A^q = -0.25$ and agrees with the values measured by flavor-tagging methods for the c and b heavy quarks. Neutrino experiments have measured the chiral weak coupling constants $(g_L^q)^2$ and $(g_R^q)^2$ for the u and d quarks from the ratio of neutral-current and charged-current interactions and extracted the axial-vector coupling constants g_A^q.[15] The present measurement is also consistent with these results.

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