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

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ABSTRACT

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 $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ 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 due to complications introduced by final state hadronization of the quarks and the large cancellation of the angular asymmetry between u-type quarks (u- and c-quark) and d-type quarks (d-, s-, and b-quark). The weak neutral couplings of charm and bottom quarks have been measured via semi-leptonic 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 due to 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 the MAC collaboration for hadronic events accompanied by a hard photon in the reaction $e^+e^- \to q\bar{q}\gamma$.[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 MAC work, 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 multi-hadron events collected with the MAC detector at the Stanford Linear Accelerator Center PEP storage ring. The integrated luminosity of the sample is 220 pb^{-1} at a center of mass energy of 29 GeV. The detector components essential to the present analysis consist of a ten-layer central drift chamber and electromagnetic and hadronic shower detectors.[6] Charged particles are momentum analyzed in the drift chamber with momentum resolution $\delta p/p \simeq 0.065 p \sin\theta$ for $25^\circ \leq \theta \leq 155^\circ$, where θ is the polar angle with respect to the beam axis. The polar angle acceptance for tracks traversing at least 5 layers is $17^\circ \leq \theta \leq 163^\circ$. Surrounding the drift chamber is a hexagonal barrel of lead-plate electromagnetic calorimeters and iron-plate hadronic calorimeters, closed by iron-plate endcap calorimeters. The energy deposition in the calorimeters is measured by proportional wire chambers with charge division (barrel) or anode and cathode strip readout (endcap), thus providing two dimensional position information.

The multi-hadron event selection criteria have been described in a previous paper.[7] The following additional requirements are imposed to select two jet events: 1) At least 5 charged tracks per event are required, with at least 2 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 7 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:

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

where Q$_i$ is the charge of the i'th charged particle of the hemisphere, η_i is the rapidity of the i'th particle and κ is a constant.[8] The simple sum of the charges corresponds to κ=0. The sum is taken over all the charged tracks with momentum greater than 100 MeV/c that have at least 6 drift chamber hits, and over all tracks with momentum greater than 500 MeV/c that have only 5 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.

Various jet charge combinations are observed. In a perfect detector events would contain either two neutral 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 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. Using these 49,402 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 using other techniques for determining the jet charge. For example, the jet charge asymmetry may be measured using 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 using individual high rapidity charged hadrons. These methods have been examined, and yield consistent results, but the expected and measured charge asymmetries are smaller.

A Monte Carlo event sample was generated based on the standard electroweak theory. Events were generated with the program of Berends, Kleiss and Jadach for $e^+e^- \to q\bar{q}(\gamma)$,[9] and the quark fragmentation and QCD corrections were subsequently simulated with the Lund program.[10,11] 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 due to interference between lowest order and higher order QED diagrams. This asymmetry was determined from the Monte Carlo and found to be negligible compared with the electroweak contribution.

Neglecting quark masses and radiative effects, the differential cross section for quark pair production is given in the electroweak theory as:

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

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

$$R_{qq} = 3(Q_q^2 - 2Q_q g_V^e g_V^q Re\chi + ({g_V^e}^2 + {g_A^e}^2)({g_V^q}^2 + {g_A^q}^2)|\chi|^2),$$

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_{qq} is the forward-backward asymmetry for full acceptance and is given by:

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

The quantity χ is given by

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

where θ_W is the Weinberg angle. The general formula for massive quark production is too lengthy to be given here,[12] 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^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 $A_{uu} = +0.09$ for the u-type quark, $A_{dd} = -0.18$ for the light d-type quark, and $A_{bb} = -0.16$ for the b quark. 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 27% for the d-type quarks. The Monte Carlo simulated events give a jet charge asymmetry $\langle A \rangle = +0.022 \pm 0.005$ 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 shown in Fig. 1(b). The data clearly shows 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 Fig. 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_{qq} is negligible (0.2% of the first term for $\sin^2\theta_W$=0.22), in agreement with measurements of the hadronic cross section.[13] Since the second term of A_{qq} is also negligible, A_{qq} 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. 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 systematic errors due to the Monte Carlo evaluation of the detection efficiencies and the quark charge misidentification probabilities are estimated by changing 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 of $\Delta(s\bar{s}/u\bar{u})$ =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 9%. 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.[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 Lund, 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 electroweak contributions from light as well as heavy quarks in e^+e^- annihilation. The value determined for the product of electron and quark electroweak axial 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.

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FIGURE CAPTIONS

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.

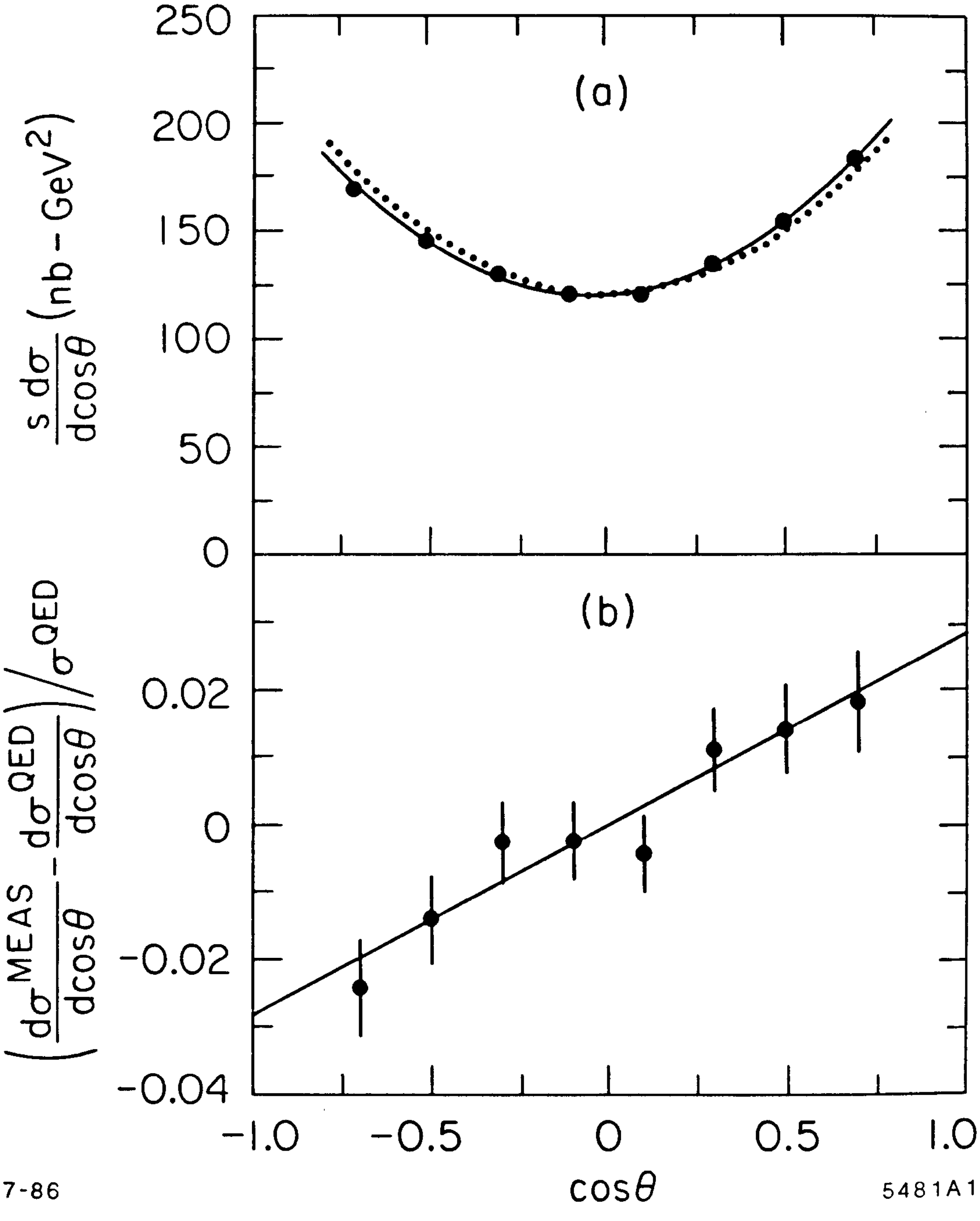
(a)
(b)
250
200
150
100
50
0
0.02
0
−0.02
−0.04
−1.0
−0.5
0
0.5
1.0
$\frac{s\,d\sigma}{d\cos\theta}$ (nb − GeV^2)
$\left(\frac{d\sigma^{MEAS}}{d\cos\theta} - \frac{d\sigma^{QED}}{d\cos\theta}\right) \Big/ \sigma^{QED}$
cosθ
7-86
5481A1

Fig. 1