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Weak Neutral Currents in e^+e^- Collisions at $\sqrt{s}=29$ GeV

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The differential cross sections for lepton pair production in e^+e^- annihilation at 29 GeV have been measured and found to be in good agreement with the standard model of the electroweak interaction. With the assumption of $e-\mu-\tau$ universality, the weak neutral-current couplings are determined to be $g_a^2=0.23\pm 0.05$ and $g_v^2=0.03\pm 0.04$.

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We report a high-statistics measurement of the differential cross sections for the reactions

$$e^+e^- \rightarrow e^+e^-, \quad (1)$$

$$e^+e^- \rightarrow \mu^+\mu^-, \quad (2)$$

$$e^+e^- \rightarrow \tau^+\tau^-, \quad (3)$$

at a center-of-mass energy \sqrt{s} of 29 GeV. These cross sections are sensitive to the interference between the electromagnetic current and the weak neutral current. The weak neutral current is characterized by two dimensionless coupling constants g_a (axial vector) and g_v (vector). For processes (1)–(3) the standard electroweak theory of minimal $SU(2) \otimes U(1)$ predicts¹ $g_a = -\frac{1}{2}$ and relates g_v to the weak mixing angle, $g_v = 2 \sin^2\theta_w - \frac{1}{2}$.

Including the exchange of a neutral vector boson of mass $M_z \gg \sqrt{s}$, the unpolarized relativistic cross section to order G_F for Reactions (2) and (3) is

$$\frac{4s}{\alpha^2} \frac{d\sigma}{d\Omega} = (1 + \cos^2\theta) \left(1 + \frac{G_F g_v^e g_v^l}{\pi \alpha \sqrt{2}} \frac{s M_z^2}{s - M_z^2} \right) + \left(\frac{2G_F g_a^e g_a^l}{\pi \alpha \sqrt{2}} \frac{s M_z^2}{s - M_z^2} \right) \cos\theta$$

where G_F is the Fermi coupling constant, and θ is the angle between the outgoing positive lepton l and the positron beam direction \hat{z} . Terms proportional to G_F arise from the interference between the weak and the QED amplitudes. The axial-vector component produces a forward-backward asymmetry in Reactions (2) and (3), and the

vector component shifts their cross section relative to QED expectations; both g_a and g_v modify the shape of the differential cross section in Reaction (1). The expression for Bhabha scattering [Reaction (1)] is more complicated because of t -channel exchange diagrams.

This measurement is based on a data sample corresponding to an integrated luminosity of 100 pb^{-1} accumulated by the Mark II detector³ at the e^+e^- storage ring PEP. Multilayer cylindrical drift chambers in a 2.3-kG solenoidal field measure charged-particle momenta with a resolution $\sigma_p \approx (0.0095 \text{ c}^2/\text{GeV}^2)p^2$. Flight times (TOF) are determined with a resolution of ~ 320 psec for particles with $|\cos\theta| < 0.76$ by scintillation counters located at a radius of 1.5 m. Eight lead-liquid argon (LA) calorimeter modules that extend to $|\cos\theta| = 0.7$ detect electromagnetic showers with an energy resolution of $\sigma_E \approx (0.14 \text{ GeV}^{-1/2})\sqrt{E}$. Proportional tubes interleaved in an iron hadron absorber (total 787 g/cm^2) detect muons over 45% of 4π . The detector is triggered by any two charged particles with momentum transverse to the beam axis $p_t > 100 \text{ MeV}/c$ entering the TOF counters (charged trigger) or by deposition of more than 1 GeV in each of two or more LA modules (neutral trigger).

In lowest order, $e^+e^- \rightarrow e^+e^-$ or $\mu^+\mu^-$ events have two collinear high-momentum tracks in the final state; however, initial- and final-state radiation introduce an acollinearity in the outgoing leptons, and photon conversions in the material (3% X_0) surrounding the interaction point increase

the multiplicity. Bhabha and μ -pair candidates are selected from events with up to six charged particles and any number of final-state photons. In these events we require two oppositely charged particles (denoted l^+ and l^-) collinear within 20° with momenta $p > 7.25$ GeV/c and measured flight times within 3 nsec of the expected times. We restrict this sample to events for which l^+ has $|\cos\theta| < 0.7$. An event is classified as a Bhabha (μ pair) if l^+ and l^- both deposit more (less) than 2 GeV in the LA system. When only one of these particles enters the active region of the LA, classification is based on its energy deposition alone. With these selection criteria our sample contains 5312 μ pairs and 81309 Bhabha events.

The selection criteria for $e^+e^- \rightarrow \tau^+\tau^-$ are more complicated because of the decay of the tau. However, the simple topology of the low-charge-multiplicity^{4,5} tau decays at 29 GeV allows events to be found with little background. A tau sample is selected from events which contain one charged prong isolated by at least 120° from all other charged prongs. Events with more than six or fewer than two charged particles are not considered. This procedure selects tau pairs with a $1+m$ ($1 \leq m \leq 5$) detected charged decay topology; the following additional criteria reduce the background contribution to this sample. The thrust axis⁶ \vec{T} is calculated from all observed charged prongs and neutral particles detected in the LA calorimeter. These particles are divided into two "jets" by the plane perpendicular to the thrust axis. Background from $e^+e^- \rightarrow$ hadrons is reduced by requiring the invariant mass of each jet to be less than 2.5 GeV/c² where all charged particles are assumed to be pions. We denote the most energetic charged particle in each jet by the symbols n_1 and n_2 and define a unit vector \hat{n} along the direction of the most energetic isolated prong. We distinguish the $e^+e^- \rightarrow \tau^+\tau^-$ events from Reactions (1) and (2) by requiring either n_1 or n_2 to have $p < 7.25$ GeV/c. To reject cosmic rays we require n_1 and n_2 to have measured flight times within 3 nsec of the expected times. To reject two-photon events ($e^+e^- \rightarrow e^+e^-l^+l^-$, $l=e, \mu, \tau$, hadrons) we require the net p_t (with respect to the beam axis) in the event to be greater than 0.5 GeV/c, and the detected energy to be greater than 6.0 GeV. We further reduce two-photon backgrounds by rejecting events in which both n_1 and n_2 penetrate the hadron absorber ($e^+e^- \mu^+\mu^-$), and by selecting events only when either n_1 or n_2 enters the LA system and deposits an energy less than half its momentum ($e^+e^-e^+e^-$).⁷ To elimi-

nate radiative Bhabhas from the tau sample we require the sum of the LA shower energy plus the momentum imbalance along the z axis to be less than 23 GeV. After background reduction the tau sample is restricted to $|\cos\theta| < 0.7$, where the value of $\cos\theta$ is taken to be $q(\hat{T} \cdot \hat{z})(\hat{n} \cdot \hat{T})/|\hat{n} \cdot \hat{T}|$ and q is the charge of the most energetic isolated prong (i.e., θ is the angle between \hat{T} , taken in the direction of the τ^+ , and the positron beam direction). Monte Carlo simulation indicates that θ accurately represents the τ^+ production angle to about 4° . After all selection criteria are applied there are 3714 events in the tau sample.

The observed $\cos\theta$ distributions are corrected bin by bin for backgrounds, selection inefficiencies, and detector acceptance. Backgrounds to $e^+e^- \rightarrow \mu^+\mu^-$ from hadrons or decays of the tau are determined from the number of $\mu^+\mu^-$ candidates that do not penetrate the hadron absorber. Other backgrounds are estimated by Monte Carlo simulation. Total background corrections of 0.03% (mostly from $e^+e^- \rightarrow \tau^+\tau^-$) and $(2.9 \pm 0.9)\%$ ($e^+e^- \rightarrow e^+e^- \mu^+\mu^-$, $\tau^+\tau^-$, hadrons) are applied to Reactions (1) and (2), respectively. Reaction (3) is corrected for contaminations of 1.6% from $e^+e^- \rightarrow \mu^+\mu^- (\gamma)$, 1.4% from $e^+e^- \rightarrow$ hadrons, and 3.1% from two-photon processes. Beam-gas and cosmic-ray backgrounds are negligible under the selection procedures. The background calculation for the two-photon processes is verified by identifying two-photon events with a small-angle tagging system which extends between 22 and 80 mrad from the beam axis. From comparisons of the observed tau invariant-mass and collinearity distributions with those from the Monte Carlo simulation we estimate that the total uncertainty in the background subtraction to Reaction (3) is approximately 1.7% .

Biases due to trigger, TOF, and charged-particle track-reconstruction efficiency are accurately measured and corrected. Corrections of this type largely cancel in any ratio of cross sections and are also shown to be angular and charge symmetric to within 0.4% .⁸ The efficiencies of both the charged trigger (0.980) and the TOF system (0.988 per track) are studied with Bhabha events which satisfy the neutral trigger. Charged-particle track-reconstruction efficiency (0.960 ± 0.003) is measured by selecting Bhabha events according to their signature in the liquid argon system. Corrections for losses due to selection cuts are determined by a Monte Carlo calculation that generates QED events to $O(\alpha^3)$. Including $\sim 9\%$ loss-

es due to the limited azimuthal coverage of the LA system, event acceptances at $\cos\theta = 0.0$ are 77%, 80%, and 60% for Reactions (1), (2), and (3), respectively, and fall to 73%, 77%, and 52% at $|\cos\theta| = 0.6$.

The acceptance-corrected, background-subtracted, differential cross sections are shown in Figs. 1(a)–1(c) and are compared to the $O(\alpha^3)$ QED prediction. Third-order QED processes can create angular asymmetries and normalization changes which are comparable to the weak-interaction effects. Asymmetries in the angular distribution arise from the interference between diagrams of opposite charge-conjugation parity.⁹ The QED prediction is derived from a Monte Carlo calculation¹⁰ that includes contributions from initial- and final-state radiation, vertex corrections, and leptonic and hadronic vacuum polarization. Within the experimental acceptance the QED forward-backward asymmetry is calculated to be $A_\mu^{\text{QED}} = 1.0\%$ in Reaction (2) and $A_\tau^{\text{QED}} = 0.5\%$ in Reaction (3).

Systematic errors in the relative normalization of Reactions (2) and (3) to Reaction (1) arise from

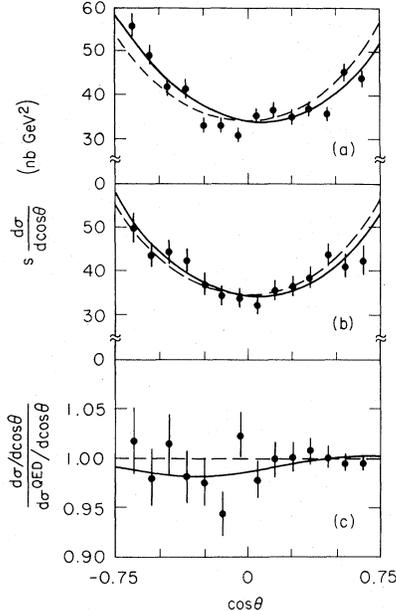


FIG. 1. The differential cross sections for (a) Reaction (2) and (b) Reaction (3), normalized to the QED prediction. (c) The ratio of the differential cross section for Reaction (1) to the $O(\alpha^3)$ QED prediction. The experimental cross section in (c) is normalized to the electroweak cross section taken from a simultaneous fit to all three reactions. In (a)–(c) the dashed line corresponds to the $O(\alpha^3)$ QED cross section and the solid line to the fitted cross section.

three major sources: (1) errors in the background estimates, 0.9% for $e^+e^- \rightarrow \mu^+\mu^-$ and 1.7% for $e^+e^- \rightarrow \tau^+\tau^-$, (2) errors in detector simulation, 0.6% in each process, and (3) uncertainty in the decay modes of the tau lepton. The error (1.8%) due to uncertainties in tau branching fractions is determined by folding the sensitivity to individual decay modes with the errors in the measurements of the branching fractions.⁴ We have neglected higher-order corrections to the $O(\alpha^3)$ QED cross section. These contributions ($\approx 1.1\%$) are estimated from a leading-log calculation¹¹ and are included in the systematic error estimate. Uncertainties in the hadronic vacuum-polarization corrections introduce an additional error in the relative normalizations of roughly 0.5%. Combining the errors from all sources listed in quadrature, we find a 1.6% normalization error on the ratio $\sigma_{\mu\mu}/\sigma_{ee}$ and a 2.8% error on the ratio $\sigma_{\tau\tau}/\sigma_{ee}$.

Reactions (1)–(3) are fitted by the $O(\alpha^3)$ QED cross section plus the weak contributions.² From maximum likelihood fits to the corrected $\cos\theta$ distributions, setting $g_v^2 = 0$, we find $g_a^e g_a^\mu = 0.32 \pm 0.07 \pm 0.02$ and $g_a^e g_a^\tau = 0.19 \pm 0.09 \pm 0.02$, where the first error is statistical and the second systematic.⁸ The fits yield acceptance-, background-, and QED-corrected forward-backward electroweak asymmetries, extrapolated to the full $\cos\theta$ interval, of $A_\mu^{\text{weak}} = -7.1\% \pm 1.7\%$ and $A_\tau^{\text{weak}} = -4.2\% \pm 2.0\%$ where the standard model predicts¹² $A^{\text{weak}} = -5.7\%$. The fitted cross sections are superimposed on the data in Figs. 1(a) and 1(b). The μ - τ universality of the axial-vector current is tested, and we find $g_a^\tau/g_a^\mu = 0.6 \pm 0.3$. If we assume e - μ - τ universality, then $g_a^2 = 0.27 \pm 0.06 \pm 0.02$ from Reactions (2) and (3). From a simultaneous fit to all three reactions which takes into account the angular distributions and relative cross sections, we find $g_a^2 = 0.23 \pm 0.05 \pm 0.02$ and $g_v^2 = 0.03 \pm 0.03 \pm 0.03$ where systematic errors have been explicitly included in the fit, and the fitted cross section is superimposed on the data in Fig. 1(c). These results are in good agreement with the standard model and with other experiments.^{5,13} The probability that QED alone would have led to the results presented here is 6×10^{-7} . The weak couplings above have been computed in the limit $M_z \rightarrow \infty$. Alternatively, the values quoted above may be considered to measure the product $g^2[M_z^2/(M_z^2 - s)]$. Also g_a^2 and g_v^2 only correspond to the couplings of the lowest-order Z^0 exchange diagram. Inclusion of the mass dependence and radiative corrections¹² to

g_a^2 for the recently discovered¹⁴ intermediate vector boson of mass $M_z \simeq 93 \text{ GeV}/c^2$ decreases g_a^2 by 2.5%.

Within the context of the standard model we have $g_a^2 = \frac{1}{4}$, $g_v^2 = (2 \sin^2 \theta_w - \frac{1}{2})^2$, and $M_z = 74.6 / \sin 2\theta_w \text{ GeV}/c^2$; allowing M_z to vary, we find from the combined fit $0.11 < \sin^2 \theta_w < 0.35$ (95% confidence limit) which is consistent with other experiments.¹³⁻¹⁶ If we assume $g_a^2 = \frac{1}{4}$ from the standard model, take $g_v^2 = 0.0016$ ($\sin^2 \theta_w = 0.23$) from neutrino-scattering experiments,¹⁵ and set $M_z = 93 \text{ GeV}/c^2$, then we find that the ratio of the measured to the expected cross section normalized to Bhabha events is $1.002 \pm 0.013 \pm 0.016$ in Reaction (2), and $0.996 \pm 0.016 \pm 0.028$ in Reaction (3).

Extended gauge models having several massive vector bosons allow the addition of a j_{em}^2 term to the effective Lagrangian

$$\mathcal{L}_{\text{eff}} = (4G_F/\sqrt{2})[(j_3 - \sin^2 \theta_w j_{em})^2 + C j_{em}^2],$$

where C is an arbitrary constant.¹⁷ Such a term in the Lagrangian cannot be probed by neutrino scattering or electron-nucleon experiments. However, this term can be seen at PEP/PETRA where the effect of C on the cross sections is to replace g_v^2 by $(\frac{1}{2} - 2 \sin^2 \theta_w)^2 + 4C$. If we assume $\sin^2 \theta_w = 0.23$ the data place an upper limit of 0.019 on C (95% confidence limit) which is comparable to other experiments.¹³

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