Experimental Study of Electroweak Parameters at PETRA Energies ($12 \leq E_{c.m.} \leq 36.7$ GeV)

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We have performed a high-statistics measurement of Bhabha scattering and of the production of hadrons in electron-positron annihilation at PETRA energies (12 GeV $\leq \sqrt{s} \leq$ 36.7 GeV). Combining the results with measurements of $\mu^+\mu^-$ and $\tau^+\tau^-$ production enables us to compare our results with electroweak theory. We find $\sin^2\theta_w = 0.27 \pm 0.08$. This is in good agreement with the value obtained from neutrino experiments which were carried out in entirely different kinematic regions.

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One of the major experimental achievements in the last decade has been the determination of the parameters of the electroweak theory. The theory of Glashow-Weinberg-Salam (GWS)[1] is characterized by a parameter denoted $\sin^2\theta_w$. Neutrino-nucleon scattering experiments,[2] which yield a value of $\sin^2\theta_w = 0.234 \pm 0.011$, are characterized by the following experimental conditions: (1) the relatively low c.m. energy, namely $s \approx 200$ GeV^2; (2) the relatively low momentum transfer $q^2 \approx -100$ GeV^2 in the spacelike region; (3) the use of nuclear targets.

We have performed a complementary experiment measuring electroweak parameters from the reactions

$$e^+ + e^- \to (\gamma + Z^0) \to l^+ l^- \quad (l = e, \mu, \tau) \tag{1}$$

and

$$e^+ + e^- \to (\gamma + Z^0) \to \text{hadrons}, \tag{2}$$

where the production of final-state leptons and hadrons is via both virtual photons (γ) and neutral intermediate vector bosons (Z^0). In comparison with neutrino experiments, the present experiment has the following unique properties: (a) high c.m. energy, namely $s \approx 1300$ GeV^2; (b) most data is at the large momentum transfer $q^2 \approx 1300$ GeV^2, and in both the spacelike and the timelike region; (c) purely pointlike particles in the initial state.

In comparing our data on $e^+e^- \to l^+l^-$ ($l = e, \mu, \tau$) with the predictions of electroweak theories,[3] we calculate the yields for Reactions (1) according to quantum electrodynamics (QED) using Monte Carlo programs which include order-α^3 radiative corrections.[4-6]

Our latest cross sections σ_{exp} for $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ have been reported elsewhere.[7] Our data limit the effects of neutral currents on these total cross sections to be near zero and therefore limit the neutral-current vector coupling to be small. The forward-backward asymmetry in $e^+e^- \to \mu^+\mu^-$ has also been used. Defining θ as the angle between the incident e^- and the outgoing μ in the forward hemisphere, the asymmetry is defined as

$$A = (N^- - N^+)/(N^- + N^+), \tag{3}$$

where N^- (N^+) is the corrected number of events with a negatively (positively) charged muon in the angular range $50° \leq \theta \leq 80°$. Our measured values for A are $A(\sqrt{s} = 30 \text{ GeV}) = -0.03 \pm 0.10$ and $A(\sqrt{s} = 35 \text{ GeV}) = +0.006 \pm 0.073$. For our experiment the corresponding predictions of the standard model[1] with $\sin^2\theta_w = 0.23$ are $A = -0.053$ at $\sqrt{s} = 30$ GeV and $A = -0.076$ at $\sqrt{s} = 35$ GeV. Our A value is ~2 standard deviations away from the $(V-A)$-theory prediction.

The cross section for $e^+e^- \to e^+e^-$ has been calculated to second order in the weak-interaction coupling strengths by Budny.[8] This experiment has a total of 2×10^5 events for $|\cos\theta| < 0.8$ for an integrated luminosity of 10 818 nb^{-1}, which represents a fourfold increase in statistics from our previous results.[3] In Fig. 1(a) we compare the combined cross section from 29.9 to 36.7 GeV with the predictions of QED. The sensitivity to weak effects is, however, demonstrated in Fig. 1(b), which shows the deviation of the combined data from the QED predictions as a function of $\cos\theta$. The errors shown in Fig. 1(b) include both statistical errors and an estimated point-to-point 3% systematic uncertainty. Also shown in Fig. 1(b) are the predictions of the electroweak theory[1] in terms of different values of vector and axial-vector coupling constants g_A and g_V. The best-fitted curve obtained from Bhabha scattering as well as $\mu^+\mu^-$, $\tau^+\tau^-$ production and $\mu^+\mu^-$ asymmetry is also included.

The overall constraints on g_A and g_V from the MARK-J data are obtained by fitting the e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$ cross sections along with the $\mu^+\mu^-$ asymmetry. In the framework of GWS we find $\sin^2\theta_w = 0.24 \pm 0.12$. We also fit g_V^2 and g_A^2 in the more general context of single-Z^0 models, and find $g_V^2 = -0.05 \pm 0.10$ and $g_A^2 = 0.21 \pm 0.18$, with $\chi^2 = 14.4$ for 23 degrees of freedom. These results, including correlations, can be converted into an allowed region in the g_V-g_A plane, as shown in Fig. 2. Also shown in the figure are neutrino electron scattering data $\nu_\mu e^- \to \nu_\mu e^-$, $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$, and $\bar{\nu}_e e^- \to \bar{\nu}_e e^-$, which limit the possible value of g_A and g_V to two regions in the g_V-g_A plane around ($g_V = 0$, $g_A = -\frac{1}{2}$) and ($g_V = -\frac{1}{2}$, $g_A = 0$).[9] By combining the MARK-J and the neutrino scattering data, the second solution is ruled out with more than 95% confidence. This confirms the conclusions drawn on the basis of deep-inelastic neutrino nuclear scattering and polar-

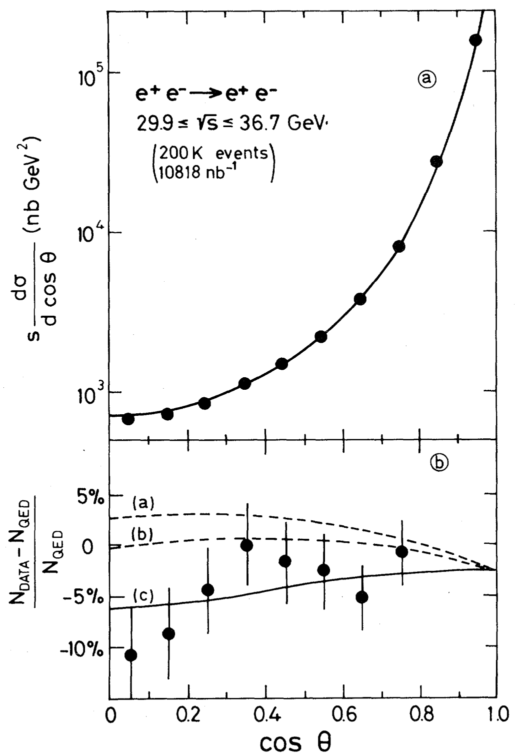

FIG. 1. (a) The differential cross section $d\sigma/d\cos\theta$ for $e^+e^- \to e^+e^-$. (b) The deviation of the QED predictions from the combined data is plotted as a function of $\cos\theta$. The error includes both statistical and 3% point-to-point systematic uncertainties. The curves *a*, *b*, and *c* represent the prediction of the electroweak theory with ($g_A^2 = \frac{1}{4}$, $g_V^2 = 0.16$), ($g_A^2 = \frac{1}{4}$, $g_V^2 = \frac{1}{4}$) and the best-fitted result ($g_A^2 = 0.21$, $g_V^2 = -0.05$), respectively. All three curves take into account that the luminosity obtained from the best fit (curve *c*) is lower than the measured one by 2.5%. (The uncertainty of the measured luminosity is 3%.)

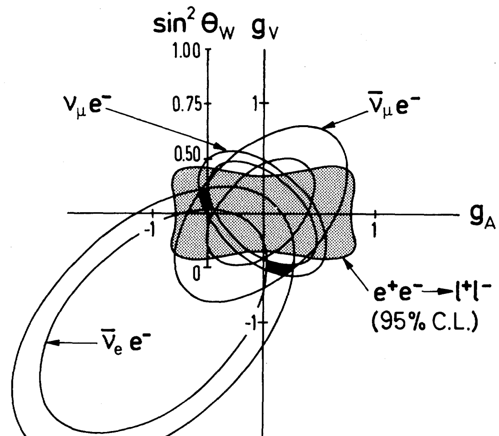

FIG. 2. Results obtained from neutrino experiments and the MARK-J experiment expressed in terms of limits on g_V and g_A. The region in between the concentric ellipses corresponds to 68%-confidence-level limits from the neutrino-electron scattering experiments. The two black areas indicate the two allowed regions for g_V and g_A from the combined neutrino data. The shaded area represents the 95%-confidence-level contour from the MARK-J experiment.

ized electron-deuterium scattering data, but without recourse to models of hadron production by the weak neutral current.

In Reaction (2) above, if one takes weak neutral-current effects into account, one can write the quark cross sections as[10]

$$R_f = \sigma(e^+e^- \to \gamma Z^0 \to f\bar{f})/\sigma_p = Q_f^2 - 8sQ_f g_V g_{V_f} g p(s) + 16s^2 g^2 (g_V^2 + g_A^2)(g_{V_f}^2 + g_{A_f}^2) p'(s), \tag{4}$$

where $\sigma_p = 4\pi\alpha^2/3s$ is the pointlike QED cross section, Q_f = charge of the final-state quark f, g_{V_f} and g_{A_f} are the weak vector and axial-vector coupling constants of quark f, and $g = 4.47\times 10^{-5}$ GeV^{-2} is related to the Fermi coupling constant. $p(s)$ and $p'(s)$ describe the propagator effects and are defined as

$$p(s) = [(s/m_Z^2 - 1) + \Gamma_Z^2/(s - m_Z^2)]^{-1} \tag{5a}$$

for γ and Z^0 interference, and

$$p'(s) = [(s/m_Z^2 - 1)^2 + \Gamma_Z^2/m_Z^2]^{-1} \tag{5b}$$

for pure Z^0 exchange.

In the framework of the GWS model, if we assume e-μ universality, the weak coupling constants are given by

$$g_{V_f} = (T_{3_f}{}^L - 2Q_f \sin^2\theta_w), \quad g_{A_f} = T_{3_f}{}^L, \tag{6}$$

where $T_{3_f}{}^L$ is the weak isospin of the left-handed quark. The mass of the Z^0 can be expressed as $m_Z = 37.28/\sin\theta_w \cos\theta_w$ GeV and the width is taken to be constant: $\Gamma_Z = 2.3$ GeV.[10]

The electroweak hadronic cross section R_T is given in the quark model by the incoherent sum over all final-state quarks including a color factor of 3 and QCD corrections[11]:

$$R_T = 3\sum_f R^f\left(1 + \frac{\alpha_s(s)}{\pi} + (1.98 - 0.115N_f)\frac{\alpha_s^2(s)}{\pi^2}\right), \tag{7}$$

where α_s is the coupling constant of the strong interaction, which has been measured at PETRA energies to be[12] $\alpha_s = 0.18$ for $\sqrt{s}$ in the 30–36 GeV range, and which changes slowly with energy. $N_f = 5$ is the number of different quark flavors.

The theoretical cross section R_T is compared with our experimental result R for different values of $\sin^2\theta_w$ in Fig. 3(a). A quantitative comparison is made with use of a χ^2 method, where χ^2 is defined as

$$\chi^2 = (F-1)^2/\sigma_{\mathrm{syst}}^2 + \sum_i (FR^i - R_T^i)/\sigma_i^2, \tag{8}$$

where the sum runs over all measurements at different c.m. energies, and where σ_i and σ_{syst} are the statistical and systematic errors, respectively. The systematic error σ_{syst} is estimated to be 10%. The scaling factor F is used in order to take into account the overall normalization uncertainties. With these data on R, we are able to limit g_V to be near zero.

Taking all MARK-J data on R into account,[13] we obtain the 95%- and 68%-confidence-level contours in the F-$\sin^2\theta_w$ plane as displayed in Fig. 3(b). The results are

$$0.12 \leq \sin^2\theta_w \leq 0.65$$

(95%-confidence-level limits) and

$$\sin^2\theta_w = 0.27^{+0.34}_{-0.08}$$

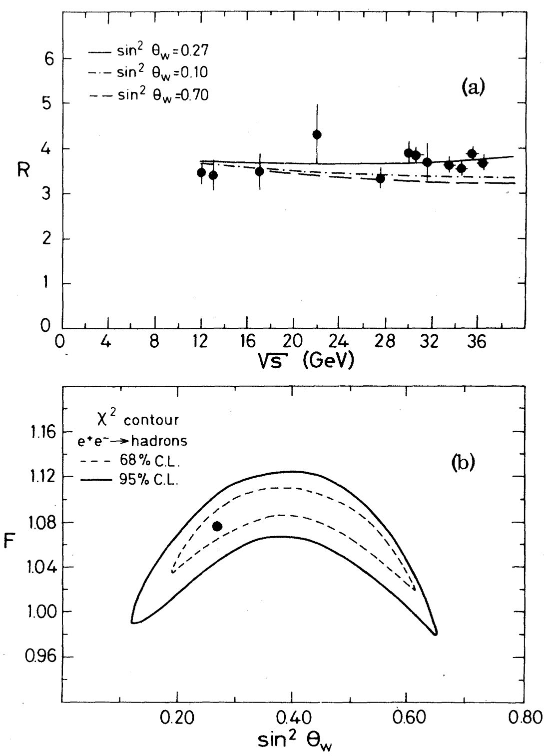

FIG. 3. (a) Experimental results on R with statistical errors as a function of the c.m. energy $\sqrt{s}$. The solid line shows the theoretical prediction R_T for the best fit to our data ($\sin^2\theta_w = 0.27$ by using $\alpha_s = 0.18$ at $\sqrt{s} = 30$ GeV). The dependence of R_T on $\sin^2\theta_w$ is also shown for two extreme values ($\sin^2\theta_w = 0.70$ and 0.10). The best-fitted results require that the normalization of the curves be scaled down by 7.5% as shown (the normalization uncertainty is 10%). (b) Scale factor F plotted against $\sin^2\theta_w$. The areas shown indicate the 95%- and 68%-confidence-level regions (inner curve). The minimum χ^2 (the dot) is obtained for $\sin^2\theta_w = 0.27$ and $F = 1.075$.

with a minimum χ^2 per degree of freedom = 1.14.

The limits on $\sin^2\theta_w$ change by $\lesssim 0.02$ for relatively large changes in α_s (0 to 0.24) and σ_{syst} (8% to 12%). The values for the coupling constant α_s and the scaling factor F are correlated; i.e., changes in α_s are compensated by an appropriate change in F. This demonstrates that the method applied is sensitive to the behavior of R as a function of energy and not to the absolute R values.

A combined analysis of MARK-J data for leptonic [Reaction (1)] and hadronic final states [Reaction (2)] yields

$$0.13 \leq \sin^2\theta_w \leq 0.42$$

(95%-confidence-level limits) and

$$\sin^2\theta_w = 0.27 \pm 0.08 .$$

We have performed many checks on our assignment of errors in the final value of $\sin^2\theta_w$. For example, we have used different sets of R values, including the use of only eleven measured points with $\sqrt{s} \geq 13$ GeV or slightly different hadron selection criteria with different energy cuts.[4] The $\sin^2\theta_w$ values obtained are within the errors assigned. Our value[14] of $\sin^2\theta_w$ is in good agreement with determinations by other groups at PETRA.[15,16]

In conclusion, our determination of $\sin^2\theta_w$ is in good agreement with the value obtained from neutrino scattering experiments.[2] The two types of experiments are done in entirely different kinematic regions. The good agreement in $\sin^2\theta_w$ obtained in the two types of experiments gives additional support to the validity of the GWS theory, and its applicability in the timelike region up to $q^2 = 1300\ \text{GeV}^2$.

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Surface Transparency and Resonant Behavior in Some Lighter–Heavy-Ion Reactions

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Resonance phenomena observed experimentally in some lighter–heavy-ion collisions at energies well above the Coulomb barrier are discussed in terms of the number of open channels available to direct reactions for the even-even C + C, C + O, and O + O systems. The calculated number of open channels shows a characteristic energy dependence which reflects the surface transparent absorption needed to observe resonant structure. The weak absorption is particularly pronounced in reactions involving ^{12}C, ^{14}C, and ^{16}O nuclei.

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Resonance phenomena are one of the most outstanding features of some lighter–heavy-ion collisons. They have now been observed in the excitation functions of various exit channels for a number of systems and for bombarding energies from the Coulomb barrier to several times the barrier heights.[1] The resonant structure was first discovered and confined to the ^{12}C + ^{12}C and ^{12}C + ^{16}O reactions[2] at energies close to the Coulomb barrier. The specificity of these two systems has been explained as a consequence of the small spreading width of the entrance-channel resonances which is due to the exceptional low level density of the corresponding compound nucleus.[3] As the experimental studies were extended to higher bombarding energies, one might have expected from a naive point of view a stronger absorption of the interaction potential resulting in smooth and gradual changes in cross sections as a function of energy. However, striking surprises emerged and recent experimental data[1] show clear evidence not only of the nonstatistical resonant behavior in many lighter–heavy-ion interactions at energies well above the Coulomb barrier but also of the key role played in the resonant process by inelastic and other direct reaction channels.

The aim of the present Letter is not to discuss the dynamics responsible for the observed structure, which is still an open question, but rather to evaluate in a quantitative way the favorable conditions for resonant phenomena not to be obscured by strong absorption at higher energies. This is because we think that the problem of the resonance width is as important as is the formation mechanism itself. Guided by the experimental observations,[1] we wanted in particular to explore the idea that at high incident energies, the observation of resonant structure might arise from weak absorption due to the small number of open direct reaction channels. If this were the case, it would be strongly correlated with a "surface transparent" interaction and not with the formation of a compound nucleus as already indicated by elastic scattering[4-6] and fusion-cross-section[7-10] experimental data and their interpretation. In particular, it has been shown recently[8-10] that the saturation of the fusion cross sections at high incident energies can be explained in terms of phase-space limitation for compound-nucleus formation. The obvious consequence is a vanishing contribution to the fusion process from the more peripheric partial waves with angular momenta between L_c, the corresponding limiting angular momentum for compound-nucleus formation, and L_g, the grazing angular momentum.

To get a systematic and quantitative understanding of resonant structure occurrence at bombarding energies above the Coulomb barrier, we have calculated for the experimentally well-studied even-even C + C, C + O, and O + O systems the number of open channels (NOC) which are, as a function of bombarding energy, available to carry away the angular momentum brought in by each incident partial wave. For each system NOC has been obtained by a triple summation over all possible two-body mass partitions in the exit channels, over all possible angular-momenta couplings, and, finally, over all possible energy

